PHYSICS
IN HOT PURSUIT

The Henryk Niewodniczanski
Institute of Nuclear Physics
Polish Academy of Sciences

July 2020

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INTRODUCTION

FOREWORD

We are constantly bombarded with streams of information. This also applies to new facts in the field of science - their number is growing rapidly. We have prepared this brochure especially for you in order to show you, in a nutshell, several interesting results of the work of our colleagues from the Institute of Nuclear Physics, Polish Academy of Sciences.

You will find that science, in this case physics, is not only attractive but easily becomes a fascinating adventure. What's more, it can change our lives in a qualitative way, as evidenced by, for example, the spread of the Internet. The World Wide Web (www) was invented to meet the need to communicate and share information within the physicists' community. Such an interesting and modern science knows no geographic or interpersonal boundaries, and we also practice it with great success in Poland, in particular at the Henryk Niewodniczański Institute of Nuclear Physics, the largest scientific institute of the Polish Academy of Sciences. At IFJ PAN, we pride ourselves on the fact that, sometimes working in large international research teams, we are also well known as part of the local and national community. Many visitors to our websites very often read popularizing reports, which we have been systematically publishing since 2015, and which then go to the EurekAlert! website, run by the American Association for the Development of Science (AAAS).

In order that you will not miss any news about modern physics, dear Reader, we invite you to browse through the 2016–2018 reports.

Editorial committee

ABOUT THE HENRYK NIEWODNICZAŃSKI INSTITUTE OF NUCLEAR PHYSICS

POLISH ACADEMY OF SCIENCES

INFORMATIONS ABOUT IFJ PAN

The Henry Niewodniczański Institute of Nuclear Physics (IFJ PAN) is the largest institute of the Polish Academy of Sciences, since 2014 rated the A+ category in the group of science and engineering. This is the highest scientific category awarded to the Institute by the Ministry of Science and Higher Education, for the second time now. The Institute, as a member of the Marian Smoluchowski Kraków Scientific Consortium "Matter – Energy – Future" also obtained the status of the Leading National Research Centre (KNOW) for the years 2012–2017. In 2017, the European Commission awarded the IFJ PAN the prestigious distinction of "HR Excellence in Research" as an institution applying the principles of the "European Charter for Researchers" and "Code of Conduct for the Recruitment of Researchers".

The Institute conducts basic and applied research in the field of physics and related sciences. Using the latest technological and IT achievements at IFJ PAN, research is carried out on the structure of matter and the properties of fundamental interactions from the cosmic scale to that of the elementary particles. In the field of basic research, which is the main task of the Institute, theoretical and experimental research is carried out in four main directions:

- particle physics and astrophysics
- nuclear physics and strong interaction
- condensed matter physics (including nano-materials)
- interdisciplinary and applied research, which involves medical physics, radiotherapy of cancer diseases with particular emphasis on protonotherapy, applications of physics in biology, dosimetry, environmental protection, nuclear geophysics, radiochemistry, high-temperature plasma diagnostics, the study of complex systems, such as the human brain, financial market or linguistics

The key activity of the Institute is participation in large-scale experiments carried out through global research collaborations. Our physicists actively participate in three major experiments (ALICE, ATLAS, LHCb) at the Large Hadron Collider (LHC) of CERN, Geneva contributing to their construction, development and maintenance, as well as in the following projects: European Laser on Free Electrons (E-XFEL, DESY, Hamburg), Large Hadron Collider (LHC, CERN, Geneva), European Spallation Source (ESS, Lund, Sweden), Système de Production d'Ions Radioactifs Accélérés en Ligne (SPIRAL2, GANIL, Caen, France), Facility for Antiproton and Ion Research (FAIR, Darmstadt), Cherenkov Telescope Array (CTA), Pierre Auger Observatory (Argentina), International Thermonuclear Experimental Reactor (ITER,Cadarache, France), Belle2 experiment (KEK, Tsukuba, Japan).

The Institute has research equipment available to the Polish and foreign scientific community. We have, among other instruments, an apparatus cluster called "IFJ PAN research infrastructure for interdisciplinary studies", having the status of a Special Research Instrument.

Many projects and undertakings of the Institute are also included in the Polish Map of Research Infrastructure, which aims to present the actual potential of Polish science and to select the best scientific projects involving the use of the most perfect equipment that ultimately makes up the broadly understood research infrastructure.

The "National Centre for Hadron Radiotherapy – Cyclotron Centre Bronowice," funded by the European Innovative Economy Operational Programme, is a flagship project of the Institute. The Cyclotron Centre Bronowice (CCB) is an infrastructure unique in Central Europe, serving as a clinical and research centre in the area of medical and nuclear physics. Since 2013, the Proteus C-235 cyclotron of the Centre has been delivering beams of protons with energies in the range of 70–230 MeV. With two experimental halls and three treatment rooms, since 2016 serviced by two rotating gantries with Pencil Scanning Beam as well as a horizontal line for eye treatment, CCB is a modern clinical centre for the treatment of cancer patients.

The staff of the Institute consists of over 550 employees, including: 33 full professors, 82 associate professors, 104 PhD associates, and a team of over 120 highly qualified engineers and technicians.

The Scientific Council of the Institute is authorized to confer doctoral and postdoctoral degrees in physical sciences. Currently, over 70 Ph.D. students enrolled in doctoral studies in the framework of the International Doctoral Studies of the IFJ PAN as well as the Interdisciplinary Environmental Doctoral Studies "FCB" and "InterDokMed" operated since 2017 under the POWER program jointly by consortia of Krakow universities (AGH and the Jagiellonian University) and institutes of the Polish Academy of Sciences: Institute of Catalysis and Physical Chemistry of the Surface PAN (IKiFP PAN), the Institute of Pharmacology PAN (IF PAN) and IFJ PAN. On May, 6th 2019 Krakow School of Interdisciplinary PhD Studies (KISD) was founded by the Henryk Niewodniczański Institute of Nuclear Physics Polish Academy of Sciences, Jerzy Haber Institute of Catalysis and Surface Chemistry Polish Academy of Sciences, Maj Institute of Pharmacology Polish Academy of Sciences, Institute of Metallurgy and Materials Science Polish Academy of Sciences, Faculty of Physics and Applied Computer Science AGH University of Science and Technology, Faculty of Materials Science and Ceramics AGH University of Science and Technology.

The average yearly publication yield of IFJ PAN includes over 600 scientific papers in high-impact international journals, and over 100 monographs, reports and conference contributions. Each year the Institute hosts international and national scientific conferences, not to speak about a large number of weekly seminars and occassional meetings. Those events give an opportunity to share recent important results, both theoretical and experimental, and offer a general forum to discuss the frontiers of physics.

The four nationally accredited laboratories at the Institute, apart from internal services, offer certified measurements of radioactivity and spectra of radiation isotopes in environmental and materials samples to external customers. They also provide regular dosimetry services evaluating individual occupational and environmental exposure of workers to radiation, especially in hospitals and radiation industry. Routine calibration of all electronic radiometers which measure the activity of gamma-, alpha- and beta-ray sources, is also available.

IN QUEST OF NEW PHENOMENA IN THE WORLD OF ELEMENTARY PARTICLES

The Henryk Niewodniczański
Institute of Nuclear Physics
Polish Academy of Sciences

Kraków, 20 December 2018

ELECTRICALLY CHARGED HIGGS VERSUS PHYSICISTS: 1-0 UNTIL BREAK

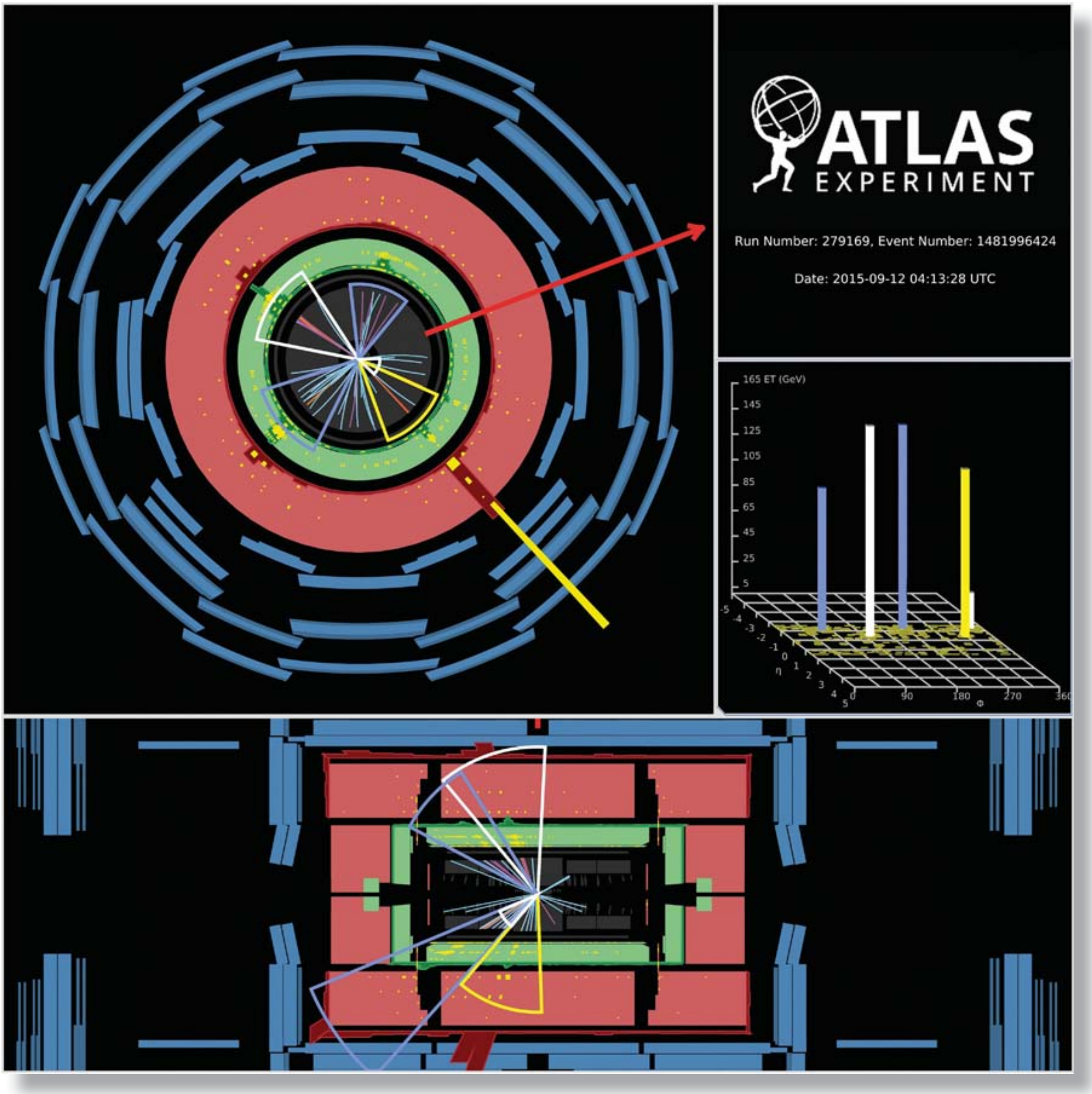
The last missing particle of the Standard Model, the Higgs boson, was discovered in 2012 in the experiments at the Large Hadron Collider. Since then, searching for new, related particles has been underway. Predicted by various theories that go beyond known physics, Higgs bosons with positive or negative electric charge are among the favorites to be observed. But do these particles really exist?

At the European Organization for Nuclear Research CERN near Geneva, the Large Hadron Collider's second run of collisions and collecting data on particles and their decays has just ended. Over the next two years, the accelerator will undergo maintenance and the upgrades will come to fruition. Meanwhile, physicists intensively analyze data from the just-completed run. Their investigation focuses primarily on the search for elementary particles beyond the Standard Model, such as the electrically charged Higgs boson. The most recent analysis in this field was carried out by an international team of physicists working within the ATLAS experiment. The group consisted of researchers from the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Kraków and five other institutions scattered around the world.

"The Standard Model is a complex theoretical structure and describes all known elementary particles with excellent accuracy. We know, however, that it works well for experimentally accessible energies. At really high energies, the Standard Model predictions break down and hence the need for new, wider description, so-called new physics," says Dr. Paweł Bruckman (IFJ PAN) and recalls that classical mechanics, for example, shows similar features. When the energy of moving bodies is low, its description is exact. However, when the speed becomes comparable to the speed of light, Newtonian physics must give way to relativistic theories.

Discovered in 2012 by ATLAS and CMS experiments, the neutral Higgs boson confirmed the existence of the mechanism necessary for the Standard Model consistency. Physicists, however, are aware that this particle may be only part of a wider Higgs sector, predicted by most theories that go beyond modern particle physics. In the most popular supersymmetric theories (where each known particle has an exotic, more-massive super-partner) there are five Higgs bosons. Three of them, including the standard one, are electrically neutral, while the other two are electrically charged (negatively and positively).

"We have been exploring a very wide range of masses. The mass of the proton, i.e. the nucleus of the hydrogen, is about one gigaelectronvolt. In turn, the mass of the quark t, the most massive of the so far discovered elementary particles, is 173 gigaelectronvolts. We were looking for traces of the existence of a charged higgs in the mass range from 90 gigaelectronvolts up to 2000 gigaelectronvolts," explains the PhD student Marzieh Bahmani (IFJ PAN).



If an electrically charged Higgs boson exists, there are not many places where it can hide. The image presents one of the events covered by the latest analysis, with four jets (white and blue cones) and marked direction of the missing momentum (red arrow). (Source: ATLAS Collaboration, CERN, IFJ PAN).

The team with Kraków researchers focused on those collision events between quarks and gluons, in which the charged Higgs bosons would be produced together with the t quark, and then decayed into a tau lepton (a much more massive equivalent of the electron) and its associated neutrino. In such events, a few neutrinos are emitted. These particles interact weakly with matter and are invisible to the detectors. Therefore, during the selection of decays, the amount of missing energy that neutrinos would carry away was important.

For the purpose of the analysis, Kraków researchers, financed by the OPUS grant from the Polish National Science Center, developed and optimized a multivariate discriminant method. The technique, based on many carefully selected variables and correlations between them, maximizes the discrimination of the expected signal from the overwhelming background.

“Within the current sensitivity, we can say at the 95% confidence level that in the selected range of masses we have not observed charged Higgs bosons. This is a very strong limitation on the new theories. We intend to improve it even further in the next round of the analysis, by taking into account all data from the recently completed second run of the LHC accelerator. It is still possible that the charged Higgs is hidden somewhere in the mass range covered by our analysis, but we are not yet sensitive enough to see its signal,” says Dr. Anna Kaczmarska (IFJ PAN).

The results of the analysis, published in the Journal of High Energy Physics, are particularly valuable to help selecting theoretical models that try to go beyond known physics. The parameter space of these models has been significantly narrowed. As a consequence, their predictions will be more precise and easier to verify.

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Kraków, 7 June 2017

COSMIC INFLATION: HIGGS SAYS GOODBYE TO HIS 'LITTLE BROTHER'

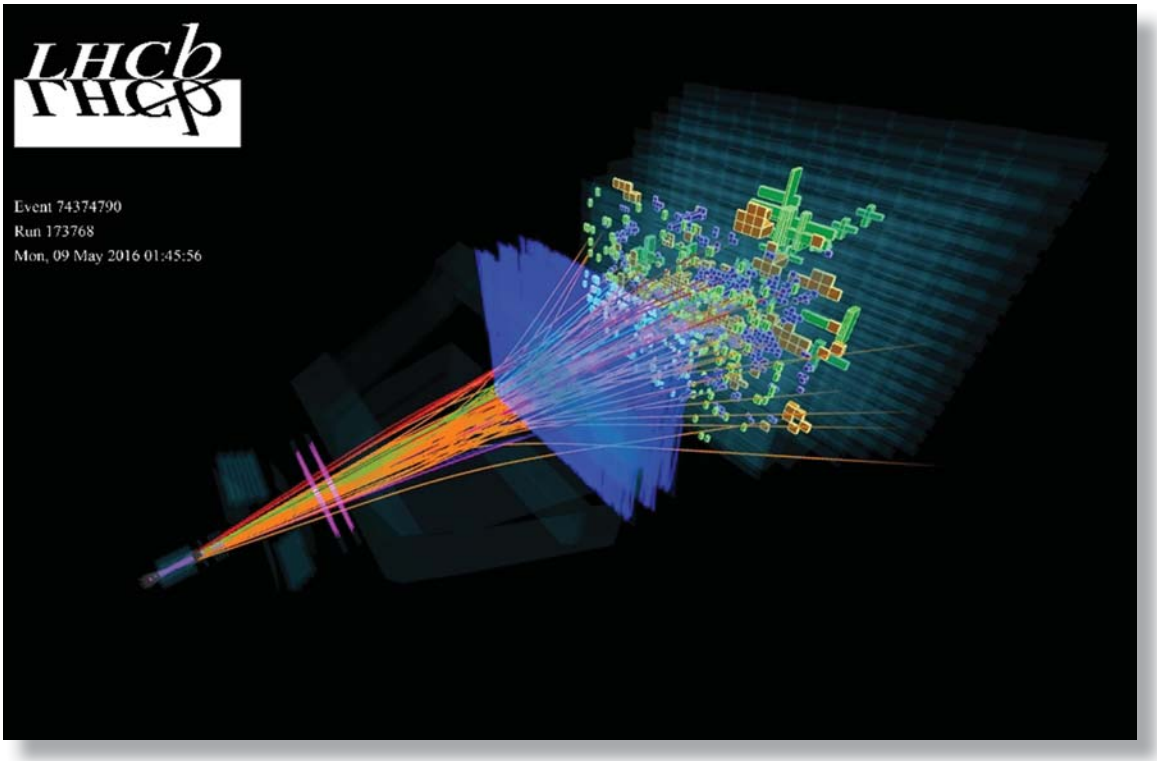
In the first moments after the Big Bang, the Universe was able to expand even billions of billions of billions of times faster than today. Such rapid expansion should be due to a primordial force field, acting with a new particle: inflaton. From the latest analysis of the decay of mesons, carried out in the LHCb experiment by physicists from Kraków and Zurich, it appears, however, that the most probable light inflaton, a particle with the characteristics of the famous Higgs boson but less massive, almost certainly does not exist.

Just after the Big Bang, the Universe probably passed through a phase of inflation, an extreme burst of expansion. If inflation did really occur, there should be a new force field behind it. Its force carriers would be hypothetical, hitherto unobserved particles, inflatons, which should have many features reminiscent of the famous Higgs boson. Physicists from the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Kraków and the University of Zurich (UZH) searched for traces of light inflatons in the decay of B^+ mesons recorded by detectors in the LHCb experiment at CERN near Geneva. Detailed analysis of the data, carried out with funds provided by the Polish National Science Centre, however, places a large question mark over the existence of light inflatons.

Despite having weak effects, gravity decides about the appearance of the Universe on its greatest scales. As a consequence, all modern cosmological models have their foundations in our best theory of gravity: Albert Einstein's general theory of relativity. Already the first cosmological models constructed on the theory of relativity suggested that the Universe was a dynamic creation. Today we know that it used to be extremely dense and hot, and 13.8 billion years ago it suddenly started to expand. The theory of relativity allows for predictions of the course of this process starting from fractions of a second after the Big Bang.

"One of the earliest survivors of these events visible to this day is the microwave background radiation that formed a few hundred thousand years after the Big Bang. It currently corresponds to a temperature of about 2.7 kelvins and uniformly fills the entire Universe. It is this homogeneity that has proved to be a great puzzle," says Dr. Marcin Chrząszcz (IFJ PAN) and explains, "When we look into the sky, the deep space fragments visible in one direction may be so distant from those visible in another direction that light has not yet had time to pass between them. So nothing that has happened in one of these areas should affect the other. But wherever we look, the temperature of distant regions of the cosmos is almost identical! How could it have become so uniform?"

The uniformity of microwave background radiation is explained by the mechanism proposed by Alan Guth in 1981. In his model, the Universe initially expanded slowly, and all its fragments observed



Inflatons, hypothetical particles beyond the Standard Model, were sought in mesons decays observed by the LHCb experiment at CERN. The image shows a typical, fully reconstructed LHCb event. (Source: LHCb Collaboration, CERN).

today had time to interact and level out the temperature. According to Guth, at some point, however, there must have been a very short but extremely rapid expansion of space-time. The new force field responsible for this inflation expanded the Universe to such an extent that today it exhibits a remarkable uniformity (as far as the temperature of the cosmological microwave background is concerned).

"A new field always means the existence of a particle that is the carrier of the effect. Cosmology has thus become interesting for physicists examining phenomena in the microscale. For a long time a good candidate for the inflaton appeared to be the famous Higgs boson. But when in 2012 the higgs was finally observed in the European LHC accelerator, it turned out to be too heavy. If higgs with its mass was responsible for inflation, today's relict radiation would look different than currently observed by the COBE, WMAP and Planck satellites," says Dr. Chrząszcz.

Theoreticians proposed a solution to this surprising situation: the inflaton would be a completely new particle, with the properties of higgs, but with clearly smaller mass. In quantum mechanics, the identical nature of characteristics causes particles to be able to oscillate: they cyclically transform one into another. An inflation model constructed in this way would have only one parameter, describing the frequency of oscillation/transformation between the inflaton and the Higgs boson.

"The mass of the new inflaton could be small enough for the particle to appear in the decay of B^+ mesons. And these beauty mesons are particles recorded in large number by the LHCb experiment at the Large Hadron Collider. So we decided to look for decay of mesons happening through the interaction with the inflaton in the data collected in the LHC in 2011-12," says PhD student Andrea Mauri (UZH).

If light inflatons actually existed, the B+ meson would sometimes decay into a kaon (K^+ meson) and a Higgs particle, which would convert into an inflaton as a result of the oscillation. After travelling a few metres in the detector, the inflaton would decay into two elementary particles: muon and antimuon. Detectors of the LHCb experiment would not record the presence of either the higgs or the inflaton. Researchers from the IFJ PAN, however, expected to see the emission of kaons and the appearance of muon-antimuon pairs respectively.

"Depending on the parameter describing the frequency of the inflaton-higgs oscillation, the course of B^+ meson decay should be slightly different. In our analysis we were looking for decays of up to 99%

of the possible values of this parameter – and we found nothing. We can therefore say with great certainty that light inflaton simply does not exist," says Dr. Chrząszcz.

Theoretically, low-mass inflaton may still be hidden in one percent of the unexamined variations in oscillation. These cases will eventually be excluded by future analyses using newer data that is now being collected at the LHC. However, physicists have to slowly become accustomed to the idea that if inflaton exists, it is a more massive particle than was thought or that it occurs in more than one variation. If, however, over time these variants also prove not to correspond to reality, inflation, which explains the observed homogeneity of the Universe so well, will become – very literally – the greatest mystery of modern cosmology.

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SCIENTIFIC PAPERS:

LHCb Collaboration, *Search for long-lived scalar particles in* $B^+ \to K^+ \chi (\mu^+ \mu^-)$ *decays*, Physical Review D **95**,071101(R), DOI: https://doi.org/10.1103/PhysRevD.95.071101

Kraków, 2 March 2016

DO WE SEE THE TRAILER FOR THE UPCOMING BLOCKBUSTER OF LHC?

In light of the latest analysis on the decay of beauty mesons, the dawn of a new era, that of 'new physics', may be approaching. An important contribution to the analysis has been made by physicists from the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) from Poland.

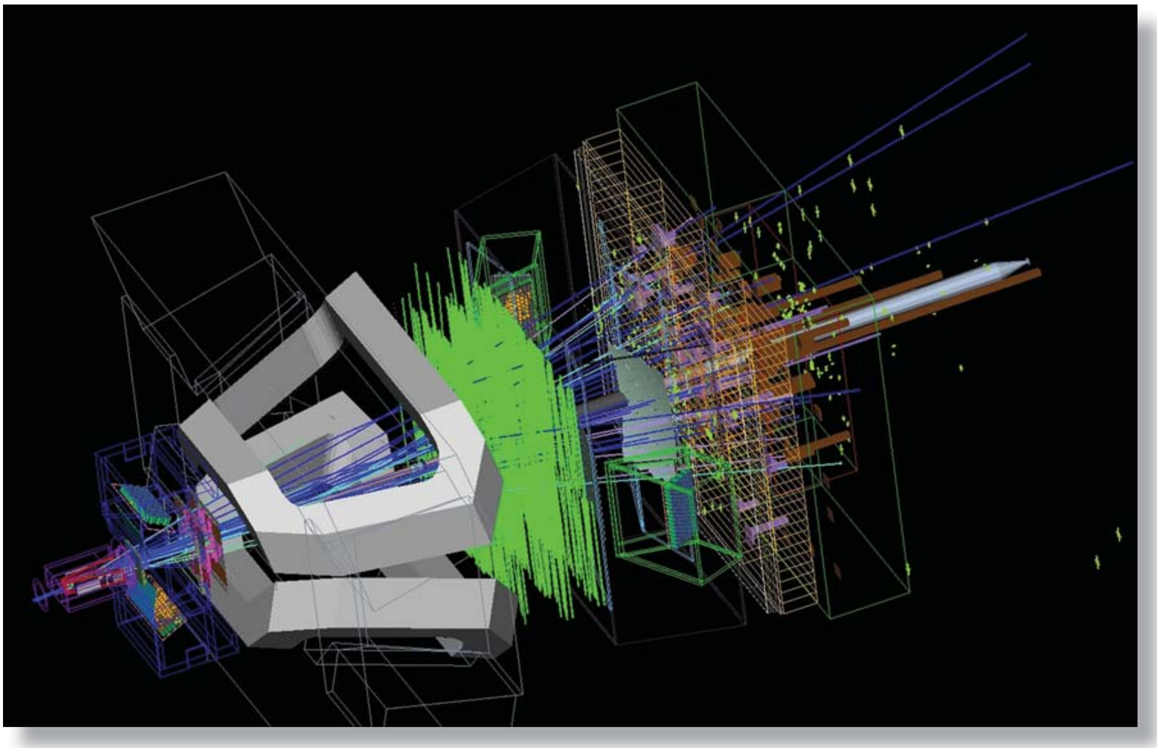
We can't call it a discovery. Not yet. However, there are some indications that physicists working at the LHC accelerator at the European Organization for Nuclear Research (CERN) near Geneva may see the first traces of physics beyond the current theory which describes the structure of matter. This indication emerges from the latest analysis of data collected by the LHCb experiment in 2011 and 2012. Physicists from the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Kraków, Poland, have made important contribution to the analysis.

"To put it in terms of the cinema, where we once only had a few leaked scenes from an much-anticipated blockbuster, the LHC has finally treated fans to the first real trailer," says Prof. Mariusz Witek (IFJ PAN).

To describe the structure of matter on the scale of elementary particles we use the Standard Model, a theoretical framework formulated in the 1970s. Particles we now consider as elementary play various roles. Bosons are carriers of forces: photons are related to electromagnetic interactions, eight types of gluons are responsible for strong interactions, and W+, W– and Z0 bosons mediate weak interactions. Matter is formed by particles called fermions, which are divided into quarks and leptons. In the Standard Model, there are six types of quarks (down, up, strange, charm, top and bottom) and six types of leptons (electrons, muons, taons and their three corresponding neutrinos) as well as 12 antiparticles associated with them. The recently discovered Higgs boson provides particles with mass (all except the gluons and photons).

"Up to now all measurements match the predictions of the Standard Model. However, we know that the Standard Model cannot explain all the features of the Universe. It doesn't predict the masses of particles or tell us why fermions are organized in three families. How did the dominance of matter over antimatter in the universe come about? What is dark matter? Those questions remain unanswered. What's more, the force we all experience every day, gravity, isn't even included in the model," says Prof. Witek.

So far the scientists working at the LHC have been concentrating on the search for the Higgs boson (the ATLAS and CMS experiments), working out the differences between matter and antimatter (the LHCb experiment) and testing quark-gluon plasma (the ALICE experiment). Now more attention is being paid to detecting new elementary particles beyond the Standard Model. The ATLAS and CMS experiments are trying to see such particles directly. However it cannot be ruled out that the mass of the new particles is just too high to be produced at the energies of the LHC accelerator. Then the only way of discovering new physics would be to observe the influence of new particles on phenomena we



Computer simulation of rare decay of Bs meson to J/psi and phi mesons in LHCb detector at CERN. (Source: CERN).

observe at lower energies. Such influence might manifest in modifying the frequency of the decay of beauty mesons or the angular distributions of their decay products.

In 2011, shortly after gathering the first large samples by the LHCb experiment, a puzzling anomaly regarding the beauty meson was noticed and announced on public site of LHCb (http://lhcb-public.web.cern.ch/lhcb-public/). These mesons are composed of a light quark, which we can find in protons and neutrons that form the matter around us, as well as a heavy beauty antiquark, which can be created in the LHC collider. The particles, made up of pairs of quark-antiquark, are unstable so they decay rapidly.

An anomaly was observed in the decay of a B meson containing two muons among its products. In describing the final state of this decay, up to eight parameters are needed. They define the angular distribution of decay products, that is, at what angles they will be flying. The traditional method of determining these parameters may lead to false results for the small number of such decays observed. Dr. Marcin Chrząszcz from IFJ PAN, one of the main authors of the analysis, proposed an alternative method in which each parameter was determined independently of the others.

"My approach can be likened to determining the year when a family portrait was taken. Rather than looking at the whole picture, it is better to analyze each person individually and from that perspective try to work out the year the portrait was taken," explains Dr. Chrząszcz.

The latest analysis, on the Polish side financed by the National Science Centre and a Diamond Grant awarded to Dr. Chrząszcz, is important not only for its accuracy. The results of data from 2011 have been confirmed by data from 2012. This increases the likelihood that physicists have encountered a genuine phenomenon rather than unforeseen artefact of the measurement.

"While searching for new phenomena or new particles, it is assumed that when the effect differs from prediction of a given theory by more than three standard deviations – 3 sigma – that is an indication, but we cannot talk of a discovery until the rate of accuracy rises to above 5 sigma. To put it slightly differently, 5 sigma means that we have a probability of less than one to three-and-a-half million that random fluctuations can provide a result like that seen. At the presently observed number of such decays the accuracy of our analysis has reached a deviation of 3.7 sigma. So we still cannot make claims of a discovery, but we certainly have an interesting clue," says Dr. Chrząszcz.

What could be the reason for the observed effect? The most popular hypothesis among theorists is the existence of a new intermediate Z-prime boson (Z') involved in the decay of B mesons. It also explains another, slightly weaker effect observed in other decays of B mesons to measure what is called lepton universality. Still, it is not an inconceivable explanation of the effect in the framework of the Standard Model: perhaps the theoretical calculations do not take into account some important factors affecting the decay mechanism.

The LHC has recently began another round of colliding protons at higher energy levels, by the end of which physicists will have at their disposal another batch of data to analyze. Will the new physics then become a reality?

As Prof. Witek sums it up: "Just like it is with a good movie: everybody wonders what's going to happen in the end, and nobody wants to wait for it".

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Kraków, 12 April 2017

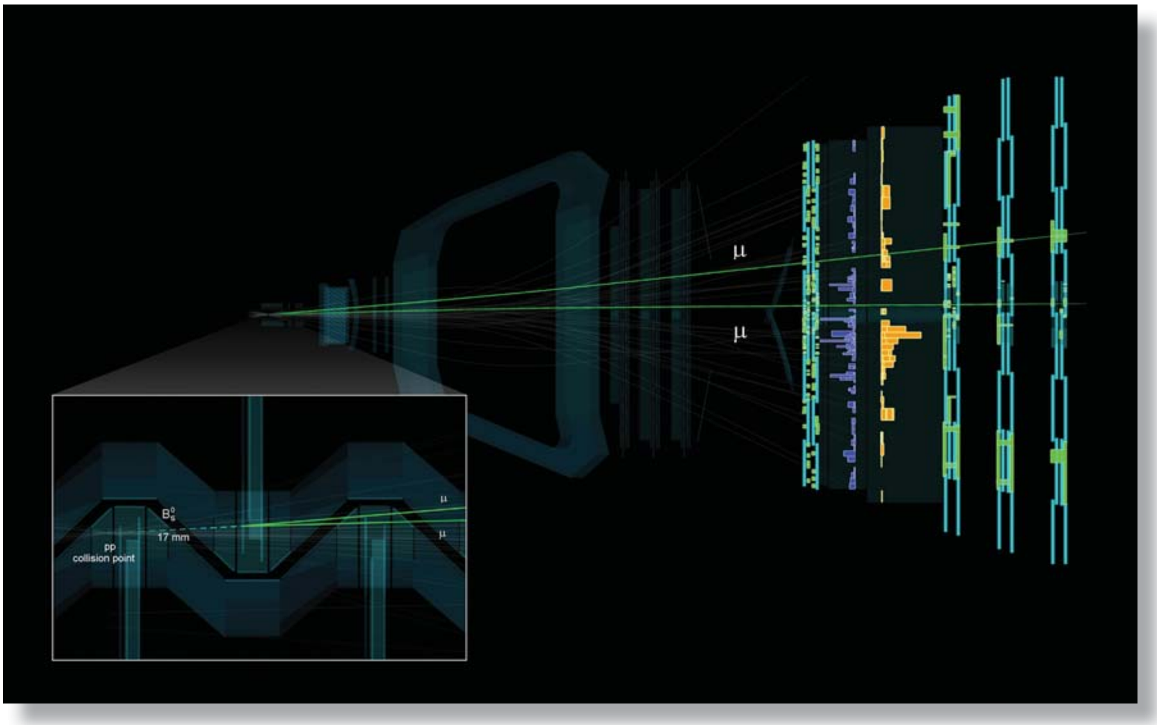
THE MOST ACCURATE MEASUREMENT OF RARE MESON DECAY CONFIRMS MODERN PHYSICS

All physical theories are to a greater or lesser extent, but always only simplified representations of reality and, as a consequence, have a specified range of applicability. Many scientists working on the LHCb experiment at CERN had hoped that the just achieved, exceptional accuracy in the measurement of the rare decay of the B_s^0 meson would at last delineate the limits of the Standard Model, the current theory of the structure of matter, and reveal the first phenomena unknown to modern physics. Meanwhile, the spectacular result of the latest analysis has only served to extend the range of applicability of the Model.

Mesons are unstable particles coming into being, among others, as a result of proton collisions in the Large Hadron Collider (LHC) at CERN near Geneva. Physicists are convinced that in some very rare decays of these particles processes can potentially occur that may lead science onto the trail of new physics, with the participation of previously unknown elementary particles. It should, then, be no surprise that scientists participating in the LHCb experiment at the LHC have for a long time been looking into one of these decays: the decay of the B_s^0 meson into a muon and an anti-muon. The most recent analysis, carried out for a much greater number of events than ever before, has achieved an accuracy that is exceptional for this kind of observation. The results show excellent agreement with the predictions of the Standard Model, the current theory of the constitution of matter.

"This result is a spectacular victory, only that it's slightly... pyrrhic. It is in fact one of the few cases where such great compliance of experimentation with theory, instead of being an occasion for rejoicing, slowly starts to lead to worry. Together with the improvement in the accuracy of measurement of the decays of B_s^0 mesons we expected to see new phenomena, beyond the Standard Model, which we know with all certainly is not the ultimate theory. But instead of enjoying the discovery of the harbinger of a scientific revolution, we have only shown that the model is more accurate than we originally thought," says Prof. Mariusz Witek from the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Kraków.

The Standard Model is a theoretical framework constructed in the 1970s to describe phenomena occurring in the world of elementary particles. In it, matter is formed of elementary particles from a group called fermions, including quarks (down, up, strange, charm, true and beauty) and leptons (electrons, muons, tauons and their associated neutrinos). In the Model, there are also particles of antimatter, associated with their respective particles of matter. Intermediate bosons are responsible for carrying forces



Extremely rare B_s^0 meson decay into two muons, registered in 2016 at the LHCb detector at CERN near Geneva. The enlargement at the bottom shows that the point of decay was 17 mm from the collision of two protons. (Source: IFJ PAN / CERN / The LHCb Collaboration).

between fermions: photons are the carriers of electromagnetic forces, eight kinds of gluons are carriers of strong forces, and bosons W^+, W^- and Z^0 are responsible for carrying weak forces. The Higgs boson recently discovered at the LHC gives particles mass (all of them except for gluons and photons).

Muons are elementary particles with characteristics similar to those of electrons, only around 200 times more massive. In turn, B mesons are unstable particles made up of two quarks: a beauty antiquark and a down, up, strange or charm quark. The decay of the B_s^0 meson into a muon and an anti-muon (endowed with positive electric charge) occurs extremely rarely. In the analyzed period of operation of the LHCb detector there were hundreds of trillions of proton collisions, and during each of them whole cascades of further disintegrating secondary particles were recorded. With such a large number of events in a multi-stage selection process it was only possible to pick out a few cases of this decay. One of them can be viewed in 3D at http://lhcb-public.web.cern.ch/lhcb-public/BsMuMu2017/lbevent/

In its most recent analysis the LHCb experiment team took into account not only the first but also the second phase of operation of the LHC. The larger statistics helped achieve exceptional accuracy of the measurement of the decay of the beauty meson into a muon and anti-muon, of up to 7.8 standard deviations (commonly denoted by the Greek letter sigma). In practice, this means that the probability of registering a similar result by random fluctuation is less than one to over 323 trillion.

"The spectacular measurement of the decay of the beauty meson into a muon-anti-muon pair agrees with the predictions of the Standard Model with an accuracy of up to up to nine decimal places!" emphasizes Prof. Witek.

The Standard Model has emerged victorious from another confrontation with reality. Nevertheless, physicists are confident that this is not a perfect theory. This belief stems from a number of facts. The Model does not take into account the existence of gravity, it does not explain the dominance of matter over antimatter in the contemporary universe, it offers no explanation of the nature of dark matter, it gives no answers as to the question of why fermions are composed of three groups called families. In addition, for the Standard Model to work, over 20 empirically chosen constants have to be entered into it, including the mass of each particle.

"The latest analysis significantly narrows down the values of the parameters that should be assumed by certain currently proposed extensions of the Standard Model, for example supersymmetric theories.

They assume that each existing type of elementary particle has its own more massive counterpart – its superpartner. Now, as a result of the measurements, theorists dealing with supersymmetry have less and less possibility of adapting their theory to reality. Instead of coming closer, the new physics is again receding," concludes Prof. Witek.

Physicists do not intend, however, to give up their studies of the decay of the B_s^0 meson into the muon and anti-muon pair. There is still a possibility that new physics actually works here, only that its effects are smaller than expected and continue to get lost in measurement errors.

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Kraków, 30 August 2018

THE POTENTIAL HARBINGERS OF NEW PHYSICS JUST DON'T WANT TO DISAPPEAR

For some time now, in the data coming in from the LHCb experiment at the Large Hadron Collider, several anomalies have been seen in the decays of beauty mesons. Are they more than just statistical fluctuations? The latest analysis, conducted with the participation of the Institute of Nuclear Physics of the Polish Academy of Sciences and taking into account so-called long-distance effects in the decays of particles, increases the probability that what is behind the anomalies is more than just another prank played by measuring techniques.

In old times, when sailors ventured into unknown waters, the only thing they could really be sure about was the vastness of the empty ocean. On occasion, after months of voyaging, one or another would glimpse a scrap of land in the distance, but usually it was just an illusion. Only sometimes did a peak emerge from behind the horizon, which became clearer the closer they approached. It seems that physicists looking for traces of new physics using the LHC accelerator are in a similar situation today. While seekers of direct traces of new physics eliminate all potential new signals in particle collisions, revealing the void predicted by the Standard Model, others looking at other phenomena begin to see more and more distinct "peaks" in the ocean of data that do not seem to intend to disappear.

The Standard Model is a set of theoretical tools constructed in the 1970s to describe phenomena occurring in the scale of atomic nuclei and elementary particles. It works very well, but cannot provide answers to some particularly important questions. Why do elementary particles have particular masses, why do they create families? Why does matter so clearly dominate over antimatter? What does dark matter consist of? There is a well-founded belief among physicists that the Standard Model only describes a fragment of reality and needs to be extended.

"For a long time in the LHC, there has been an intense hunt for everything whose presence cannot be explained by current physics. At present, the search for new particles or phenomena in a direct way remains fruitless. However, several anomalies have been found in data containing decays of beauty mesons. They are becoming more interesting day by day because the more data we process and the more effects we take into account when describing them, the better they are visible," explains Dr. Marcin Chrząszcz (IFJ PAN, University of Zurich), co-author of the latest publication, financed by the Polish National Science Centre and presented in the journal European Physical Journal C. The other three authors are Christoph Bobeth from the Technical University of Munich, Danny van Dyk from the University of Zurich (UZ), and Javier Virto from the PM and the Centre for Theoretical Physics at the Massachusetts Institute of Technology in Cambridge, USA.

Will anomalies observed in the decays of beauty mesons disappear with the new data, as exotic lands disappeared from maps of cartographers? The latest analysis, taking into account long-range interactions, proves that the anomalies are visible not less, but better. (Source: IFJ PAN).

Researchers looked at the anomalies detected in the decays of beauty mesons. Mesons, particles made of quark-antiquark pairs, come in many varieties. The afore-mentioned B (beauty) mesons contain a down quark, one of the components of protons and neutrons that is common in nature, and a beauty anti-quark. Mesons are unstable systems and quickly disintegrate in many ways that are described as channels of decay. One of these anomalies was observed in the decay channel of meson B to another meson (K*; this meson contains a strange quark instead of a beauty quark) and a muon-antimuon pair (muons are elementary particles with properties similar to electrons, only almost 200 times more massive).

"In previous calculations, it was assumed that when the meson disintegrates, there are no more interactions between its products. In our latest calculations we have included the additional effect: long-distance effects called the charm-loop. They consist of the fact that with a certain probability the products of decay interact with each other, for example exchanging gluon, the particle responsible for strong interactions, bonding quarks in protons and neutrons," says Dr. van Dyk (UZ).

The effect of measurements in physics is usually described by the value of the sigma standard deviation. An effect differing from predictions by more than three standard deviations (3 sigma) is treated as an observation, a discovery is said to have been made when the accuracy rises above 5 sigma (which means a probability of less than one in three and a half million, that random fluctuation will give the observed result). Analyses of the decays of B mesons to K* mesons and a muon-antimuon pairs, carried out with the participation of researchers from the Institute of Nuclear Physics PAS, shown a tension with Standard Model prediction of 3.4 sigma (in other decay channels anomalies of a similar nature were observed). Meanwhile, the inclusion of long-range effects in the theoretical description increased this value to 6.1 sigma. Researchers hope that the mathematical methods proposed by them, applied to similar decay channels, will also significantly increase the precision of estimates.

"The detected anomalies do not disappear in subsequent analyses. Now that the theoretical description of these processes has been worked out, everything depends only on the statistical precision, which is determined by the number of decays being analyzed. We will probably have a sufficient amount within two or three years to confirm the existence of an anomaly with a credibility entitling us to talk about a discovery," says Dr. Chrząszcz.

The question of what is the origin of the observed anomalies remains open. Many physicists suppose that an unknown elementary particle outside the Standard Model may be responsible for their existence. A good candidate, for example, would be the Z' boson, proposed by theoreticians. Direct verification of this hypothesis, however, would require further experiments performed on an accelerator more powerful than the modern LHC configuration.

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Kraków, 22 February 2017

INVERTED, BUT NOT PERFECTLY: FIRST TRACE OF DIFFERENCES BETWEEN MATTER AND 'ORDINARY' ANTIMATTER

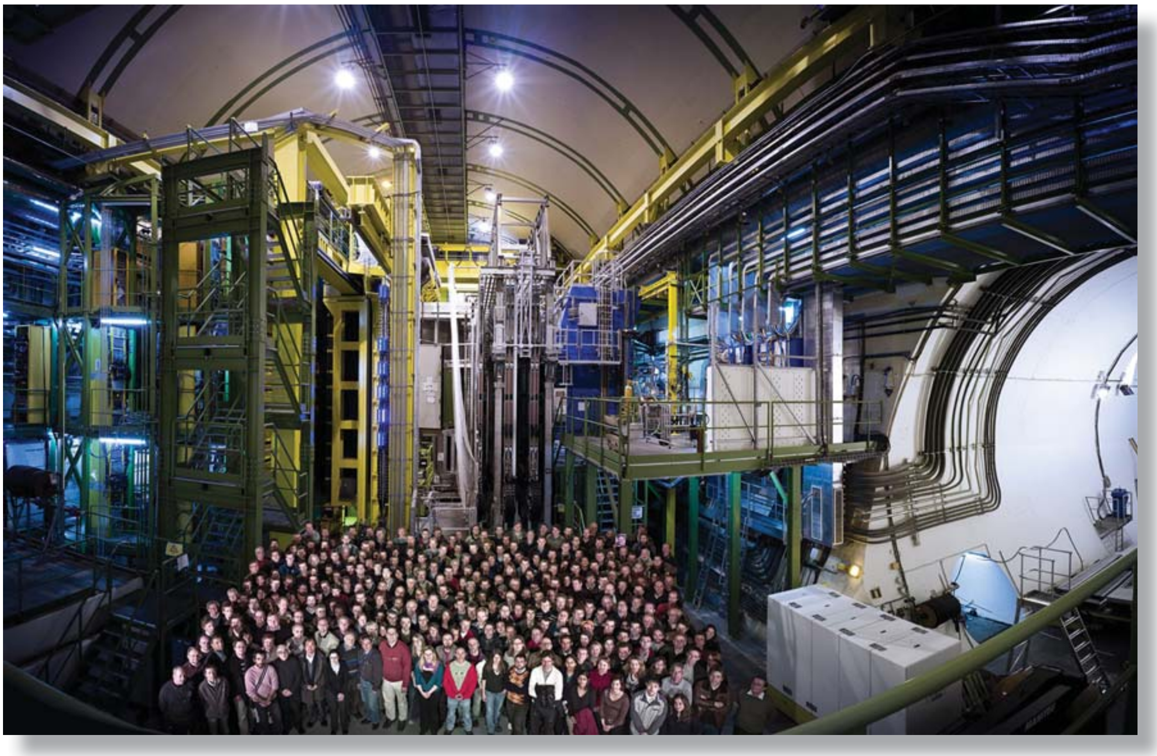
The world around us is mainly constructed of baryons, particles composed of three quarks. Why are there no antibaryons, since just after the Big Bang, matter and antimatter came into being in exactly the same amounts? A lot points to the fact that after many decades of research, physicists are closer to the answer to this question. In the Large Hadron Collider beauty (LHCb) experiment the first trace of the differences between baryons and antibaryons has just been encountered.

In data collected during the first phase of operation of the Large Hadron Collider the LHCb collaboration team has discovered an interesting asymmetry. The most recent analysis of decays of the beauty baryon Lambda b, a particle six times more massive than a proton, suggests that it decays a little differently than its antimatter counterpart. If this result is confirmed, it will be possible to talk about having observed the first difference between antibaryons and baryons, i.e. the family of particles which to a greater degree make up our everyday world.

Certain differences between matter and antimatter have already been observed previously. In 1964, it was noticed that kaons – that is, K mesons, particles made up of a strange quark and an up or down antiquark – sometimes decay somewhat differently than antikaons (the Nobel Prize was awarded for this discovery in 1980). In turn, in recent years there have been reports of the discovery of slightly clearer differences in the decays of antimesons and B mesons of various types (the B meson consists of a beauty quark and an up, down, strange or charm quark).

Mesons are quark-antiquark pairs with short lifetimes, appearing today in the Universe in small quantities, and on Earth, produced mainly in high-energy collisions in particle accelerators. Meanwhile the matter of which the macroscopic structures of our world are composed is made up of leptons (these include electrons) and to a greater degree baryons – clusters of three quarks (the proton is a baryon containing two up quarks and one down, as is the neutron which is composed of two down quarks and one up). The most recent analysis of data from the LHCb collaboration, published in the journal Nature Physics and concerning the decays of Lambda b particles composed of down, up and beauty quarks, is thus the first indication of the possible differences between baryonic matter and its antimatter reflection.

"We cannot yet talk about a discovery. Nevertheless, we are dealing with something that seems to be an increasingly promising observational clue, taken from the data from the first stage of operation of the LHC accelerator. We will, however, have to wait for the final confirmation – or denial... – of the current result another dozen or so months until the official end of the analysis of data from the second



The first trace of differences between matter and "common", baryonic antimatter has just been encountered in decays of the beauty baryon Lambda b. Pictured above: LHCb Collaboration in front of LHCb detector. (Source: CERN, The LHCb Collaboration).

run," stresses Prof. Marcin Kucharczyk from the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Kraków, one of the participants of the LHCb collaboration.

Modern particle physics and cosmological models suggest that antimatter came into being in exactly the same amounts as matter. This fact is linked with spectacular consequences: When a particle encounters its antiparticle, there is a great likelihood of mutual annihilation, i.e. a process in which both particles completely transform into energy. This mechanism is extremely efficient. The amount of energy generated by the annihilation of a kilogram of antimatter with a good approximation corresponds to the amount of energy that would be released as a result of burning the annual petrol production of all the refineries in Poland.

If in the contemporary Universe there were planets, stars or galaxies made of antimatter, they should emit large amounts of radiation with very characteristic energies. This would arise due to the inevitable interactions with matter of the opposite type, leading to annihilation. Meanwhile, astronomers only observe annihilation radiation here and there and in residual amounts, well explained by physical phenomena which are also today responsible for the formation of small amounts of antimatter. Thus the fundamentally important question arises: since originally matter and antimatter filled the Universe in exactly equal amounts, why have they not completely disappeared? Why has a small portion of matter managed to survive the era of annihilation?

In the living world great extinctions leading to the extinction of species last for tens and hundreds of thousands of years. Meanwhile, everything points to the fact that antimatter annihilated by matter disappeared from our universe fractions of a second after the Big Bang. For every few billion particles of matter just one particle survived the giant cataclysm. If a similar scale of destruction touched the human species, within seconds the Earth's population would be down to one live individual. The question of why only he survived would certainly be most apt.

"In modern physics, it is assumed that the existence of matter should be due to some minor differences between the properties of particles and antiparticles. In equations, to convert a particle into an antiparticle, you have to change the sign of the corresponding quantum characteristics – in the case of electrons or the quarks making up protons or neutrons it is the electrical charge – and change the character of the spatial coordinates, i.e. form a mirror image. The combination of these two operations is called CP symmetry, that is, charge and parity symmetry. Thus, attempts to detect differences between matter and antimatter boil down to tracking events in which CP symmetry is not preserved," explains Prof. Kucharczyk.

Looking for signs of CP violation, the LHCb collaboration researchers chose from a huge number of collisions and the products of their decays approx. 6,000 cases in which Lambda b particles decayed to a proton and three pi mesons (pions), and approx. 1,000 cases with a decay path leading to a proton, a pion and two kaons. Detailed analysis revealed that the angles at which the products of decays diverge are sometimes somewhat different for Lambda b baryons than for their antimatter partners. The result is confirmed with a statistical significance of 3.3 standard deviations (sigma), which corresponds to a probability of approx. 99% that it is not a random fluctuation. In particle physics it is assumed, however, that one can talk of a discovery only with a statistical significance of over 5 sigma, that is, when the probability of a random fluctuation is less than one to more than three million.

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Kraków, 2 August 2018

“NEW PHYSICS” CHARMINGLY ESCAPES US

In the world of elementary particles, traces of a potential “new physics” may be concealed in processes related to the decay of baryons. Analysis of data from the LHCb experiment at the Large Hadron Collider performed by scientists from the Institute of Nuclear Physics of the Polish Academy of Sciences in Kraków have, however, shown that one of the rarest decays of baryons containing the charm quark so far shows no anomalies.

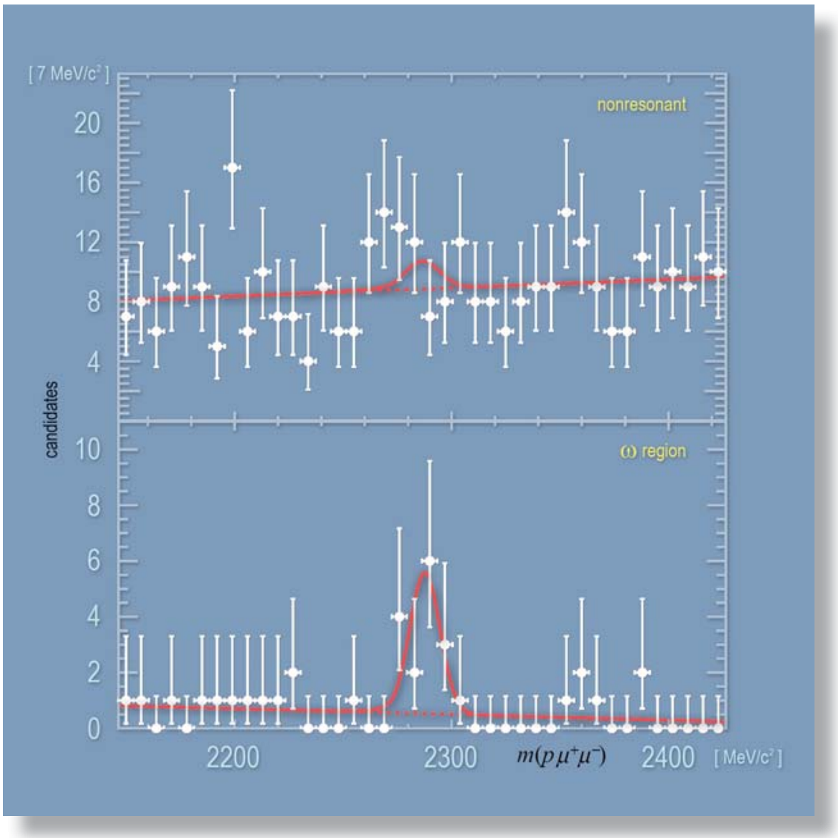
Baryons, which are composite particles made of three quarks, can decay into lighter particles. These types of decays usually occur indirectly via intermediate state (resonant). Sometimes, however, the decay proceeds directly in one step (nonresonant). The Standard Model, the best tool of modern physics formulated half a century ago to describe phenomena occurring among elementary particles, predicts that some of nonresonant baryon decays are extremely rare: depending on the type of baryon they should occur once per billion cases or even less frequently.

“If the frequency of some nonresonant decays were to be different than predicted by the Standard Model, it could indicate the existence of processes and particles not known yet, that indicate existence of ‘new physics’. This is why nonresonant decays have attracted our attention for so long,” explains Prof. Mariusz Witek from the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Kraków.

Prof. Witek led a five-member group of physicists from Kraków searching for nonresonant decays of charmed baryon Lambda c in data collected in 2011 and 2012 by the international LHCb experiment at the Large Hadron Collider in Geneva.

Why was the attention of the researchers drawn this time to Lambda c baryons, i.e. particles made of down (d), up (u) and charm (c) quarks? The most massive top (t) quark decays so fast that it does not combine with other quarks at all, so it does not create baryons, whose decays could be observed. The decays of particles containing the second largest quark in terms of mass, the beauty (b) quark, has already been analyzed earlier on, because their decays were slightly easier to detect. The Kraków group was involved here and contributed to observation of interesting deviation from theoretical predictions (https://press.ifj.edu.pl/news/2016/03/). In this situation, only the decays of charmed byrons remained largely unexplored.

“The Standard Model predicts that nonresonant decays of Lambda c baryons into three particles: a proton and two muons, should occur more or less once in hundreds of billions of decays. This is a much rarer phenomenon than the decays of baryons containing the beauty quark, which we were analysed earlier,” emphasizes Dr. Marcin Chrząszcz (IFJ PAN) and adds, “Measurements and analyses are now much more difficult, we have to look into a much larger group of events registered in the LHCb experiment. However, it is worth doing, because as a reward you can come across a trail of much more subtle processes. If we manage to observe any inconsistencies with predictions, this would most likely be a signal of a ‘new physics’.”



Baryons containing a charm quark can decay at once into a proton and two muons. Using data from the LHCb experiment, scientists from the Institute of Nuclear Physics of the Polish Academy of Sciences in Kraków have shown that in these extremely rare processes there are still no signs of the ‚new physics'. The signal of the nonresonant decay is visible at the top, the signal of the resonant decay into a proton and omega meson is presented below. (Source: IFJ PAN, CERN, The LHCb Collaboration).

With such rare phenomena, the distinguishing of nonresonant decays of Lambda c baryons from background has proved to be a hard and time-consuming task. Nonetheless, the Kraków-based physicists have managed to improve an upper limit on frequency of nonresonant decays by up to 100 times. It was estimated to be less than one in hundreds of millions.

"The taking into account of additional data, including the second run of the LHC accelerator, should soon improve our result by a factor of 10. So we would be very close to the predictions of the Standard Model. If some sort of 'new physics' is manifesting itself in the decays of Lambda c baryons, this will be the last chance for it to reveal itself. At present, there is not the slightest trace of it," sums up Prof. Witek.

During the analyses, the Kraków-based researchers also observed resonant decays, in which the Lambda c baryon decayed into a proton and omega meson. The lack of signals indicating yet another path of resonant decay – into a proton and a rho meson – was somewhat surprising. However, this result turned out to be in line with theoretical predictions.

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Kraków, 14 December 2017

GAMBIT NARROWS THE HIDING PLACES FOR 'NEW PHYSICS'

The elementary particles of 'new physics' must be so massive that their detection in the LHC, the largest modern accelerator, will not be possible. This none- too-optimistic conclusion comes from the most comprehensive review of observational data from many scientific experiments and their confrontation with several popular varieties of supersymmetry theory. The complicated, extremely computationally demanding analysis was carried out by the team of the international GAMBIT Collaboration – and leaves a shadow of hope.

Is it possible for today's apparatus to detect the elementary particles of 'new physics' that are capable of explaining such mysteries as the nature of dark matter or the lack of symmetry between matter and antimatter? To answer this question, scientists from the international GAMBIT (Global and Modular Beyond-the-Standard-Model Inference Tool) Collaboration have developed a set of software tools that comprehensively analyse data collected during the most sophisticated contemporary experiments and measurements. The first results, which are quite intriguing for physicists, have just been published in the European Physical Journal C. The Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Kraków participated in the work of the team.

Theoretical physicists are today firmly convinced that the Standard Model, our current, well-verified theory of the structure of matter, needs to be expanded. A strong pointer to the existence of unknown elementary particles is the movements of stars in galaxies. The Polish astronomer Marian Kowalski was the first to investigate the statistical characteristics of these movements. In 1859 he discovered that the movements of the stars close to us cannot be explained by the movement of the Sun itself. This was the first indication of the rotation of the Milky Way (Kowalski is thus the man who "moved the entire galaxy from its foundations"). In 1933, the Swiss astrophysicist Fritz Zwicky took the next step. From his observation of galaxies in the Coma cluster, he concluded that they move around the clusters as if there were a large amount of invisible matter there.

Although almost a century has passed since Zwicky's discovery, it has not been possible to investigate the composition of dark matter to this day, nor even to unambiguously confirm its existence. Over this time, theoreticians have constructed many extensions of the Standard Model containing particles that are to a greater or lesser extent exotic. Many of these are candidates for dark matter. The family of supersymmetric theories is popular, for example. Here, certain new equivalents of known particles that are massive and interact weakly with ordinary matter constitute dark matter. Naturally, many groups of experimental physicists are also looking for traces of such 'new physics'. Each of them, based on theoretical assumptions, carries out a certain research project, and then deals with the analysis and interpretation of data flowing from it. This is almost always done in the context of one, usually quite narrow, field of physics, and one theory for what might be beyond the Standard Model.

For 80 million working hours, the GAMBIT Collaboration tracked possible clues of 'new physics' with the Kraków supercomputer Prometheus, confronting the predictions of several models of supersymmetry with data collected by the most sophisticated contemporary scientific experiments. (Source: KSAF, Maciej Bernas).

"The idea of the GAMBIT Collaboration is to create tools for analyzing data from as many experiments as possible, from different areas of physics, and to compare them very closely with the predictions of new theories. Looking comprehensively, it is possible to narrow the search areas of 'new physics' much faster, and over time also eliminate those models whose predictions have not been confirmed in measurements," explains Dr. Marcin Chrząszcz (IFJ PAN).

The idea to build a set of modular software tools for the global analysis of observational data from various physical experiments arose in 2012 in Melbourne during an international conference on high energy physics. Currently, the GAMBIT group includes more than 30 researchers from scientific institutions in Australia, France, Spain, the Netherlands, Canada, Norway, Poland, the United States, Switzerland, Sweden and Great Britain. Dr Chrząszcz, financed by the SONATA grant from the National Science Centre in Poland, joined the GAMBIT team three years ago in order to develop tools modelling the physics of massive quarks, with particular reference to beauty quarks (usually this field of physics has a much more catchy name: heavy flavour physics).

Verification of the new physics proposals takes place in the GAMBIT Collaboration as follows. Scientists choose a theoretical model and build it into the software. The program then scans the values of the main model parameters. For each set of parameters, predictions are calculated and compared to the data from the experiments.

"In practice, nothing is trivial here. There are models where we have as many as 128 free parameters. Imagine scanning in a space of 128 dimensions! It's something that kills every computer. Therefore, at the beginning, we limited ourselves to three versions of simpler supersymmetric models, known under the abbreviations CMSSM, NUHM1 and NUHM2. They have five, six and seven free parameters, respectively. But things get complicated anyway, because, for example, we only know some of the other parameters, of the Standard Model, with a certain accuracy. Therefore, they have to be treated like free parameters too, only changing to a lesser extent than the new physics parameters", says Dr. Chrząszcz.

The scale of the challenge is best demonstrated by the total time taken for all the calculations of the GAMBIT Collaboration to date. They were carried out on the Prometheus supercomputer, one of several of the fastest computers in the world. The device, operating at the Academic Computer Centre CYFRONET of the University of Science and Technology in Kraków, has over 53,000 processing cores and a total computing power of 2,399 teraflops (a million million floating-point operations per second). Despite the use of such powerful equipment, the total working time of the cores in the GAMBIT Collaboration amounted to 80 million hours (over 9,100 years).

"Such lengthy calculations are, amongst other things, a consequence of the diversity of the measured data. For example, groups from the main experiments at the LHC publish exactly the results the detectors measured. But each detector distorts what it sees in some way! Before we compare the data with the predictions of the model being verified, the distortions introduced by the detector must be removed from them", explains Dr Chrząszcz and adds: "On the astrophysics side we have to perform a similar procedure. For example, simulations should be carried out on how 'new physics' phenomena would affect the behavior of the galactic halo of dark matter."

For seekers of 'new physics', the GAMBIT Collaboration does not bring the best news. The analyses suggest that if the supersymmetric particles predicted by the studied models exist, their masses must be on the order of many teraelectronvolts (in particle physics the mass of particles is given in energy units, one electronvolt corresponds to the energy necessary to shift the electron between points with a potential difference of one volt). In practice, this means that seeing such particles at the LHC will be either very difficult or even impossible. But there is also a shadow of hope. A few superparticles – known as neutralinos, charginos, staus and stops – although having quite large masses, do not exceed one teraelectronvolt. With some luck, their detection in the LHC remains possible. Unfortunately, in this group only the neutralino is considered a potential candidate for dark matter.

Unlike many other analytical research tools, the codes of all the GAMBIT modules are publicly available on the project website (http://gambit.hepforge.org) and can be quickly adapted to the analysis of new theoretical models. Researchers from the GAMBIT Collaboration hope that the openness of the code will speed up the search for 'new physics'.

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The Henryk Niewodniczański
Institute of Nuclear Physics
Polish Academy of Sciences

Kraków, 1 March 2018

HOW ARE HADRONS BORN AT THE HUGE ENERGIES AVAILABLE IN THE LHC?

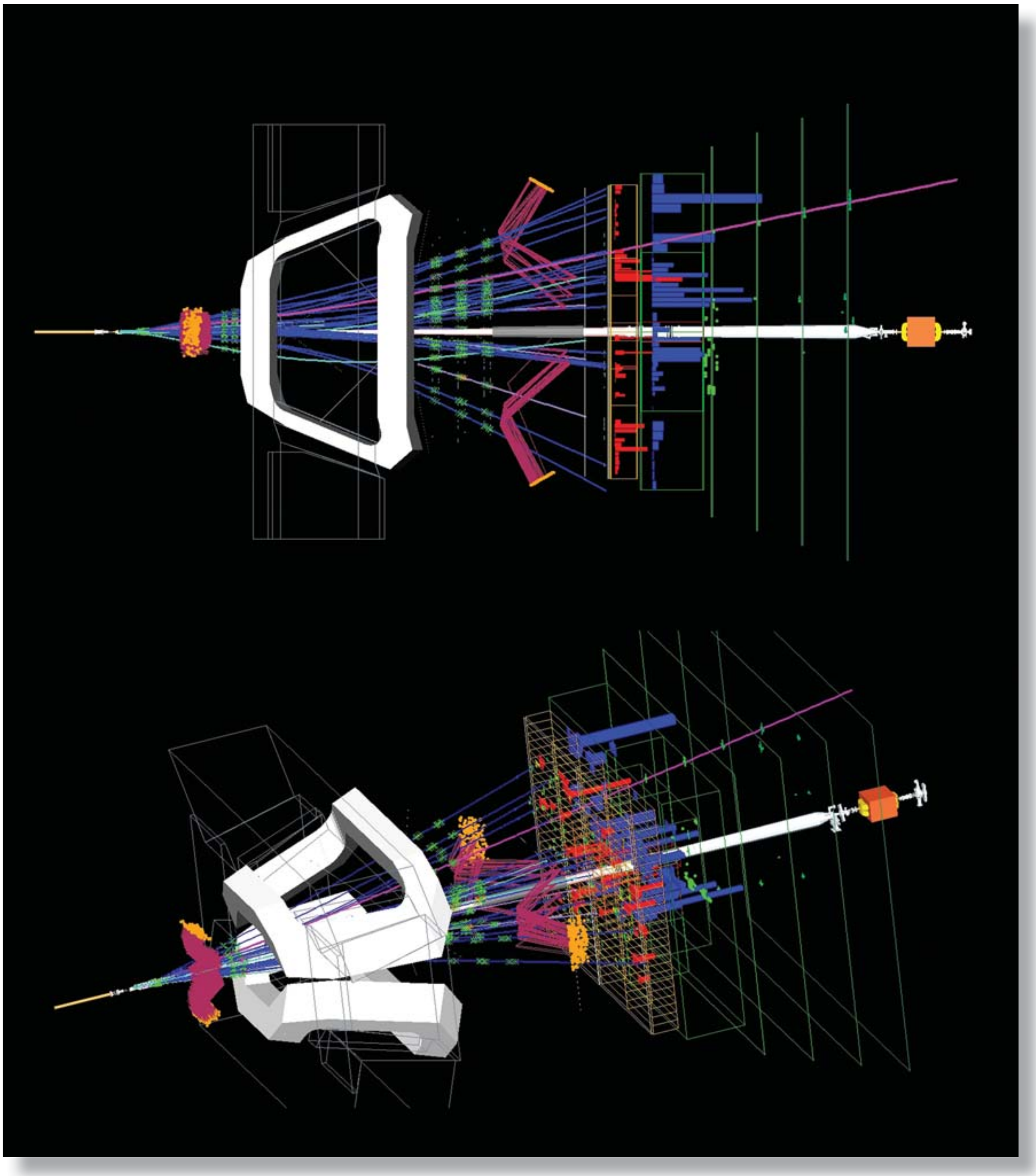
Our world consists mainly of particles built up of three quarks bound by gluons. The process of the sticking together of quarks, called hadronisation, is still poorly understood. Physicists from the Institute of Nuclear Physics Polish Academy of Sciences in Kraków, working within the LHCb Collaboration, have obtained new information about it, thanks to the analysis of unique data collected in high-energy collisions of protons in the LHC.

When protons accelerated to the greatest energy collide with each other in the LHC, their component particles – quarks and gluons – create a puzzling intermediate state. The observation that in the collisions of such relatively simple particles as protons this intermediate state exhibits the properties of a liquid, typical for collisions of much more complex structures (heavy ions), was a big surprise. Properties of this type indicate the existence of a new state of matter: a quark-gluon plasma in which quarks and gluons behave almost as free particles. This exotic liquid cools instantly. As a result, the quarks and gluons re-connect with each other in a process called hadronisation. The effect of this is the birth of hadrons, particles that are clumps of two or three quarks. Thanks to the latest analysis of data collected at energies of seven teraelectronvolts, researchers from the Institute of Nuclear Physics Polish Academy of Sciences (IFJ PAN) in Kraków, working within the LHCb Collaboration, acquired new information on the mechanism of hadronisation in proton-proton collisions.

"The main role in proton collisions is played by strong interaction, described by the quantum chromodynamics. The phenomena occurring during the cooling of the quark-gluon plasma are, however, so complex in terms of computation that until now it has not been possible fully understand the details of hadronisation. And yet it is a process of key significance! It is thanks to this that in the first moments after the Big Bang, the dominant majority of particles forming our everyday environment was formed from quarks and gluons," says Assoc. Prof. Marcin Kucharczyk (IFJ PAN).

In the LHC, hadronisation is extremely fast, and occurs in an extremely small area around the point of proton collision: its dimensions reach only femtometres, or millionths of one billionth of a metre. It is no wonder then, that direct observation of this process is currently not possible. To obtain any information about its course, physicists must reach for various indirect methods. A key role is played by the basic tool of quantum mechanics: a wave function whose properties are mapped by the characteristics of particles of a given type (it is worth noting that although it is almost 100 years since the birth of quantum mechanics, there still exists various interpretations of the wave function!).

"The wave functions of identical particles will effectively overlap, i.e. interfere. If they are enhanced as a result of interference, we are talking about Bose-Einstein correlations, if they are suppressed



Particles produced during one of the collisions of two protons, each with energies of 7 TeV, registered by the detectors of the LHCb experiment in 2011; view from two different sides. (Source: CERN, LHCb).

– Fermi-Dirac correlations. In our analyses, we were interested in the enhancements, that is, the Bose-Einstein correlations. We were looking for them between the pi mesons flying out of the area of hadronisation in directions close to the original direction of the colliding beams of protons," explains Ph.D. student Bartosz Małecki (IFJ PAN).

The method used was originally developed for radioastronomy and is called HBT interferometry (from the names of its two creators: Robert Hanbury Brown and Richard Twiss). When used with reference to particles, HBT interferometry makes it possible to determine the size of the area of hadronisation and its evolution over time. It helps to provide information about, for example, whether this area is different for different numbers of emitted particles or for their different types.

The data from the LHCb detector made it possible to study the hadronisation process in the area of so-called small angles, i.e. for hadrons produced in directions close to the direction of the initial proton beams. The analysis performed by the group from the IFJ PAN provided indications that the parameters describing the source of hadronisation in this unique region covered by LHCb experiment at LHC are different from the results obtained for larger angles.

"The analysis that provided these interesting results will be continued in the LHCb experiment for various collision energies and different types of colliding structures. Thanks to this, it will be possible to verify some of the models describing hadronisation and, consequently, to better understand the course of the process itself," sums up Prof. Mariusz Witek (IFJ PAN).

The work of the team from the IFJ PAN was financed in part by the OPUS grant from the Polish National Science Centre..

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The Henryk Niewodniczański
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Kraków, 23 May 2018

MATTER-ANTIMATTER ASYMMETRY MAY INTERFERE WITH THE DETECTION OF NEUTRINOS

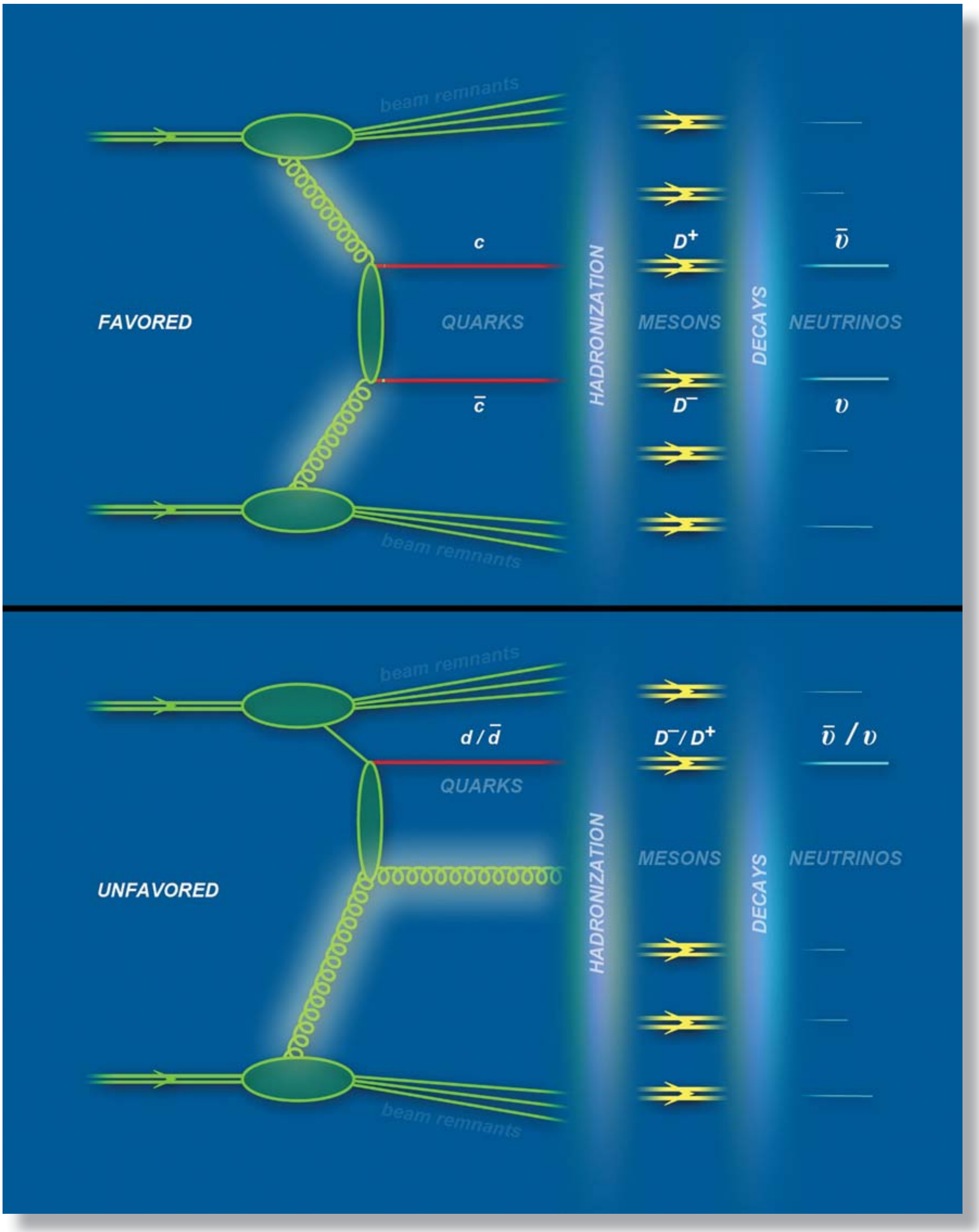
From the data collected by the LHCb detector at the Large Hadron Collider, it appears that the particles known as charm mesons and their antimatter counterparts are not produced in perfectly equal proportions. Physicists from Kraków have proposed their own explanation of this phenomenon and presented predictions related to it, about consequences that are particularly interesting for high-energy neutrino astronomy.

In the first moments after the Big Bang, the Universe was filled with equal amounts of particles and antiparticles. While it was cooling down, matter and antimatter began to merge and annihilate, turning into radiation. Why did some of this matter, from which the present Universe is built, survive this conflagration? In order to decipher this great mystery of modern science, physicists are trying to better understand all the mechanisms responsible for even the smallest disproportions in the production of particles and antiparticles. A group of scientists from the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Kraków, associated with the LHCb experiment at the Large Hadron Collider in Geneva, recently looked into one of these processes: the asymmetry appearing at the birth of charm mesons and antimesons. Interestingly, the conclusions from the analysis could be of very tangible practical significance.

According to modern knowledge, quarks are the most important indivisible building blocks that make up matter. We know of six flavours of quarks: up (u), down (d), strange (s), charm (c), bottom (b) and top (t); each flavour also has its own antimatter counterpart (often marked with a dash above the letter, read as "bar"). Quarks generally are formed in quark-antiquark pairs. They are extremely sociable particles: almost immediately after coming into being, they bind into hadrons, or groups of two, three, and sometimes more quarks or antiquarks, bonded with gluons (i.e. particles transferring strong nuclear interactions). The process of combining quarks/antiquarks into complexes is called hadronization.

Unstable hadrons built from quark-antiquark pairs are called mesons. If one of the quarks in a meson is a charm quark, the particle is called a charm meson and is denoted by the letter D (or for the charm antiquark: D with a bar above it). A pair built of a charm quark and a down antiquark is a D^+ meson, and one consisting of a charm antiquark and down quark is a D- meson.

In measurements conducted in the last quarter of a century, including recently as part of the LHCb experiment, an interesting asymmetry was noticed. It turned out that D^+ and D^- mesons are not always produced in exactly the same proportions. In the case of processes observed in LHCb, initiated in collisions of counter-current beams of high-energy protons, this asymmetry was small, less than one percent.



Comparison of mechanisms of favored and unfavored fragmentation of quarks. (Source: IFJ PAN)

"Charm quarks are mainly formed during gluon collisions in so-called hard interactions, and after birth they hadronise into D mesons. We investigated another meson formation mechanism, known as unfavoured quark fragmentation. Here, the charm meson is created as a result of hadronization of a light (up, down, or strange) quark or antiquark. By means of the nuances of this mechanism, the asymmetry between kaons and antikaons, i.e. K^+ and K^- mesons, was explained earlier. Until now, however, it has not been investigated whether a similar mechanism could explain the asymmetry between the relatively massive D^+ and D^- mesons," says Dr. Rafał Maciula (IFJ PAN), the first author of the publication in the journal Physical Review D.

The LHCb detector mainly measures particles diverging from the point of collision of protons at large angles to the original direction of movement of these protons. According to the Kraków-based physicists, the asymmetry in the production of D mesons should be much greater if particles produced in a forward direction are taken into account, that is, along the direction of the proton beams. This means that the currently observed disproportion may be just the tip of an iceberg. Calculations suggest that in the case of "forward" collisions, unfavoured fragmentation (d, u, s → D) may be comparable to conventional fragmentation (c → D). As a result, the asymmetry between D^+ and D^- mesons may reach even a high percentage and also with lower collision energies than those currently occurring in the LHC.

The research of the physicists from the IFJ PAN may have far-reaching consequences for neutrino observatories, such as the IceCube Observatory in Antarctica. This detector, in which 49 scientific institutions from 12 countries collaborate, monitors a cubic kilometre of ice, located almost a kilometre below the surface, using thousands of photomultipliers. Photomultipliers track subtle light flashes, initiated by the interaction of ice-forming particles with neutrinos, elementary particles very weakly interacting with ordinary matter.

IceCube registers several hundred neutrinos a day. It is known that a large proportion of them are created in the Earth's atmosphere in processes initiated by cosmic rays and taking place with the participation of protons. Other neutrinos may come, for example, from the Earth's core or from the Sun. It is assumed, however, that neutrinos with significant energies have reached the detector directly from distant cosmic sources: supernovae or merging black holes or neutron stars.

"When interpreting data from the IceCube detector, the production of neutrinos in the Earth's atmosphere caused by ordinary cosmic radiation, including collisions involving protons, is taken into account. The thing is that some of these processes, resulting in the formation of neutrinos with high energies, take place with the participation of D mesons. Meanwhile, we show that the mechanism of production of these mesons in the atmosphere can be much more efficient than previously thought. So, if our assumptions are confirmed, some of the highly energetic neutrinos registered, now considered to be of cosmic origin, have actually appeared just above our heads and are disturbing the real picture of events in the depths of space," explains Prof. Antoni Szczurek (IFJ PAN).

When just the tip of the iceberg can be seen, inferences about what the rest of it looks like is more than risky. The model proposed by the Kraków-based physicists has the status of a hypothesis today. Perhaps it does fully describe the mechanism that occurs in reality. But it may also be that other processes are responsible for the asymmetry in the production of D mesons, maybe partially or even in their entirety.

"Fortunately, no other competitive proposal predicts such a clear increase in asymmetry in the production of D mesons at lower collision energies. So, to check our assumptions, it would suffice in the LHC accelerator to direct a single beam onto a stationary target, which would significantly reduce the collision energy. Our model therefore meets the criteria of very reliable science: it not only explains previous observations, but above all it can be rapidly verified. In addition, this can be done very cheaply!" sums up Prof. Szczurek.

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The Henryk Niewodniczański
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Krakow, 19 May 2016

PHOTON COLLISIONS: PHOTONIC BILLIARDS MIGHT BE THE NEWEST GAME!

When one snooker ball hits another, both spring away from each other in an elastic manner. In the case of two photons a similar process – the elastic collision – has never been observed. Physicists from the Institute of Nuclear Physics of the Polish Academy of Sciences have shown, however, that such a process does not only occur, but even could soon be registered in heavy ion collisions at the LHC accelerator.

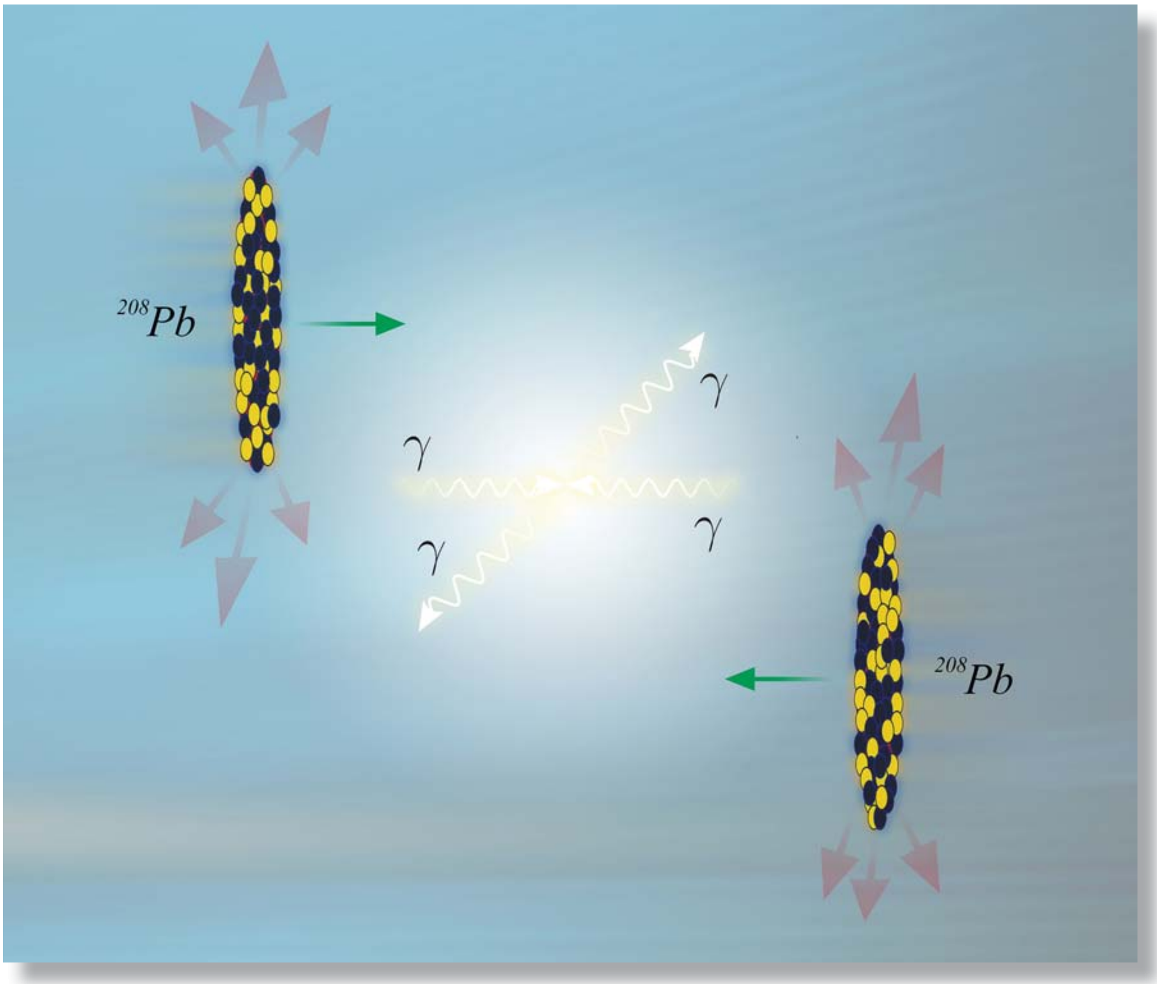
When photons collide with each other, do they act like billiard balls, springing away from each other in different directions? Such a course of interaction between particles of light has never been observed, even in the LHC, the most powerful accelerator in the world. An observation may, however, happen soon, thanks to a highly detailed analysis of the course of events in such a collision, conducted by physicists from the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Krakow, Poland, and just published in the journal Physical Review C.

Preliminary analysis of the elastic scattering of a photon-photon collision was presented several years ago in a study by scientists from the European Organization for Nuclear Research (CERN). Krakow scientists, however, funded by a grant from the Polish National Science Centre, have examined the process in much finer detail. Not only has it been established that collisions occur, but it has also taken into account more mechanisms of interaction between photons and predicted the directions in which most photons will scatter post-collision – and whether they can be measured. The results suggest that at least some of the photons deflected as a result of elastic collisions should hit the detectors installed by the ATLAS, CMS and ALICE projects. If the described phenomenon actually occurs, and by all appearances it will, observation would become possible within the next few years.

“Elastic collisions of photons with photons seemed, until recently, very unlikely. Many physicists regarded the registration of such collisions in the LHC as impossible. Meanwhile, we have proven that the phenomenon can be seen, though not in the collisions of protons, which occur much more frequently”, says Prof. Antoni Szczurek (IFJ PAN).

The LHC collides beams of protons with protons, or lead nuclei beams with lead nuclei. The IFJ PAN had shown earlier that if the collisions of protons occurred for elastic collisions between photons, the process would not be visible: it would obscure photons emitted by a different mechanism (initiated by gluons, the particles carrying the strong nuclear force). Luckily, the Polish scientists had some other ideas in store.

According to the rules of classical optics, light cannot be affected by light. Photons, however, can interact with each other through quantum processes. When two photons fly next to each other within that extremely short instant there is nothing preventing the creation of ‘virtual’ loops of quarks or leptons (which include electrons, muons, tau particles, neutrinos and the antiparticles associated with



Ultra-peripheral collisions of lead nuclei at the LHC accelerator can lead to elastic collisions of photons with photons. (Source: IFJ PAN).

them). Such particles would be termed virtual, as they would be impossible to see. However, despite this they would be responsible for the interaction between photons, after which they would again be transformed into 'real' photons. To the outside observer, the whole process would look like one photon reflected by the other photon.

Unfortunately, the energy of the photons generated by even the most powerful contemporary light sources can be registered only in millions of electron volts. These are miniscule values, even by the standards of modern nuclear physics and particle physics. At these energies, the probability of a collision with a photon-photon process involving quantum is infinitesimal, and the streams of photons necessary for its occurence would have to be colossal.

"In this situation, we decided to see whether elastic collisions of photons involving virtual particles can occur during collisions of heavy ions. And it worked! Large electric charges in the nuclei of lead may in fact lead to the creation of photons. If the process occurs in collisions of nuclei which have just passed, the photon generated by one nucleus has a chance to collide with photons produced by the second. We calculated that the probability of such a course of events is admittedly small, but nonzero. So everything indicates that the process could be observed", says Dr. Mariola Kłusek-Gawenda (IFJ PAN).

Interestingly, the collisions studied theoretically by Krakow physicists were very specific, as they did not analyze direct collisions of lead nuclei with one another as such, but processes without direct contact between nuclei. Interaction occurs between the electromagnetic fields of two atomic nuclei, which can fly even from long distances between them. These collisions are known as ultra-peripheral.

Potentially, photons can interact with each other as a result of another process: when a quantum transforms into virtual mesons, or quark-antiquark pairs. The mesons produced could interact with each other via the strong nuclear force, the fundamental force responsible for binding quarks inside protons and neutrons. The physicists from the IFJ PAN were the first to present this mechanism. It seems, however, that the observation of light collision with his participation at the event will not be possible: the gentle photons bouncing off each other just fly next to the detectors currently operating at the LHC.

The study of photon-photon elastic collisions not only provides a better understanding of the physics we already know. Quantum processes carrying the interaction between photons could potentially be involved as elementary particles, something we do not yet know. So if measurements of elastic scattering of photons off photons provided results other than those predicted by Krakow physicists, this could be a signal leading to a completely new physics engaged in the phenomena.

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Krakow, 8 June 2016

AT THE LHC, CHARMED TWINS WILL SOON BE MORE COMMON THAN SINGLES

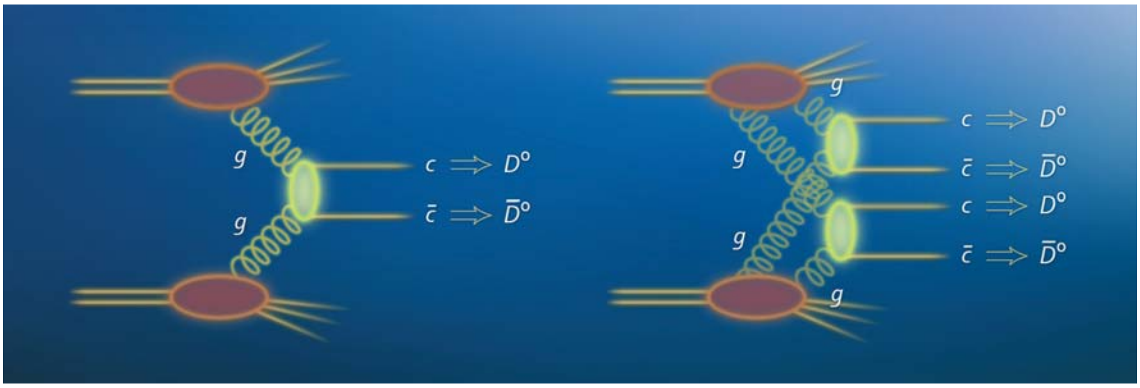
In the range of energies penetrated by the LHC accelerator, a new mechanism of the creation of particles is becoming more prominent, say scientists from the Institute of Nuclear Physics of the Polish Academy of Sciences in Krakow. The comparison between theoretical predictions and test data leaves no doubt: the energy in collisions is now so great that some of the elementary particles, mesons containing charm quarks, are beginning to emerge in pairs as often as single ones – and even more often.

A proton-proton collision is an extremely complex physical process of interactions wherein a variety of different particles arise. So far, today's particle accelerators (RHIC, Tevatron and now the LHC) studying the products of such collisions have recorded, among others, D^0 mesons appearing one by one. Recently, however, the LHC has been accelerating protons to their limits, and in the new energy an interesting effect has been observed: where once only solo D^0 mesons were formed, they are now appearing in pairs. Scientists from the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Krakow have explained the essence of this phenomenon and showed that with increasing energy, it undoubtedly plays a dominant role in the production of charm particles. The latest research, published in the journal Physics Letters B, was carried out in cooperation with Russian physicists from the Samara National Research University.

"A few years ago, we predicted that collisions of protons at sufficiently high energy should result in more charm mesons produced in pairs rather than alone. Our latest publication not only describes in detail why this happens, but it also proves that in the LHC this effect is clearly visible," says Prof. Antoni Szczurek (IFJ PAN).

According to the Standard Model currently used by physicists, particles considered to be elementary perform different functions. Bosons are carriers of forces: photons are related to electromagnetism, gluons are responsible for strong interactions, and bosons W^+, W^- and Z^0 mediate weak interactions. Matter is formed by particles called fermions. These include leptons (electrons, muons, tau particles and their associated neutrinos) and quarks (down, up, strange, charm, beautiful and top). The first three types of quarks are called light while the last three are called heavy. In addition, each quark and lepton has its antimatter partner. Complementing the whole is the Higgs boson, which gives particles mass (except for gluons and photons).

In our everyday world heavy quarks are present in small amounts and only appear for an extremely short time, mainly in the Earth's atmosphere. All visible and stable material of which atoms are constructed, including protons and neutrons, consists of up and down quarks. But when it comes to



Production of mesons and antimesons D^0 in interactions between gluons g. Left: creation of a single pair, right: two pairs are born. (Source: IFJ PAN)

collisions of particles at sufficient energies heavy quarks may arise. In the case of charm quarks (the least massive heavy quarks) the dominant process of their creation is the fusion of two gluons. In the LHC this occurs during proton-proton collisions, formed by the merger of quark-antiquark pairs. Neither a quark or an antiquark can stand alone, so they quickly form pairs with other quarks. When one of the quarks is a charm quark, the particle is called a meson D; when one of them is a charm antiquark, an antimeson D is the result.

"At lower energies two particles usually arise from a collision: the D0 meson and its antimeson. We have shown that the energies at the LHC, however, are so high that in the course of a collision gluons are not scatter only once, but twice or even more. The result of a single collision can then be numerous D0 mesons, plus, of course, appropriate antimesons", explains Prof. Szczurek.

Physicists often call quarks and gluons partons. The phenomenon of multiple parton scattering is already well-known, but had not been dealt with more closely because it never played a significant role in the investigated processes. Now scientists at IFJ PAN have shown that the situation has changed. Energies of accelerators are already so high that multiple parton scattering has become the leading mechanism responsible for the production of charm mesons and antimesons. Theoretical analysis of the measurements collected were supported by a group at the LHCb, leading one of the four major experiments carried out at the LHC.

"The data from the LHCb experiment have shown many cases where instead of one D^0 meson we have two of them. It is precisely the effect that we expected: production of twins is becoming as likely as the production of single mesons. In future accelerators, such as the already designed Future Circular Collider, the LHC's successor, this phenomenon will play quite a dominant role in the production of charm particles. Perhaps then we will see collisions with a resulting effect of not only two, but three or more D mesons," says Dr. Rafał Maciula (IFJ PAN).

Potentially, multiple parton scattering can lead to the formation of mesons containing other heavy quarks, such as beauty quarks. The calculations of Krakow physicists, however, show that at current energies of collisions in the LHC these processes are much less likely. It has to do with the masses of the quarks: the greater the mass, the less likely they will be produced, and beauty quarks are significantly heavier than their charm counterparts.

"For now all we can say for sure is that the production of twin charm mesons seems to be much more likely than twin beauty mesons," says Prof. Szczurek with a wink.

The analysis and prediction of physicists from the IFJ PAN are important not only for the future designers of large particle accelerators, but also for contemporary experiments on the registration of neutrinos coming from outer space, such as the famous IceCube detector in Antarctica. Physical and technological limitations mean that neutrino detectors cannot be built in space. Meanwhile, there is a risk that some of the neutrinos registered by the device on or below the Earth's surface are formed by the action of high-energy cosmic rays in the atmosphere of our planet. Colliding with atoms and molecules of the atmosphere, cosmic rays can in fact create charm quarks, which are then transformed into short-lived D mesons. The problem is that some of the decay products of D mesons may just be neutrinos and antineutrinos. Research on multiple scattering of partons can therefore help in determining how many neutrinos observed in detectors actually came to us from the depths of space, and how much is just noise resulting from the presence of the atmosphere.

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Kraków, 14 February 2018

THE SEARCH FOR DARK MATTER: AXIONS HAVE EVER FEWER PLACES TO HIDE

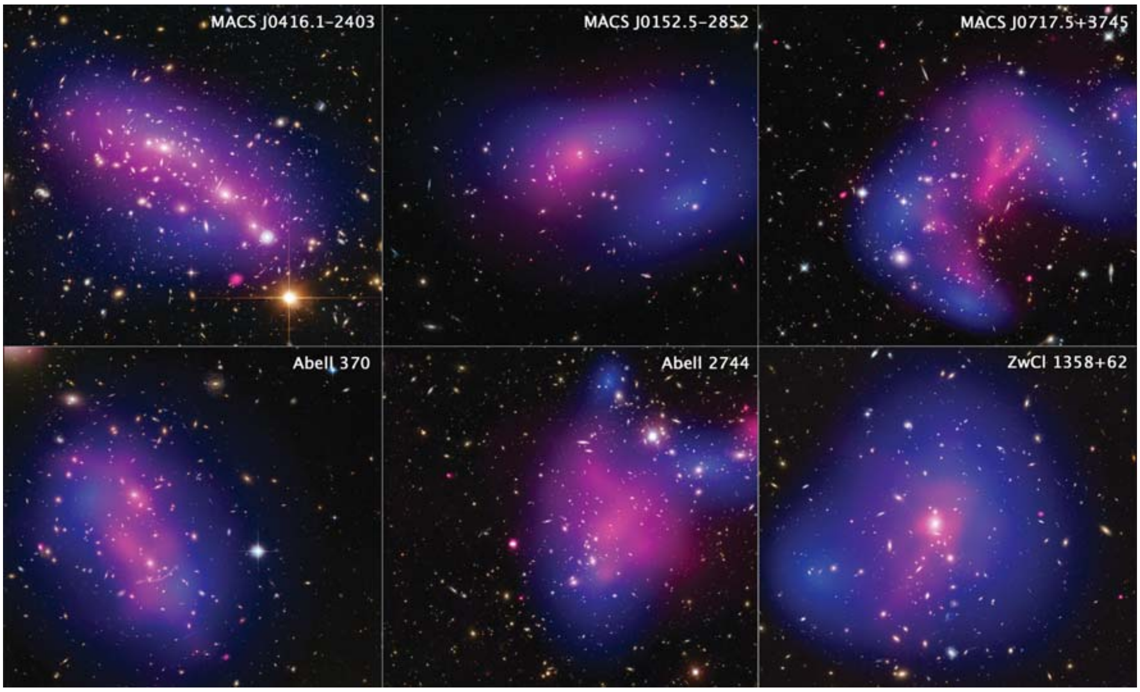
If they existed, axions – one of the candidates for particles of the mysterious dark matter – could interact with the matter forming our world, but they would have to do this to a much, much weaker extent than it has seemed up to now. New, rigorous constraints on the properties of axions have been imposed by an international team of scientists responsible for the nEDM experiment.

The latest analysis of measurements of the electrical properties of ultracold neutrons published in the scientific journal Physical Review X has led to surprising conclusions. On the basis of data collected in the nEDM (Electric Dipole Moment of Neutron) experiment, an international group of physicists – including the Kraków-based scientists from the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) and the Jagiellonian University – showed in an innovative way that axions, the hypothetical particles that may form cold dark matter, if they existed, would have to comply with much stricter limitations than previously believed with regard to their mass and manners of interacting with ordinary matter. The presented results are the first laboratory data imposing limits on the potential interactions of axions with nucleons (i.e. protons or neutrons) and gluons (the particles bonding quarks in nucleons).

"Measurements of the electric dipole moment of neutrons have been conducted by our international group for a good dozen or so years. For most of this time, none of us suspected that any traces associated with potential particles of dark matter might be hidden in the collected data. Only recently, theoreticians have suggested such a possibility and we eagerly took the opportunity to verify the hypotheses about the properties of axions," says Dr. Adam Kozela (IFJ PAN), one of the participants of the experiment.

The first traces of dark matter were found when analyzing the movements of stars in galaxies and galaxies in galaxy clusters. The pioneer of statistical research on star movements was the Polish astronomer Marian Kowalski. Already in 1859 he noticed that the movements of stars close to us could not be explained solely by the movement of the Sun. This was the first observational premise suggesting the rotation of the Milky Way (Kowalski is thus the man who "shook the foundations" of the galaxy). In 1933, the Swiss Fritz Zwicky went one step further. He analyzed the movements of structures in the Coma galaxy cluster by several methods. He then noticed that they moved as if there were a much larger amount of matter in their surroundings than that seen by astronomers.

Despite decades of searching, the nature of dark matter, which (as background microwave radiation measurements suggest) there should be almost 5.5 times as much of in the Universe as ordinary matter, is still unknown. Theoreticians have constructed a whole plethora of models predicting the existence of particles that are more exotic or less so, that may be responsible for the existence of dark matter. Among



The distribution of dark matter (colored in blue) in six galaxy clusters, mapped from the visible-light images from the Hubble Space Telescope. (Source: NASA, ESA, STScI, and CXC).

the candidates are axions. If they did exist, these extremely light particles would interact with ordinary matter almost exclusively by gravity. Almost, because current models predict that in certain situations a photon could change into an axion, and after some time this would transform back into a photon. This hypothetical phenomenon was and is the basis of the famous "lighting through a wall" experiments. These involve researchers directing an intense beam of laser light onto a thick obstacle, counting on the fact that at least a few photons will change into axions that will penetrate the wall without any major problems. After passing through the wall, some axions could become photons again with features exactly like the photons originally falling on the wall.

Experiments related to measuring the electric dipole moment of neutrons, conducted by a group of researchers from Australia, Belgium, France, Germany, Poland, Switzerland and Great Britain, have nothing to do with photons. The measuring apparatus that was initially located at the Institut Laue-Langevin (ILL) in Grenoble (France) is currently operating at the Laboratory for Particle Physics at the Paul Scherrer Institute (PSI) in Villigen (Switzerland). In experiments that have been conducted for over ten years, scientists measure changes in the frequency of nuclear magnetic resonance (NMR) of neutrons and mercury atoms that are in a vacuum chamber in the presence of electric, magnetic and gravitational fields. These measurements enable conclusions to be drawn about the precession of neutrons and mercury atoms, and consequently on their dipole moments.

To the surprise of many physicists, in recent years theoretical works have appeared that envisage the possibility of axions interacting with gluons and nucleons. Depending on the mass of the axions, these interactions could result in smaller or larger disturbances having a character of oscillations of dipole electrical moments of nucleons, or even whole atoms. The theoreticians' predictions meant that experiments conducted as part of the nEDM cooperation could contain valuable information about the existence and properties of potential particles of dark matter.

"In the data from the experiments at PSI, our colleagues conducting the analysis looked for frequency changes with periods in the order of minutes, and in the results from ILL – in the order of days. The latter would appear if there was an axion wind, that is, if the axions in the near Earth space were moving in a specific direction. Since the Earth is spinning, at different times of the day our measuring equipment would change its orientation relative to the axion wind, and this should result in cyclical, daily changes in the oscillations recorded by us," explains Dr. Kozela.

The results of the search turned out to be negative: no trace of the existence of axions with masses between 10^{-24} and 10^{-17} electronvolts were found (for comparison: the mass of an electron is more than half a million electronvolts). In addition, scientists managed to tighten the constraints imposed by theory on the interaction of axions with nucleons by 40 times. In the case of potential interactions with gluons, the restrictions have increased even more, more than one thousand-fold. So then, if axions do exist, in the current theoretical models they have fewer and fewer places to hide.

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TRACKING THE RIDDLES OF COSMOS

The Henryk Niewodniczański
Institute of Nuclear Physics
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Kraków 18 march 2016

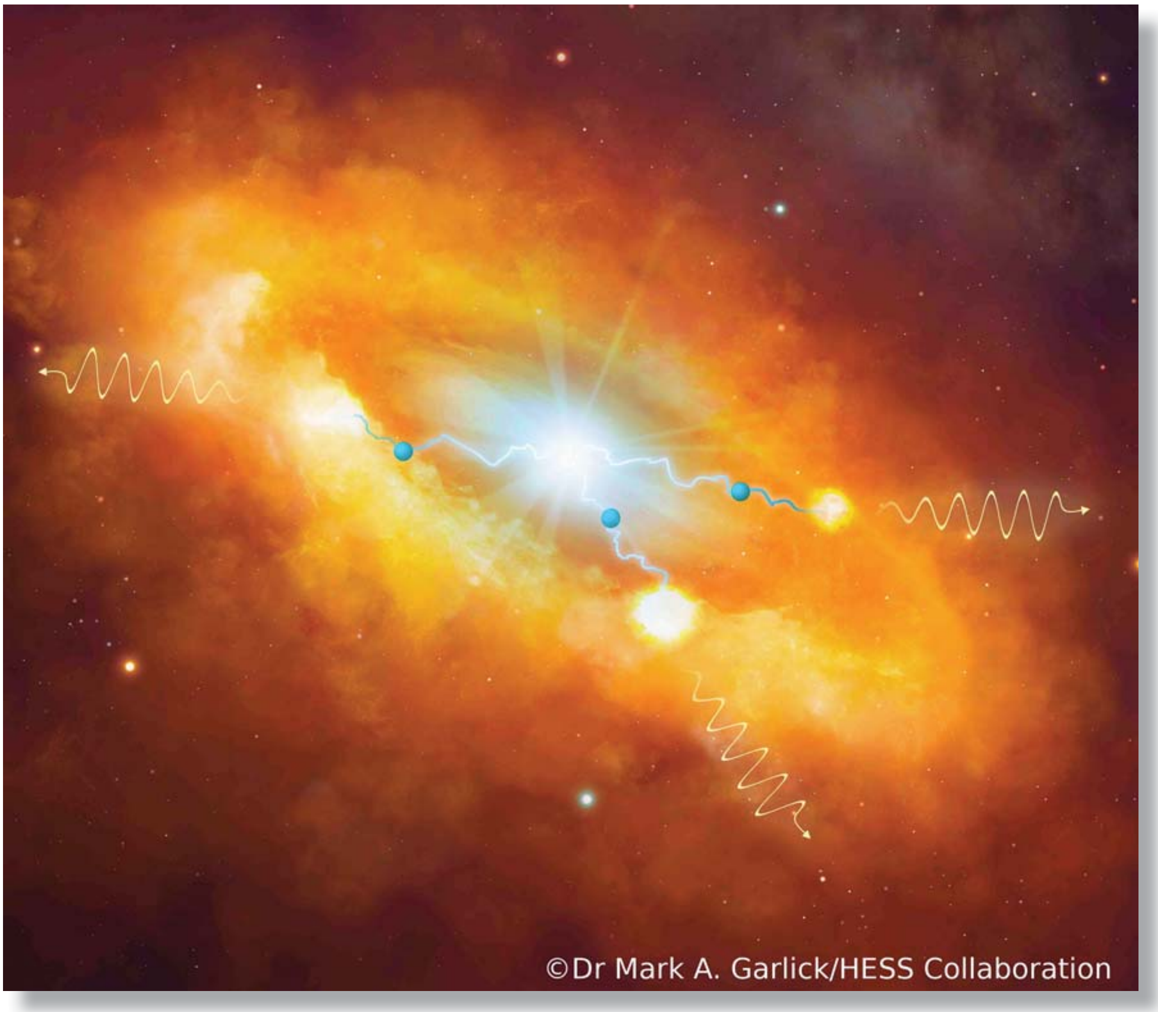
"A SOURCE ACCELERATING GALACTIC COSMIC RAYS TO UNPRECEDENTED ENERGY DISCOVERED AT THE CENTRE OF THE MILKY WAY"

For more than ten years the H.E.S.S. observatory in Namibia, run by an international collaboration of 42 institutions in 12 countries, has been mapping the centre of our galaxy in very-high-energy gamma rays. These gamma rays are produced by cosmic rays from the innermost region of the Galaxy. A detailed analysis of the latest H.E.S.S. data, published on 16th March 2016 in Nature, reveals for the first time a source of this cosmic radiation at energies never observed before in the Milky Way: the supermassive black hole at the centre of the Galaxy, likely to accelerate cosmic rays to energies 100 times larger than those achieved at the largest terrestrial particle accelerator, the LHC at CERN.

The Earth is constantly bombarded by high energy particles (protons, electrons and atomic nuclei) of cosmic origin, particles that comprise the so-called "cosmic radiation". These "cosmic rays" are electrically charged, and are hence strongly deflected by the interstellar magnetic fields that pervade our galaxy. Their path through the cosmos is randomised by these deflections, making it impossible to directly identify the astrophysical sources responsible for their production. Thus, for more than a century, the origin of the cosmic rays remains one of the most enduring mysteries of science.

Fortunately, cosmic rays interact with light and gas in the neighbourhood of their sources, producing gamma rays. These gamma rays travel in straight lines, undeflected by magnetic fields, and can therefore be traced back to their origin. When a very-high-energy gamma ray reaches the Earth, it interacts with a molecule in the upper atmosphere, producing a shower of secondary particles that emit a short pulse of "Cherenkov light". By detecting these flashes of light using telescopes equipped with large mirrors, sensitive photo-detectors, and fast electronics, more than 100 sources of very-high-energy gamma rays have been identified over the past three decades. The H.E.S.S. (High Energy Stereoscopic System) observatory in Namibia represents the latest generation of such telescope arrays. It is operated by scientists from 42 institutions in 12 countries, with major contributions by MPIK Heidelberg, Germany, CEA and CNRS, France.

Today we know that cosmic rays with energies up to approximately 100 teraelectronvolts (TeV) are produced in our galaxy, by objects such as supernova remnants and pulsar wind nebulae. Theoretical



Artist's impression of the giant molecular clouds surrounding the Galactic Centre, bombarded by very high energy protons accelerated in the vicinity of the central black hole and subsequently shining in gamma rays. © Dr Mark A. Garlick/ H.E.S.S. Collaboration

arguments and direct measurements of cosmic rays reaching the Earth indicate, however, that the cosmic-ray factories in our galaxy should be able to provide particles up to one petaelectronvolt (PeV) at least. While many multi-TeV accelerators have been discovered in recent years, so far the search for the sources of the highest energy Galactic cosmic rays has, so far, been unsuccessful.

Detailed observations of the Galactic centre region, made by H.E.S.S. over the past ten years, and published today in the journal Nature, finally provide direct indications for such PeV cosmic-ray acceleration. During the first three years of observations, H.E.S.S. uncovered a very powerful point source of gamma rays in the galactic-centre region, as well as diffuse gamma-ray emission from the giant molecular clouds that surround it in a region approximately 500 light years across. These molecular clouds are bombarded by cosmic rays moving at close to the speed of light, which produce gamma rays through their interactions with the matter in the clouds. A remarkably good spatial coincidence between the observed gamma rays and the density of material in the clouds indicated the presence of one or more accelerators of cosmic rays in that region. However, the nature of the source remained a mystery.

Deeper observations obtained by H.E.S.S. between 2004 and 2013 shed new light on the processes powering the cosmic rays in this region. According to Aion Viana (MPIK, Heidelberg), "the unprecedented amount of data and progress made in analysis methodologies enables us to measure simultaneously the spatial distribution and the energy of the cosmic rays." With these unique measurements, H.E.S.S. scientists are for the first time able to pinpoint the source of these particles: "Somewhere within the central 33 light years of the Milky Way there is an astrophysical source capable of accelerating protons to energies of about one petaelectronvolt, continuously for at least 1,000 years", says Emmanuel Moulin (CEA, Saclay). In analogy to the "Tevatron", the first human-built accelerator that reached energies of 1 TeV, this new class of cosmic accelerator has been dubbed a "Pevatron". "With H.E.S.S. we are now able to trace the propagation of PeV protons in the central region of the Galaxy", adds Stefano Gabici (CNRS, Paris).

The centre of our galaxy is home to many objects capable of producing cosmic rays of high energy, including, in particular, a supernova remnant, a pulsar wind nebula, and a compact cluster of massive stars. However, "the supermassive black hole located at the centre of the Galaxy, called Sgr A*, is the most plausible source of the PeV protons", says Felix Aharonian (MPIK, Heidelberg and DIAS, Dublin), adding that, "several possible acceleration regions can be considered, either in the immediate vicinity of the black hole, or further away, where a fraction of the material falling into the black hole is ejected back into the environment, thereby initiating the acceleration of particles".

The H.E.S.S. measurement of the gamma-ray emission can be used to infer the spectrum of the protons that have been accelerated by the central black hole – revealing that Sgr A* is very likely accelerating protons to PeV energies. Currently, these protons cannot account for the total flux of cosmic rays detected at the Earth. "If, however, our central black hole was more active in the past", the scientists argue, "then it could indeed be responsible for the bulk of the Galactic cosmic rays that are observed today at the Earth". If true, this would dramatically influence the century old debate concerning the origin of these enigmatic particles.

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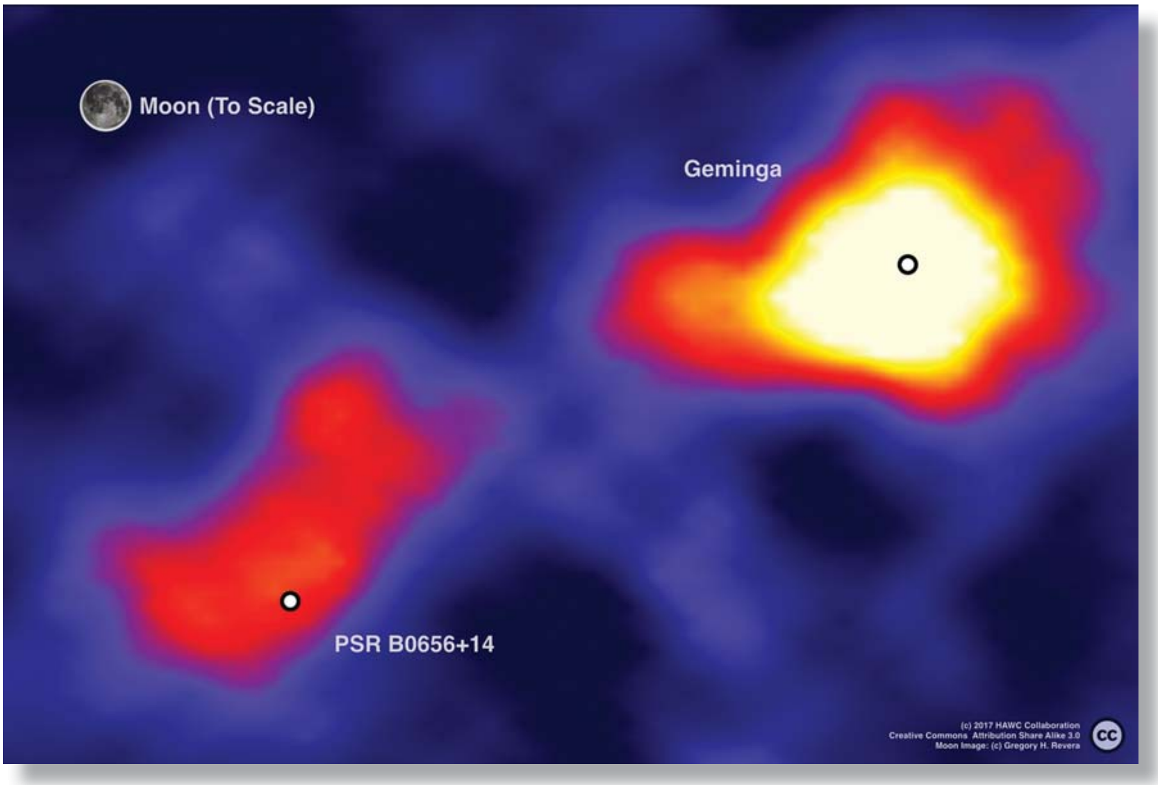
Kraków, 16 November 2017

NEARBY PULSARS SHED LIGHT ON THE ANTIMATTER PUZZLE

There are too many high-energy positrons in the cosmic rays reaching the Earth. These positrons (particles that are antimatter equivalents of electrons) could be being produced by pulsars in our vicinity. The most recent measurements from the HAWC Observatory in Mexico have practically excluded this possibility, strengthening the competing and much more exotic hypothesis concerning the origin of the excess positrons.

Our planet is immersed in cosmic rays. The particles reaching the Earth from the depths of the Universe include positrons – antimatter equivalents of electrons. Astrophysicists have long been intrigued by why there are far more high-energy positrons in the cosmic rays than could be expected by current theoretical models. The latest attempt at an answer is the observations made by a team of several dozen



In cosmic rays there are more high-energy positrons than could be produced by pulsars in our vicinity: Geminga and PSR B0656+14. (Source: John Pretz).

The High-Altitude Water Cherenkov Gamma-Ray Observatory (HAWC) detector, Sierra Negra, Mexico. (Source: Jordan A. Goodman).

researchers from the United States, Mexico, Germany and Poland, conducted using the recently activated High-Altitude Water Cherenkov Gamma-Ray Observatory (HAWC) detector. The analysis of the measurements of the cosmic ray particles, which has just been published in the prestigious scientific journal Science, included the participation of a research group from the Institute of Nuclear Physics Polish Academy of Sciences (IFJ PAN) in Kraków, financed by the Polish National Science Centre OPUS grant.

"We know that high-energy particles of cosmic rays, travelling through our galaxy, quickly dissipate their energy by interacting with other radiation and magnetic fields. This is how particles of primary cosmic rays behave. Positrons are secondary, they come from interactions in which primary radiation is involved. We would therefore expect a similar dependence: a marked decrease in the number of high-energy positrons," explains Prof. Sabrina Casanova (IFJ PAN) and adds: "The reality is different. Satellite and terrestrial observatories record many more high-energy positrons than they should. Our aim was to check whether the source of the positron excess was astronomical objects in our vicinity, such as pulsars and their surrounding nebulae."

The HAWC Observatory is located on the slopes of the Mexican volcano Sierra Negra at an altitude of over 4100 metres above sea level. It houses 300 water tanks, surrounded by detectors sensitive to fleeting flashes of light, known as Cherenkov radiation. This radiation appears in the tank when a particle moving at a speed greater than the speed of light in water falls into it. Each day at HAWC, in this manner, the presence of cosmic gamma photons with energies from 100 gigaelectronvolts (GeV) to 100 teraelectronvolts (TeV) is recorded. These are energies even trillions of times greater than the energy of visible light photons and are over a dozen times greater than the energy of protons in the LHC accelerator. (It is worth noting that throughout the history of cosmic ray measurements, particles with energies of even up to 300 000 000 TeV have been recorded.)

"Detectors at the HAWC observatory record gamma radiation emitted, among others, by a certain population of electrons produced by pulsars and accelerated by them to huge energies. The basic question was: are there enough of these electrons for interactions with them to then produce the right number of positrons?" says Dr. Francisco Salesa Greus (IFJ PAN).

The experimental team conducted a very detailed analysis of the data collected for two relatively close pulsars known as Geminga and PSR B0656+14. The first is about 800 and the other over 900 light years distant from us. Both are among the strongest sources of cosmic rays in our region of the galaxy.

The analysis, covering 17 months of observation, showed that the radiation from both pulsars and their surrounding nebulae was indeed responsible for some of the positrons in the cosmic rays. However, contrary to the expectations of a large group of researchers, this contribution turned out to be several times too small to explain the actual number of TeV positrons.

“Since the involvement of close-by pulsars in the generation of high-energy positrons reaching us is so modest, other explanations become more and more likely. The most interesting is the hypothesis about the origin of excess positrons from the decay or annihilation of dark matter,” comments Prof. Casanova.

If the hypothesis of the origin of positrons from the annihilation or decay of dark matter turns out, over time, to be true, the excess positrons in cosmic rays would be the first particles recorded by humans to be derived from the interaction of dark matter. Whether or not they really are, will be decided by future observations.

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Kraków, 3 October 2018

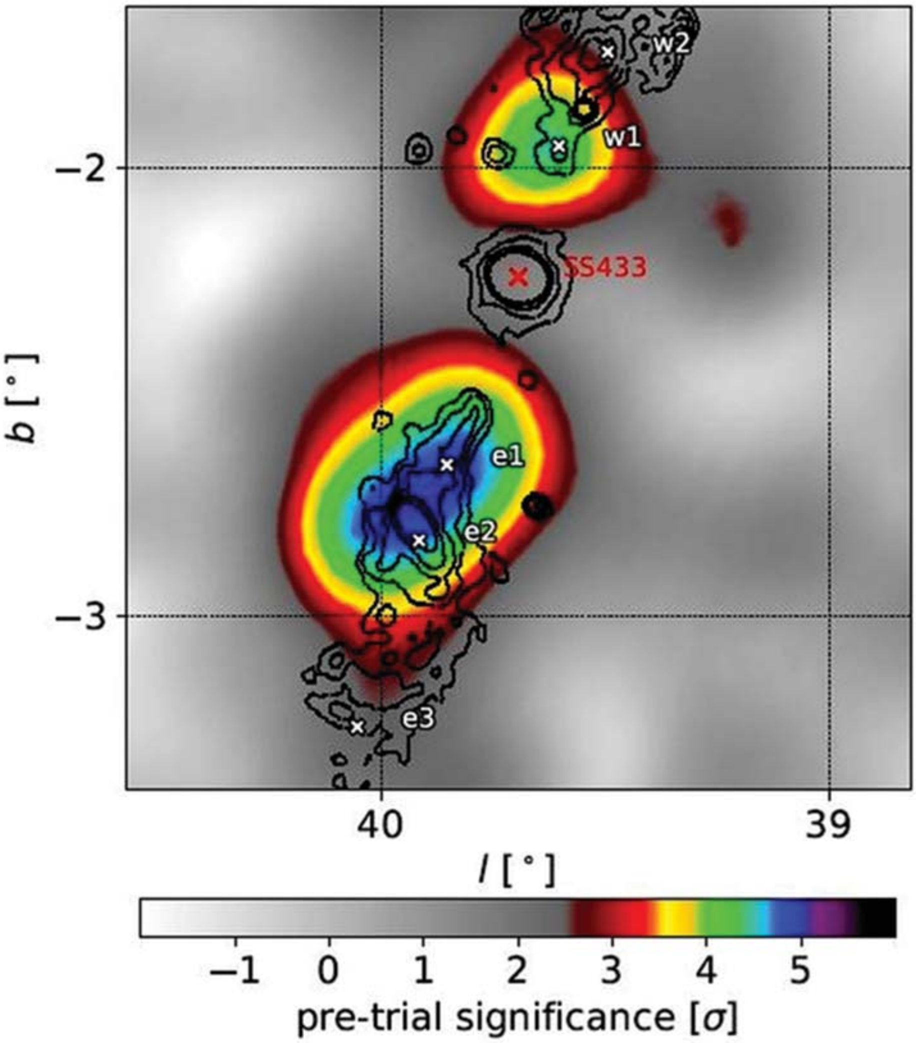
HAWC: MICROQUASAR SS 433 REVEALS THE NATURE OF THE BRIGHTEST LANTERNS OF THE UNIVERSE

They shine even from billions of light years away. Intriguing and enigmatic, quasars are loath to uncover their secrets. Fortunately, we can find out more about them by looking at their star counterparts – microquasars. Many years of observation of the microquasar SS 433, carried out in the HAWC observatory, have made it possible to identify, for the first time, spectacular details of the processes responsible for the production of high-energy radiation.

This is probably one of the most majestic views a man could ever see. Just next to a gigantically bloated, blindingly bright star lurks a voracious ball of ”nothingness”: a black hole that scrupulously engulfs the matter from its shining companion. These particles, falling to the horizon of events, form a flat whirlpool, part of which flows towards the axis of rotation of the black hole. From both poles, narrow jets of matter shoot in opposite directions. Collimated by the invisible claws of magnetic fields, like a giant's hairpins, they pierce the abyss of the cosmos, breaking off on the expanding shell of matter surrounding the system – the remnants of a supernova explosion. Welcome to the world of the microquasar SS 433, in recent months one of the main objects of interest of the High-Altitude Water Cherenkov Observatory Gamma-Ray Observatory (HAWC).

The latest observations of SS 433 are of a pioneering nature. For the first time in the history of the study of microquasars, gamma radiation at such high energies has been recorded, and careful analysis of the data has led to surprising conclusions about the sites and mechanisms responsible for its production. The results of the research have just been presented in the prestigious scientific journal Nature. This spectacular achievement is the work of the international team of the HAWC project, which includes scientists from the United States, Mexico, Poland, and Germany. The Polish side is represented by the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Kraków.

Quasars, active galactic nuclei, are some of the most unusual and at the same time brightest objects in the Universe. The driving force of a quasar is the supermassive black hole found at its centre, surrounded by an accretion disk formed by falling matter. Quasars are sources of extremely intense electromagnetic radiation, covering almost the entire spectrum, from radio waves to high-energy gamma rays. Being a type of galactic nucleus, quasars are by definition distant objects. The nearest quasar Markarian 231, powered by a pair of supermassive black holes madly spinning around each other, is in the nucleus of a galaxy 600 million light years away. This is not a distance that is conducive to carrying out high-resolution observations to facilitate an understanding of the nature of the processes taking place here.



Sources of very high-energy gamma radiation around the microquasar SS 433 surrounded by the W50 nebula. (Source: HAWC Observatory).

Fortunately, the rich menu offered to us by the Universe includes quasars in miniature. What a quasar does on a galactic scale, the microquasar does on the scale of the star system. Markarian 231's black holes are gigantic: the smaller one has a mass 4 million times that of the Sun, the larger one's mass is as much as 150 million times as great. The microquasar closest to us, SS 433, located in the background of the Aquila constellation, is a binary system with radically smaller dimensions. There is a very dense object here, probably a black hole with a mass of several suns, which is the remnant of a supernova explosion. It devours matter from an accretion disk powered by a stellar wind coming from a nearby spectral type A supergiant (a similar star, easily visible in the night sky, is Deneb, the brightest star in the Cygnus constellation). This picturesque pair, spinning around each other at an impressive rate of 13 days and surrounded by the W50 nebula, is only 18 thousand light years from Earth.

"Both quasars and microquasars can generate jets, that is, very narrow and very long streams of matter, emitted in both directions along the axis of rotation of the object. The jets are created by particles accelerated to speeds not infrequently close to the velocity of light. In terms of speed, the jets from SS 433 are not particularly impressive: they reach only 26% of the velocity of light. What is more important is something else," says Prof. Sabrina Casanova (IFJ PAN), and elaborates: "Most of the observed quasars have jets that are to a greater or lesser degree directed towards us. This orientation makes it difficult to distinguish details. On the other hand, SS 433 was kind enough to direct its jets not towards us, but almost perpendicular to the direction in which we look. Therefore, not only do we have the object almost at hand, it is also optimally positioned when it comes to observing details such as the sites from where the radiation originates."

In our galaxy SS 433 belongs to an elite group of just a dozen or so microquasars and is one of the few to emit gamma radiation. For 1017 days, this radiation was recorded at the HAWC observatory, operating at an altitude of over 4,100 m above sea level on the slope of the Mexican Sierra Negra volcano. The detector built here consists of 300 tanks of water, instrumented with photomultipliers sensitive to fleeting light flashes, known as Cherenkov radiation. It appears in the tank when a particle moving at a velocity faster than the velocity of light in water falls into it. Of key importance is the fact that some of the flashes come from particles generated as a result of high energy collisions of gamma quanta with the Earth's atmosphere. Appropriate analysis of the flashes in the tanks makes it possible to identify the reason for their existence. In this way, HAWC indirectly registers gamma photons with energies from 100 gigaelectronvolts (GeV) to 100 teraelectronvolts (TeV). These are energies up to a trillion times greater than the energy of photons of visible light and several times larger than the energy of protons in the LHC accelerator.

During observations of SS 433, conducted at the limit of HAWC's resolution capability, scientists have managed to register photons with energies above 25 TeV, i.e. three to ten times higher than those reported in the entire history of microquasar studies. To the surprise of the researchers, the brightest object in the system in the range of high-energy gamma radiation was not SS 433 itself, but the places on both sides of it where the jets break off colliding with the matter rejected by the supernova.

"That's not the end of the surprises. Gamma photons with energies of 25 TeV have to be produced by particles of even higher energies. These could be protons, but then they would have to have enormous energies at a level of 250 TeV. The data we collected, however, showed that this mechanism, even if it actually works, is not able to generate the right amount of gamma radiation in the case of SS433," explains Dr. Francisco Salesa Greus (IFJ PAN).

In further work, data from HAWC were compared with SS 433 measurements in the remaining spectral ranges from other observatories. In the end, it was established that high-energy gamma quanta – or at least the majority of them – have to be emitted by electrons in the jet during their collisions with the low-energy microwave background radiation filling the entire cosmos. The above mechanism, described here for the first time, could not have been detected in observations of quasars with jets directed towards Earth. SS 433 has thus helped to reveal not only its own secrets, but also the secrets of the brightest lanterns of the Universe.

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Kraków, 12 June 2018

CREDO: YOU TOO CAN HELP UNVEIL THE DEEPEST PUZZLES OF THE UNIVERSE

Are astrophysical phenomena occurring millions or even billions of light years from Earth responsible for some diseases? Does dark matter really exist? What is the true nature of our spacetime – is it continuous or digital? Can the exotic effects of quantum gravity be tested experimentally? Install the CREDO Detector app, become part of the largest particle detector in history and help unveil the fundamental secrets of the Universe!

When a particle with an energy of the highest order observed in the Universe approaches from the depths of the cosmos, it initiates a spectacular phenomenon in the Earth's atmosphere: a gigantic cascade of secondary particles, called an extensive air shower. After reaching the Earth, a cascade caused by a single particle can cover the surface of even a large agglomeration. Where do the primary particles with such extreme energies, hundreds of millions of times larger than those achieved by protons accelerated in the LHC accelerator, come from? Do they indicate the decay of particles of dark matter? Or do they herald a completely new physics?

Today, everyone can help in the scientific search for answers to these fascinating questions of modern physics. All you need do is install the CREDO Detector on a smartphone equipped with a camera, an application prepared as part of the international Cosmic-Ray Extremely Distributed Observatory project (CREDO), initiated and coordinated by a team of scientists from the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Kraków. The maintenance and development of this app is supervised by the Kraków University of Technology, and the Academic Computer Centre CYFRONET of the AGH University of Science and Technology in Kraków supervises the collection and processing of data from around the world. Although the CREDO Detector is not the only app for the detection of cosmic-ray particles or local radioactivity, it is the first program of this type with an open-access code available to everyone. What's more, the CREDO Detector is part of a global scientific venture dedicated to the study of the laws of nature at a fundamental level. The world premiere of the app took place on 17th May during the Kraków Festival of Science and Art.

"The scientific capital of human enthusiasm is gigantic. We want to use it, at least in part, to penetrate the areas of physical reality that have, so far, been unavailable to scientific research. This is something we can do because today almost everyone carries around a device capable of recording single particles of cosmic rays in their pockets. All that's needed to get involved in our research is to want to," says the head of the CREDO project, Dr. Piotr Homola (IFJ PAN).

By interacting, thousands and millions of smartphones can potentially create the largest cosmic particle radiation detector, covering the entire planet. How can you become a part of this? There's nothing

CREDO Detector transforms your smartphone into an important element of the largest particle detector in history. (Source: IFJ PAN).

simpler: the free CREDO Detector app for Android smartphones can be downloaded from the official Google Play store, from the IFJ PAN account. After installation, you have to register in the CREDO system. It's worth doing this with real contact details. In scientific research, it is assumed that anyone who contributes to the collection of data has the right to co-authorship of scientific publications based on these data. It is no different with CREDO: any user who initiates particle detection in the CREDO Detector for even a moment, has the right to membership in the international CREDO collaboration and to sign its publications with his/her name.

The huge scientific potential of the CREDO project lies in the possibility of observing time and/or spatial correlations between events registered by different, even very distant detectors, including smartphones. If we could detect such correlations, we would probably obtain new information not only about events involving extremely energetic particles of ordinary matter, but there is also a chance for a new light being shed on the properties of dark matter particles, the nature of quantum gravity, and potentially even the deepest structure of spacetime. Who knows, maybe CREDO will help us to finally determine if our spacetime is digital?

“If CREDO gains even moderate popularity, data from smartphones scattered across all continents have a chance to revolutionize not only theoretical physics, but also areas much closer to our everyday life,” notes Dr. Homola.

Examples? Particles coming from space are very sensitive to changes in the geomagnetic field and these, it seems, may accompany the tides of liquid iron in the Earth's interior, potentially generating seismic phenomena. If CREDO were to confirm the relationship between changes in the frequency of recording of secondary cosmic ray particles and earthquakes, perhaps we could predict the latter, hopefully with a sufficiently early notice that would provide the opportunity to save human life. In turn, in medicine, there is a hypothesis, among others, on the possible correlation of the geographical distribution of certain diseases of unknown aetiology, such as multiple sclerosis, with the distribution of cosmic radiation intensity at the surface of the Earth. The widely dispersed CREDO infrastructure would be the first really good research tool to confirm or disprove this hypothesis.

“We have created CREDO for the scientific need to organize a global infrastructure, with which it will be possible to implement not one but many specialized experiments. The first of them, the Quantum Gravity Previewer, was launched on 17th May. We expect that already this autumn we will have gathered enough data to present the first major scientific reports. This is what the true beauty of our project is all about: we are exploring such exotic areas of our reality that we can expect even... the unexpected,” says Dr. Homola.

Tracks of particles detected by the CREDO Detector app. (Source: IFJ PAN / CREDO / user smph-kitkat).

The CREDO Detector uses the image detector in the smartphone's camera. If the camera's lens is obscured, the images recorded should consist of only black pixels. When this condition is met, the CREDO Detector starts working. If a particle of secondary cosmic radiation passes through the detector on the smartphone, or possibly a particle of local radiation, it will stimulate some of its pixels. A few to several dozen lighter pixels, stuck together in a group of more or less fanciful shapes, sometimes circular, sometimes stretched into a line, should then appear on the homogeneous black background. In one 24-hour period there can be from one to several hundred detections.

The CREDO Detector app only captures images when the camera lens is obscured so it inherently guarantees the privacy of users. What's more, it is the owner of the smartphone who decides when the app monitors the camera. Additional credibility is provided by the authority of the creators of CREDO: IFJ PAN is the largest research institute of the Polish Academy of Sciences, with the highest Polish scientific category (A+). Physicists working here have for decades been hugely involved in the most sophisticated particle physics experiments, including those implemented by the European Organization for Nuclear Research (CERN) on the LHC. Furthermore, currently CREDO is an international collaboration of over one hundred scientists from over a dozen countries. Anyone, from student to professor, can participate in the analysis of the collected data.

For many people, it will be important to know that the effect of CREDO on the battery life of a smartphone can be kept to a minimum. All you need do, in the settings, is to enable the option to start the detector only when the smartphone is connected to a charger, which usually takes place at night. It is also possible to restrict excessive use of the Internet connection. This can be done by the option of forcing data transfer to the experiment server only when the smartphone is connected to the Internet via a wireless network.

The CREDO project software, including the CREDO Detector application, will be made available to everyone on the MIT licence, which means that it can be developed and used in other scientific, school, and even commercial projects.

The CREDO project is co-financed by the governments of the Czech Republic, Hungary, Poland and Slovakia through the Visegrad Grants programme as part of the International Visegrad Fund (IVF).

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UNVEILING THE SECRETS OF ATOMIC NUCLEI

Kraków, 26 October 2017

THE MOST EXOTIC FLUID HAS AN UNEXPECTEDLY LOW VISCOSITY

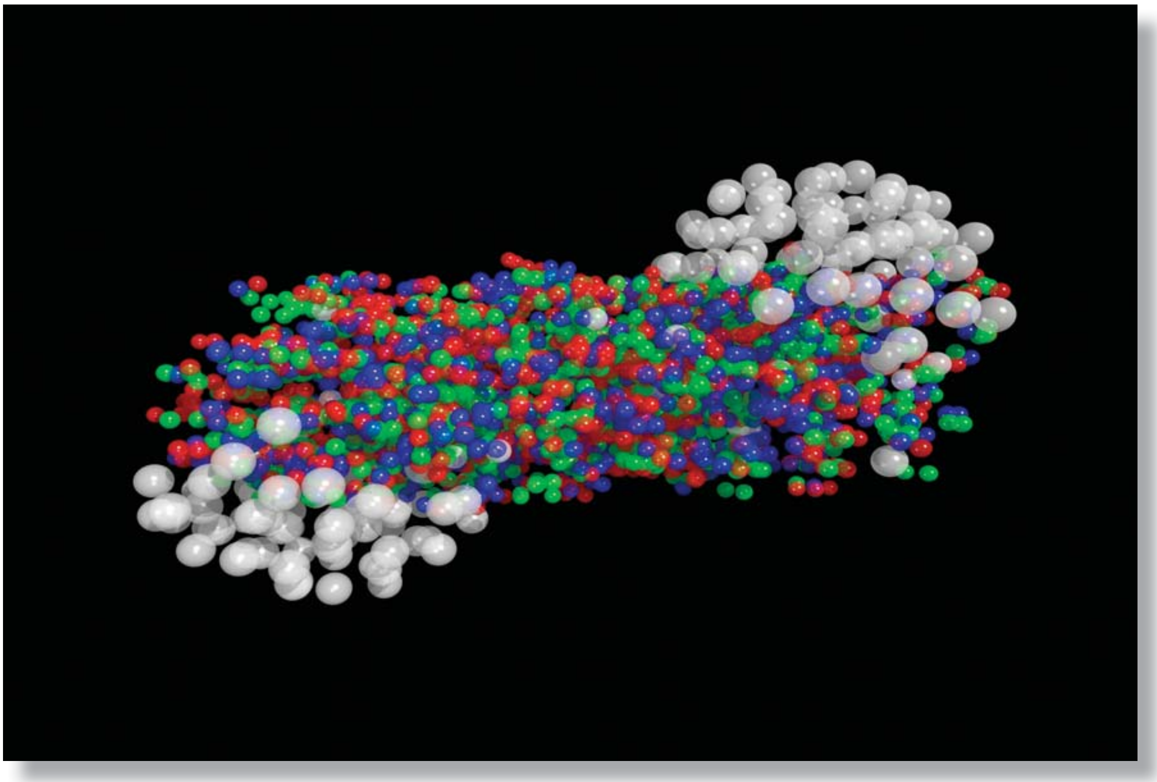
Collisions of lead nuclei in the Large Hadron Collider (LHC) particle accelerator take place at such great energies that quarks that are normally confined inside nucleons are released and, together with the gluons that hold them together, form a stream of particularly exotic fluid: quark-gluon plasma. A new, more detailed theoretical model for this plasma, presented by a group of physicists from Poland and the USA, predicts that it has a much lower viscosity than previously estimated.

Our everyday world consists of structures built mainly of protons and neutrons, particles each containing three quarks held together by strong interactions conveyed by carriers called gluons. In contrast to gravity, which acts more weakly the further away from each other the masses are, strong interactions increase with greater distance. That's why quarks behave as if they were tied together with springs – the more we try to pull them apart, the harder they try to stay close to one another. However, the energies of particles accelerated inside the LHC are so high that, during collisions, quarks are released from protons. For a short while, quark-gluon plasma is then produced, without the slightest doubt the most exotic fluid examined in laboratories on our planet. Up to now, it had seemed that it was quite viscous. A different conclusion is arrived at from the deliberations and analyses of researchers from the Institute of Nuclear Physics Polish Academy of Sciences (IFJ PAN) in Kraków and Kent State University in Kent (Ohio, USA).

"In physics, flows are described using hydrodynamic equations. When apllying the simplest versions of these to quark-gluon plasma evolution, the predictions are quite consistent with LHC collision measurements. At first glance, the quark and gluon soup really does seem to behave according to simple expectations. However, when we start to look closely, it rapidly becomes evident that we are dealing with a very complex phenomenon," says Dr. Radosław Ryblewski (IFJ PAN).

The mathematical description of fluid becomes simplest assuming that the fluid is perfect, i.e. devoid of viscosity. Since there are no perfect fluids in nature, various corrections are introduced to improve the accuracy of hydrodynamic equations. However, the resulting variants of viscous fluid hydrodynamics are based on further assumptions, for example, that pressures in fluid change the same way in all directions.

"The problem is that quark-gluon plasma in the LHC is produced in a very specific way, as a result of collisions of lead nuclei approaching along one direction at velocities close to the speed of light. As a result, the fluid formed by quarks and gluons initially moves along the direction of the beam, and only then does it begin to cool down and dilute in all directions," explains Dr. Ryblewski. "When creating a model, the scale of the challenge increases even more when we try to take into account the fact that at the beginning of the process we have a different fluid than at the end – since after cooling, the quarks gradually begin to stick together again! So, together with Prof. Wojciech Florkowski, we began at our



Quark-gluon plasma in the LHC is produced as a result of collisions of lead nuclei (in white) approaching along one direction at velocities close to the speed of light. The fluid formed by quarks and gluons (in red, green and blue) initially moves along the direction of the beam. Anisotropic hydrodynamics, presented by researchers from the Institute of Nuclear Physics Polish Academy of Sciences in Kraków, Poland, is currently the most accurate description of the phenomena occurring in quark-gluon plasma. (Source: CERN/Henning Weber).

institute to develop a more detailed model of the phenomenon: anisotropic hydrodynamics, built on the assumption that the described system does not behave in the same manner in all directions."

The latest theoretical model, constructed on the basis of anisotropic hydrodynamics, has just been presented in the well-known scientific journal Physical Review Letters. One of its most interesting conclusions concerns the viscosity of quark-gluon plasma (we are talking here about volume viscosity which should not be confused with shear viscosity between the layers of flowing fluid). This viscosity turned out to be six times less than the numerical predictions of other models based on the hydrodynamics of viscous fluid.

The equations presented by the Kraków-based physicists have an important advantage: in contrast to the previous ones, for certain cases they can be solved with practically any level of accuracy. By combining their predictions with data from other models and repeatedly confronting them with actual measurements in the ALICE experiment at the LHC, the Polish-American team has managed to show that anisotropic hydrodynamics is currently the most accurate description of the phenomena occurring in quark-gluon plasma.

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The Henryk Niewodniczański
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Kraków, 21 June 2018

WHEN FLUID FLOWS ALMOST AS FAST AS LIGHT – WITH QUANTUM ROTATION

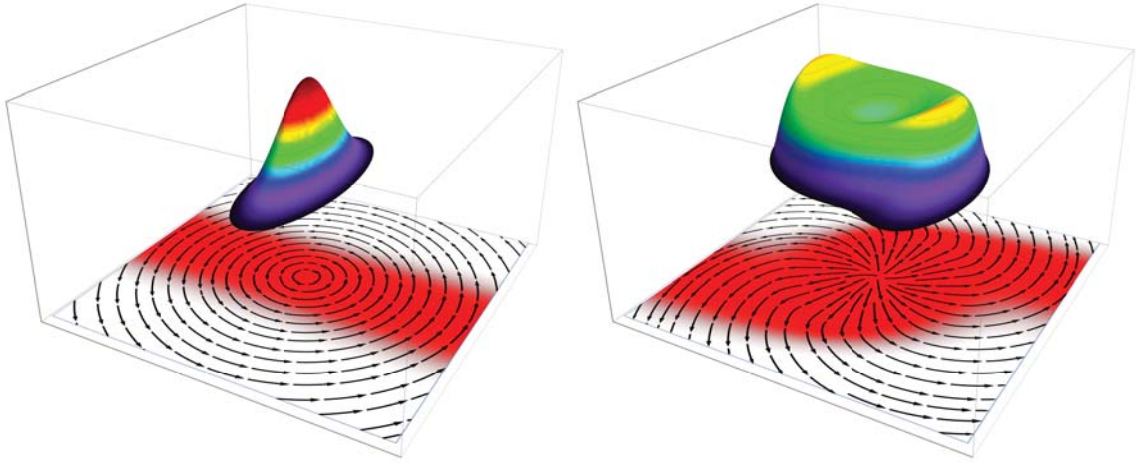
Quark-gluon plasma is formed as a result of high energy collisions of heavy ions. After a collision, for a dozen or so yoctoseconds (that's 10^{-24} seconds!), this most perfect of all known fluids undergoes rapid hydrodynamic expansion with velocities close to the velocity of light. An international team of scientists, associated with the IFJ PAN and the GSI Centre, has presented a new model describing these extreme flows. Interestingly, for the first time effects resulting from the fact that the particles creating the plasma carry spin, that is, quantum rotation, are taken into account.

Each proton and each neutron is composed of several quarks bound by strong interactions carried by intermediary particles called gluons. When heavy ions built of protons and neutrons, accelerated to velocites very close to the velocity of light, collide with each other, they usually undergo destruction, transforming into an exotic fluid: quark-gluon plasma. Due to its negligible viscosity, this plasma is considered to be the most perfect fluid in the Universe. New experimental measurements, however, suggest that the particles leaving the plasma exhibit nontrivial arrangement of their spin directions. In order to explain these results, a group of scientists from the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Kraków and the GSI Helmholtz Centre for Heavy Ion Research in Darmstadt (Germany) has presented a new model of relativistic flows of quark-gluon plasma, taking into account the phenomena arising from the quantum spin of the particles forming it.

For about ten microseconds after the Big Bang, quark-gluon plasma filled the entire Universe. However, it rapidly cooled down and gluons stuck the quarks together into groups – the particles of which our world is built. As a result, quark-gluon fluid can today only be seen as the effect of high-energy collisions of heavy ions (and, possibly, also of smaller colliding systems consisting of protons and ions). Collisions of this type are currently being carried out in just a few accelerator centres in the world.

The flow of fluids and gases is dealt with in hydrodynamics, a field that has been under development for centuries. After the emergence of the theory of relativity, classical hydrodynamics was extended by relativistic phenomena, occurring when fluid flows at velocities close to the velocity of light. After the birth of quantum theory, with time, hydrodynamics can be extended by descriptions of the flow of particles with spin.

Spin is a feature of elementary particles associated with the properties of their wave functions relative to rotation. It can only take on discrete values, e.g. 0, 1/2, 1, 3/2, etc. The direction of spin of particles with spin 1/2 can be equal to +1/2 or −1/2 with respect to any axis. The non-zero polarization of particles with spin 1/2 means that the produced particles are more likely to take on one spin direction (+1/2 or −1/2).



Ultrarelativistic flow of quark-gluon plasma with spin. On the left, the initial state of the system, on the right – the result of hydrodynamic evolution. The arrows on the bottom view show the plasma flow lines. The red area is the region of polarized particles that evolves according to the flow of matter. The top graphs show plasma temperature profiles. (Source: IFJ PAN).

"Hydrodynamics is an excellent tool for describing many physical phenomena. We have broadened its scope of applicability. We are the first to present a coherent description of relativistic particle flows with spin 1/2," explains Prof. Wojciech Florkowski (IFJ PAN, UJK, EMMI), who in collaboration with the group of Prof. Bengt Friman (GSI) has developed a new flow model.

Work on the model of relativistic flows with spin was inspired by recent measurements of the polarization of spins of particles known as Lambda hyperons (these are conglomerates of three quarks: up, down and strange, with a total spin of 1/2), recorded in heavy-ion collisions. Physicists have long been experimenting in trying to better understand the polarization of Lambda hyperons. The measurements, however, were subject to considerable uncertainty. Only recently in experiments carried out at the Brookhaven National Laboratory on Long Island near New York has it been shown that the spins of the Lambda hyperons formed in collisions of heavy nuclei are indeed polarized.

It has been known for a long time that the spin of a quantum object contributes to its total momentum. For example, in ferromagnetic materials, the Einstein-de Haas effect can be observed: when a non-polarized system is placed in a magnetic field, the spin of the particles it is composed of starts to orientate according to the magnetic field which means that to maintain the total angular momentum the system must begin to rotate. Observation of the polarization of the Lambda hyperons formed as a result of quark-gluon plasma transformations thus indicates the difficult to ignore role of spin in shaping the flow of this plasma.

The model presented by the group of physicists from IFJ PAN and GSI is a generalization of the hydrodynamics of perfect fluid. Since there is spin in the described systems, the principle of angular-momentum conservation should have been included in the theoretical description.

"Just as temperature is associated with the principle of conservation of energy, velocity with the principle of conservation of momentum, and electric potential with the principle of conservation of charge current, so in the systems described by us, spin polarization is associated with the principle of conservation of momentum. When you take this principle into account, you get additional equations, better describing the evolution of the system," explains Prof. Florkowski.

Quark-gluon plasma is such an exotic state of matter that for decades or even hundreds of years there will be no question of its technological applications. However, these studies have important implications today. Relativistic flows of particles with spin are in fact a new window to the world of strong interactions, which, among others, bind quarks in protons and neutrons. Thus, strong interactions play a very important role in the Universe, but they are extremely complicated to describe. Therefore, researchers hope that in relativistic flows with spin it will be possible to get to know these effects a little better.

This study was co-funded, among others, by the ExtreMe Matter Institute (EMMI), which operates at the GSI Helmholtz Centre for Heavy Ion Research in Darmstadt (Germany).

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Kraków, 10 May 2017

‘FIRE-STREAKS’ ARE CREATED IN COLLISIONS OF ATOMIC NUCLEI

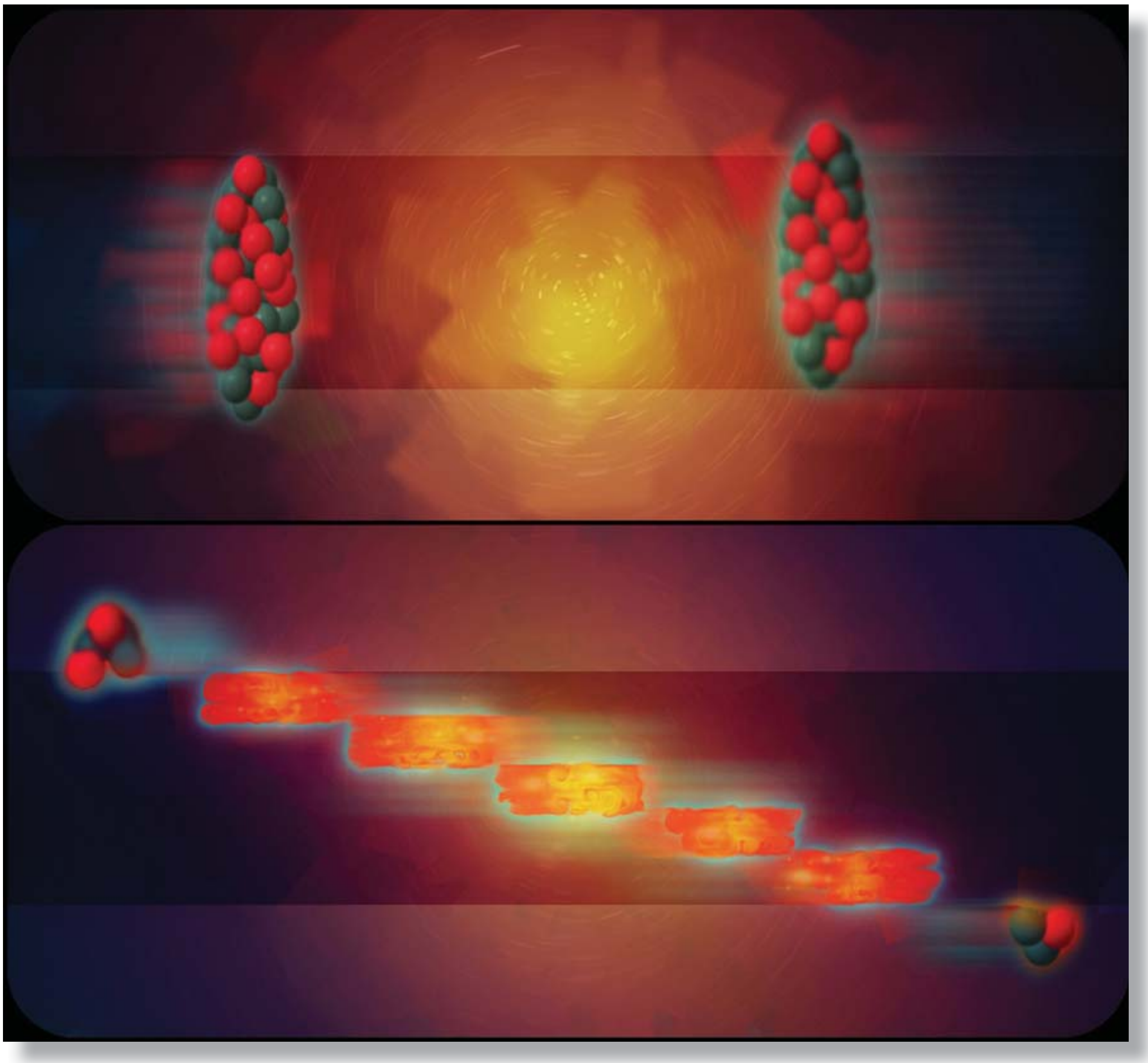
At very high energies, the collision of massive atomic nuclei in an accelerator generates hundreds or even thousands of particles that undergo numerous interactions. At the Institute of Nuclear Physics of the Polish Academy of Sciences in Kraków, Poland it has been shown that the course of this complex process can be represented by a surprisingly simple model: extremely hot matter moves away from the impact point, stretching along the original flight path in streaks, and the further the streak is from the plane of the collision, the greater its velocity.

When two massive atomic nuclei collide at high energies, the most exotic form of matter is formed: the quark-gluon plasma behaving like a perfect fluid. The theoretical considerations of physicists from the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Kraków, Poland show that after impact the plasma forms into streaks along the direction of impact, moving faster the further away it moves from the collision axis. The model, its predictions and the effects of their confrontation with hitherto experimental data are presented in the journal Physical Review C.

Collisions of atomic nuclei occur extremely rapidly and at distances of merely hundreds of femtometres (i.e. hundreds of millionths of one billionth of a metre). The physical conditions are exceptionally sophisticated and direct observation of the phenomenon is not currently possible. In such situations, science copes by constructing theoretical models and confronting their predictions with the data collected in experiments. In the case of these collisions, however, a huge disadvantage is that the resulting conglomerate of particles is the quark-gluon plasma. Interactions between quarks and gluons are dominated by forces that are so strong and complex that modern physics is not capable of describing them precisely.

“Our group decided to focus on the electromagnetic phenomena occurring during the collision because they are much easier to express in the language of mathematics. As a result, our model proved to be simple enough for us to employ the principles of energy and momentum conservation without too much trouble. Later on, we found that despite the adopted simplifications the model predictions remain at least 90% consistent with experimental data,” says Dr. Andrzej Rybicki (IFJ PAN).

Massive atomic nuclei accelerated to high velocities, observed in the laboratory, are flattened in the direction of motion as a result of the effects of the theory of relativity. When two such proton-neutron ‘pancakes’ fly towards each other, the collision is generally not central: only some of the protons and neutrons of one nucleus reach the other, entering into violent interactions and forming the quark-gluon plasma. At the same time, some of the external fragments of the nuclear pancakes do not encounter any obstacles on their way and continue their uninterrupted flight; in the jargon of physicists they are called spectators.



Fragments of extremely hot matter, produced in the collision of heavy atomic nuclei at the SPS accelerator at the European CERN centre, move away from each other at high velocities, forming streaks along the direction of the collision. (Source: IFJ PAN, Iwona Sputowska).

"Our work was inspired by data collected in earlier experiments with nuclear collisions, including these made at the SPS accelerator. The electromagnetic effects occurring in these collisions that we examined showed that the quark-gluon plasma moves at a higher velocity the closer it is to the spectators," says Dr. Rybicki.

In order to reproduce this course of the phenomenon, the physicists from IFJ PAN decided to divide the nuclei along the direction of movement into a series of strips – "bricks'. Each nucleus in cross section thus looked like a pile of stacked bricks (in the model their height was one femtometre). Instead of considering the complex strong interactions and flows of momentum and energy between hundreds and thousands of particles, the model reduced the problem to several dozen parallel collisions, each occurring between two proton-neutron bricks.

The IFJ PAN scientists confronted the predictions of the model with data collected from collisions of massive nuclei measured by the NA49 experiment at the Super Proton Synchrotron (SPS). This accelerator is located at the CERN European Nuclear Research Organization near Geneva, where one of its most important tasks now is to accelerate particles shot into the LHC accelerator.

"Due to the scale of technical difficulties, the NA49 experiment's results are subject to specific measurement uncertainties that are difficult to completely reduce or eliminate. In reality, the accuracy of our model can even be greater than the already mentioned 90%. This entitles us to say that even if there were any additional, still not included, physical mechanisms in the collisions they should no longer significantly affect the theoretical framework of the model," comments doctoral student Miroslaw Kielbowicz (IFJ PAN).

After developing the model of collisions of 'brick stacks', the IFJ PAN researchers discovered that a very similar theoretical structure, called the fire streak model, had been proposed by a group of physicists from the Lawrence Berkeley Laboratory (USA) and the Saclay Nuclear Research Centre in France – already in 1978.

"The previous model of fire streaks which, in fact, we mention in our publication, was built to describe other collisions occurring at lower energies. We have created our structure independently and for a different energy range," says Prof. Antoni Szczurek (IFJ PAN, University of Rzeszow) and emphasizes: "The existence of two independent models based on a similar physical idea and corresponding to measurements in different energy ranges of collisions increases the probability that the physical basis on which these models are built is correct."

The Kraków fire streak model provides new information on the expansion of quark-gluon plasma in high energy collisions of massive atomic nuclei. The study of these phenomena is being further extended in the framework of another international experiment, NA61/SHINE at the SPS accelerator.

The research of the IFJ PAN group is being financed by the SONATA BIS grant from the National Science Centre.

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Kraków, 14 June 2018

THE CHANCES OF DETECTING CLUMPS IN ATOMIC NUCLEI ARE GROWING

What do atomic nuclei really look like? Are the protons and neutrons they contain distributed chaotically? Or do they perhaps bind into alpha clusters, that is, clumps made up of two protons and two neutrons? In the case of several light nuclei, experimental confirmation of the individualism or family nature of nucleons will now be simpler thanks to predictions presented by Polish physicists from Kraków and Kielce.

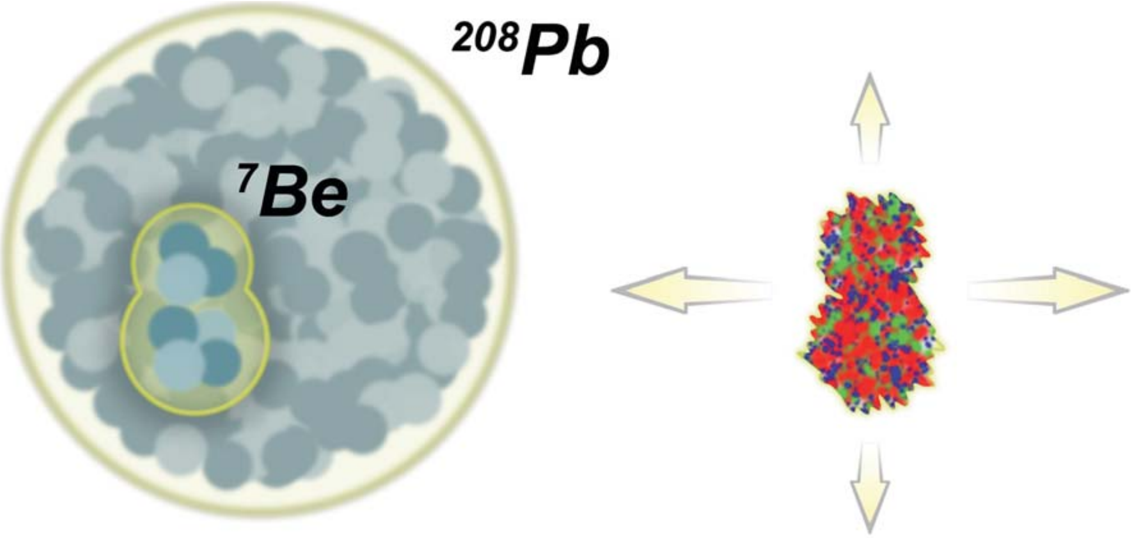
Any high school student worth his salt knows exactly what an atomic nucleus looks like: it is a conglomerate of randomly distributed protons and neutrons (i.e. nucleons). Physicists themselves, however, do not have such clear-cut ideas. Already in 1931, only 20 years after the discovery of the atomic nucleus, the first suggestions were put forward that protons and neutrons in atomic nuclei merge into helium nuclei, that is, into groups of two protons and two neutrons, often called alpha clusters. Atomic nuclei are, however, structures that are so extremely small and difficult to study that although almost a century has passed since the first predictions, it still has not been possible to explicitly confirm the occurrence of alpha clusters in them.

The lowering of energy in physical systems favours the merging of structures into groups. This powerful, universal mechanism occurs in nature on all size scales: quarks combine into mesons or baryons, atoms into molecules, stars into galaxies, and galaxies into groups of galaxies. In the case of atomic nuclei, computer simulations suggest that e.g. the nucleus of beryllium ^{9}Be contains two alpha clusters and one neutron (the whole complex would look like a dumbbell). In the ^{12}C carbon nucleus there should be three alpha clusters (the shape of the nucleus would thus be triangular), four in oxygen ^{16}O (here the nucleus would resemble a pyramid), ten in calcium ^{40}Ca and fourteen in nickel ^{56}Ni.

In 2014, scientists from the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Kraków, in collaboration with physicists from the Universidad de Grenada, presented a method of detecting traces of the original structure of atomic nuclei in the distribution of velocities of particles diverging from the points of ultrarelativistic collisions of light atomic nuclei with a shield made of heavy nuclei, such as lead ^{208}Pb lead or gold ^{197}Au. Those predictions focused on methods of detection of alpha clusters in ^{12}C carbon nuclei.

“In our latest publication, written together with physicists from the Institute of Physics at the Jan Kochanowski University in Kielce, we present more detailed predictions concerning the possibility of observing traces of alpha clusters in atomic nuclei. We show how these clusters could be detected in subsequent nuclei, not only carbon ^{12}C, but also beryllium ^{7}Be and ^{9}Be and oxygen ^{16}O,” says Prof. Wojciech Broniowski (IFJ PAN, UJK).

The method of detecting alpha clusters in atomic nuclei, described in the publication distinguished by the editors of Physical Review C, is based on an interesting relationship. Heavy atomic nuclei, even if they were to consist of alpha clusters, are so large that with good approximation they can be treated as quite homogeneous spheres. When a light atomic nucleus strikes such a nucleus at an ultrarelativistic velocity (thus very close to the speed of light), the collision energy is so great that for fractions of



The ultrarelativistic collision of a clustered beryllium nucleus 7Be with a heavy lead nucleus ^{208}*Pb creates a fireball of quark-gluon plasma. The initial shape of the fireball and its expansion rates in various directions carry information about the original structure of the beryllium nucleus. (Source: IFJ PAN).*

a second, protons and neutrons disintegrate into quarks and the gluons that stick them together. Then probably the most exotic fluid is formed: quark-gluon plasma.

"In our work, we note that if the light atomic nucleus is not homogeneous, the cloud of quark-gluon plasma created as a result of the collision is deformed. Its shape will at least to some extent correspond to the shape of the light nucleus. Plasma will therefore spill over in all directions, but in different directions at slightly different speeds," explains Dr. Maciej Rybczynski.

The quark-gluon plasma cools down so fast that its direct observation is not currently possible. After just a few femtoseconds (millionths of one billionth of a second), the quarks and gluons merge again into particles in a process called hadronization.

"In the directions in which the quark-gluon plasma flows slightly faster, we can expect slightly higher particle velocities caused by hadronization. So if we record momenta of particles diverging from the point of collision with sufficient precision, we are potentially able to extract information about the shape of the nucleus that has struck the shield from minor differences. In addition, this information will concern nuclei in the ground state," explains Milena Piotrowska, PhD student at UJK.

The research of physicists from the IFJ PAN and UJK, co-financed by Polish National Science Centre grants, provides specific theoretical predictions. The next step now belongs to the experimental physicists working on high-energy accelerators, such as Super Proton Synchrotron (SPS) or Large Hadron Collider (LHC) in the European CERN organization or Relativistic Heavy-Ion Collider (RHIC) in the American Brookhaven National Laboratory. Since experiments confirming the lumpy structure of atomic nuclei do not require the expansion of currently operating apparatus, it will be possible to carry out these experiments within the next few years.

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The Henryk Niewodniczański
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Krakow, 19 October 2016

FINDING THE LIGHTEST SUPERDEFORMED TRIAXIAL ATOMIC NUCLEUS

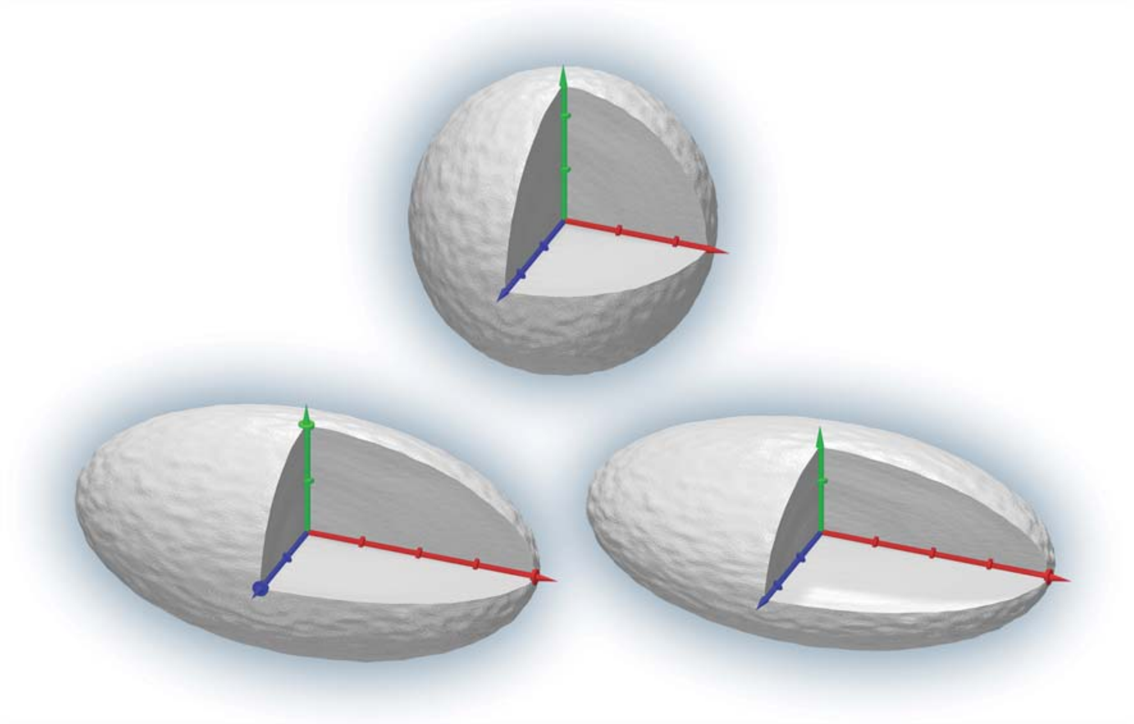
The nuclei of atoms of heavy elements do not necessarily take a spherical shape: they may be variously extended or flattened along one, two or even three axes. An international team of physicists, led by scientists from the Institute of Nuclear Physics of the Polish Academy of Sciences in Krakow (IFJ PAN) and the Heavy Ion Laboratory at the University of Warsaw (HIL), has recently presented the results of experiments showing that complex superdeformed nuclei occur in much lighter elements as well.

The majority of heavy atomic nuclei do not look at all like a perfect sphere, but are subtly flattened or extended. The prestigious journal Physical Review Letters has published results of experiments evidencing that highly explicit and complicated deformations, thus far observed solely in heavy nuclei, do appear in lighter elements such as calcium. The research was conducted by scientists of the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Krakow and the Heavy Ion Laboratory, University of Warsaw (HIL) along with broad international cooperation.

“Regarding that, we’ve known for several years that the nuclei can be slightly deformed even in light elements. Our experiments, however, have shown that in the case of calcium 42Ca they come to a particularly clear and complex deformation, called a triaxial superdeformation. Similar effects have been observed, but only in heavy elements, built from approximately 130-170 protons and neutrons,” explains Prof. Adam Maj (IFJ PAN), who along with Prof. Faical Azaiez from the French Institut de Physique Nucléaire d’Orsay was one of the originators of the search.

Atomic nuclei contain from one proton to more than 200 protons and neutrons. Glued together by strong forces, which overcome powerful electrostatic repulsion between positively charged protons, the nuclei are structures shaped by very complex quantum phenomena. The dynamics of the processes occurring here is so fast that observing the atomic nucleus over a sufficiently long period of time (in the microworld, still only fractions of a second), we see the nucleus only as a statistically averaged shape. In some cases, it is simply that of a sphere. Since the 1950s, however, researchers have observed nuclei which are elongated, sometimes significantly, such as an ellipsoid with one axis twice the length of the 2 others – such a case is known as nuclear superdeformation (relatively common nuclei are also found stretched at an axis ratio of 3:2). At this distortion it is possible to become more refined, as large deviations from the spherical shape occur not only along one, but even along three axes. The distorted nuclei, known as super-deformed triaxial, have so far been observed only in heavy elements.

Atomic nuclei have a size of several femtometers, or one quadrillionth of a meter. Direct observation of such small objects is, of course, impossible. Information about their structure relies more on indirect methods, by analyzing the gamma radiation emitted by the nucleus passing from states of higher



Atomic nuclei do not in any case look like a perfect sphere (top). With a larger number of protons and neutrons the nuclei can be flattened or extended along one, two or three axes. The latter case (bottom right) is known as superdeformed triaxial. (Source: IFJ PAN).

energies to states of lower energies. Depending on the structure of the nuclei and the method of their excitation, the nature of the resulting excited state may differ: the nucleus can vibrate in various ways as a whole, but can also, for instance, be activated to spin. The Polish physicists are especially interested the latter, spinning, states.

Currently, Coulomb excitation is the most reliable method to observe deformed nuclei, a process in which nuclei are excited as a result of collisions occurring exclusively through electromagnetic interactions. As a result, the theoretical description of the phenomenon can avoid accounting for the extremely complex strong interactions, and in practice the use of well-known tools of classical electrodynamics is sufficient.

Experiments on superdeformed light nuclei were based on very careful observation and detailed analysis of the gamma radiation emitted by the nucleus of calcium ^{42}Ca, caused to spin as a result of a collision with a target constructed of lead ^{208}Pb or gold ^{197}Au (each ^{42}Ca nucleus was striking the target nucleus with the kinetic energy of 170 MeV, or million electron volts). The measurements were carried out at the Italian INFN Laboratori Nazionali di Legnaro (LNL), and they were used in the AGATA gamma radiation detector. This detector, the most advanced of the gamma-ray Germanium detectors currently in use, is the product of international cooperation and is characterized by an extremely high power of resolution. The experiment concerning superdeformation of the nuclei of calcium was the first one using this sophisticated device.

"While processing the data provided by AGATA, we used many methods and tools, such as the well-known GOSIA program for analysis of Columb excitation, which has been under development for several years at the Heavy Ion Laboratory in Warsaw. It turns out that the excited ^{42}Ca nuclei are superdeformed and at the same time triaxial, which is confirmed by calculations using advanced theories of the structure of the atomic nucleus," says Dr. Katarzyna Hadyńska-Klęk (HIL), who led the analysis of the data.

Exciting ^{42}Ca nuclei to the superdeformed triaxial state requires relatively low levels of energy (approx. 2 MeV), and because the superdeformed energy state is very near the basic spherical state, we can talk about a certain state of coexistence between the two states.

"A full analysis of the data collected in Legnaro took us three years. Along the way we had to conduct another, complementary experiment at the Warsaw cyclotron. Its results exclude one of the alternative variants of interpretation of the AGATA detector," says Dr. Paweł Napiórkowski, the project leader at HIL.

The discovery of triaxial superdeformation in ^{42}Ca will help physicists to better understand the phenomena in atomic nuclei. Modern theoretical tools do not allow for accurate modeling of nuclei with an atomic number far exceeding 40, which has limited the development of research into superdeformation. Meanwhile, in the case of calcium many theoretical obstacles disappear. It is also likely that the measurements and analysis will be used in the future to search for other superdeformed states at low excitation energy, including a longer life-span than the typical quadrillionths of a second. Finding such states would allow scientists to turn our attention to the formation of what is known as inversion, a scenario in which the majority of nuclei are attained not in the ground state, but in the excited state. This would be a significant step towards building a nuclear laser capable of emitting coherent nuclear gamma radiation.

Cooperation between the centres of Krakow and Warsaw is done within the consortium of the National Cyclotron Laboratory. Scientists from many countries have played an important role in the research, in particular Dr. Jose Javier Valiente Dobon (INFN LNL, Italy) and Dr. Magda Zielinska (HIL, Poland; CEA, France). In Poland, research was funded by grants from the National Center for Science and the European Union.

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Kraków, 7 September 2017

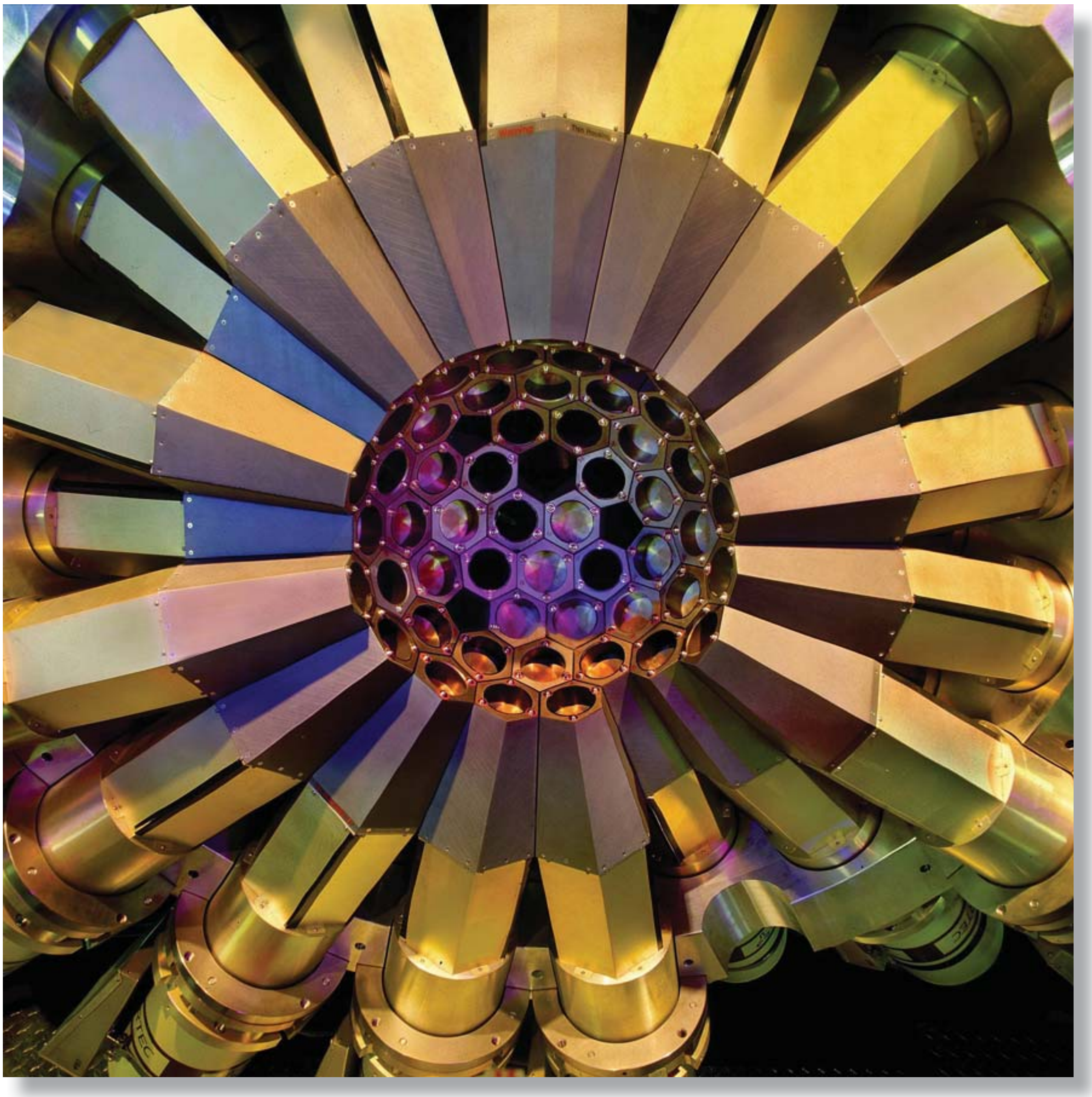
THE DOUBLY MAGIC NUCLEUS OF LEAD-208 – IT SPINS, THOUGH IT SHOULDN'T!

We generally imagine atomic nuclei to be more or less spherical, but always relatively chaotic, clusters of protons and neutrons. Experiments at the Argonne National Laboratory, inspired by physicists from the Institute of Nuclear Physics of the Polish Academy of Sciences in Kraków, are trying to verify these simple ideas. Using an astronomical analogy we can say that in as much as the majority of nuclei are similar in outline to rocky objects such as moons or asteroids of different shapes, then nuclei of lead-208 under certain conditions resemble planets surrounded by a dense atmosphere that can move around a rigid core.

For a dozen or so years physicists from the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Kraków, in collaboration with researchers from Argonne National Laboratory (ANL) in Illinois, USA, have been investigating the properties of the nuclei of lead-208 atoms. A recently published analysis summarizing the experiments conducted at ANL using the ATLAS superconducting accelerator and Gammasphere, the most sophisticated gamma ray detector in the world, has led to interesting conclusions. It turns out that under certain conditions new, relatively stable energy states unpredictable from theory are produced in lead-208 nuclei. What's more, there are indications suggesting the existence in such nuclei of previously unrecognized structure of a collective nature.

"Atomic nuclei can be excited to a variety of energy states, including those in which they spin rapidly. However, not all nuclei in such states must actually spin," says Prof. Rafal Broda (IFJ PAN), the first author of a publication distinguished by the journal Physical Review C, and explains: "The nucleus of lead-208 consists of 82 protons and 126 neutrons and, with a very good approximation, can be considered spherical. When we use quantum mechanics equations to describe nuclei of this shape, talking about spinning of the nucleus becomes senseless since the positions in different phases of spin are indistinguishable, so there are no changes in energy. Therefore, it is assumed that spherical nuclei do not spin, and the spin-related physical size – the spin of the nucleus – is derived entirely from several coupled nucleons moving around their orbits. Meanwhile, our research shows that in the nuclei of lead-208 a wide range of spin values is observed, up to high-spin states, a sequence of states that can be interpreted as related to collective spin. The sixty-four-thousand-dollar question then is: what is it that is spinning in such a nucleus?"

In modern physics, the structure of whole atoms is described using a shell model. This assumes that electrons, carrying a negative electrical charge, move at considerable distances around a positively charged, practically punctate nucleus. However, the probability of finding an electron is only high in certain areas, where the electron energy assumes strictly defined values. The nucleus in the atom is therefore surrounded by a spatial structure formed by a lesser or greater number of energetic shells.



One hemisphere of the Gammasphere, the most advanced instrument for detecting gamma rays. (Source: Roy Kaltschmidt, Lawrence Berkeley Lab photographer).

Each shell has a certain maximum capacity, and if the number of electrons exceeds this capacity, the excess electrons must transition to the next shell, further away from the nucleus.

When the outermost electron shell becomes filled with electrons, the atom is reluctant to react with other atoms or molecules. In chemistry, such elements are called noble gases due to their particular stability and lack of chemical activity.

Atomic nuclei are much more complex objects than atoms treated as a punctate positive charge surrounded by a group of distant electrons. Nucleons, or the protons and neutrons that make up the nucleus, have masses that are thousands of times greater than the electron, and additionally, all the particles are close together and enter into numerous nuclear and electromagnetic interactions. Therefore, at the time, it was a great surprise for physicists to discover that the shell model also works for atomic nuclei. However, the situation here is more interesting, because the neutrons and protons form their own shells in the nuclei, which are particularly stable for numbers of nucleons that are known as magic numbers. Physicists call nuclei with completely filled proton and neutron shells doubly magic. Lead-208 is unique in this group because it is the most massive doubly magic nucleus.

The properties of lead-208 nuclei in low-spin states are quite well known, but as far as high-spin states are concerned, until recently this was not the case. Atomic nuclei in such states are produced by the process of fusion taking place in collisions that occur when a target made of a suitably selected material is bombarded with matched particles. Unfortunately, there is no particle-target combination capable of producing lead-208 nuclei in high-spin states. This is why for three decades the Kraków group headed by Prof. Broda has been working on the use of deep inelastic collisions to study nuclei that are inaccessible in fusion processes. In collisions of this kind, the bombarding nuclei interact with the target nuclei, but do not merge with them.

“In a high-spin state – the effect of a deep inelastic collision – the nucleus is excited and is trying to return to the lowest energy state. It gets rid of its excess in several to a few dozen stages, each one emitting gamma radiation with an energy characteristic for its transition. By analyzing the energies of this radiation, we are able to obtain a lot of information about the structure of atomic nuclei and the processes taking place within them”, explains Dr. Lukasz Iskra (IFJ PAN).

The latest analysis uses measurements taken at ANL together with Prof. Robert Janssens' group. In these experiments, lead-208 or uranium-238 targets were bombarded with ions of lead-208, selenium-82, germanium-76, nickel-64 or calcium-48. The gamma radiation was recorded by a Gammasphere detector, consisting of 108 high quality germanium detectors (this spectacular instrument can be seen, among others, in the film The Hulk).

To the surprise of the researchers, the latest analysis has permitted the detection in lead-208 nuclei of structures and phenomena that were not anticipated by current theory. Many new energy states were observed, and three were found to be isomeric states, and thus much more stable than others. In normal states the nucleus occurs for picoseconds, whereas in one of the isomeric states the nucleus was detected for up to 60 nanoseconds (billionths of a second), that is, a thousand times longer.

Of most interest were the results suggesting collective spin – in a nucleus that is spherical, and therefore from the point of view of quantum mechanics should not spin! Researchers assume that at high spins a rigid core is formed in the nucleus of lead-208, the next up from the point of view of mass is the doubly magic nucleus, i.e. tin-132. It seems that this core does not spin, but the outer layer formed by the other 76 nucleons rotates.

“Beginning with certain high-spin states, the lead-208 nucleus ceases to be a homogeneously rigid object, such as, for example, the geologically almost dead Moon. A better astronomical analogy would be a rocky body with a very dense atmosphere, but not as calm as Venus or Titan. This atmosphere should move swiftly over the surface, so it could be like a global hurricane,” says Prof. Broda.

In modern physics the shell model is the basic tool for describing atomic nuclei. The new effects, which it has so far been impossible to predict within this model, discovered by the Polish-American experiments with lead-208 nuclei, will enable theoreticians to incorporate further phenomena into the model and increase the precision of its predictions.

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The Henryk Niewodniczański
Institute of Nuclear Physics
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Kraków, 19 July 2017

THE FIRST LIGHT ATOMIC NUCLEUS WITH A SECOND FACE

To some degree of approximation, atomic nuclei look like spheres which in most cases are distorted to a greater or lesser extent. When the nucleus is excited, its shape may change, but only for an extremely brief moment, after which it returns to its original state. A relatively permanent 'second face' of atomic nuclei has so far only been observed in the most massive elements. In a spectacular experiment, physicists from Poland, Italy, Japan, Belgium and Romania have for the first time succeeded in registering it in a nucleus recognized as being light.

Atomic nuclei are able to change their shape depending on the amount of energy they possess or the speed at which they spin. Changes related only to the addition of energy (and thus not taking into account spin) are relatively stable only in nuclei of the most massive elements. Now, it turns out that the nuclei of much lighter elements, such as nickel, can also persist a little longer in their new shape. The discovery was made by a team of scientists from the Italian Universita' degli Studi di Milano (UniMi), the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Kraków, the Romanian National Institute of Physics and Nuclear Engineering (IFIN-HH), the Japanese University of Tokyo and the Belgian University of Brussels. The calculations necessary for the preparation of the experiment proved to be so complex that a computer infrastructure of about one million processors was required to perform them. The effort did not go to waste: the publication describing the achievement was distinguished by the editors of the prestigious physical journal Physical Review Letters.

Constructed of protons and neutrons, atomic nuclei are generally considered to be spherical structures. However, in reality, most atomic nuclei are structures that are deformed to a greater or lesser extent: flattened or elongated along one, two, or sometimes even all three axes. What's more, just as a ball flattens more or less depending on the force exerted on it by a hand, so atomic nuclei can change their deformation depending on the amount of energy they possess, even when they are not spinning.

"When an atomic nucleus is supplied with the right amount of energy, it can transition into a state with a different shape deformation than is typical for the basic state. This new deformation – illustratively speaking: its new face – is, however, very unstable. Just like a ball returns to its original shape after the hand that has distorted it is removed, so the nucleus returns to its original form, but it does so much, much faster, in billionths of a billionth of a second or an even shorter time. So, instead of talking about the second face of the atomic nucleus, it's probably better to talk about just a grimace," explains Prof. Bogdan Fornal (IFJ PAN), whose research team included Dr. Natalia Cieplicka-Oryńczak, Dr. Łukasz Iskra and Dr. Mateusz Krzysiek.

In the last few decades, evidence has been gathered confirming that a relatively stable state with a deformed shape is present in the nuclei of a small number of elements. Measurements have shown that the nuclei of some actinides – elements with atomic numbers from 89 (actinium) to 103 (lawrencium)

In an experiment performed at the Romanian accelerator centre IFIN-HH, an international team of physicists observed a 'second face' of the nickel-66 nuclei: a relatively stable excited state in which the shape of nucleus is changed. (Source: IFIN-HH).

– are capable of maintaining their 'second face' even tens of millions of times longer than other nuclei. Actinides are elements with a total number of protons and neutrons well above 200, so very massive. Up to now, among the non-spinning nuclei of lighter elements an excited state with a deformed shape, characterized by increased stability, has never been observed.

"Together with Professor Michel Sferrazza, now working at the University of Brussels, already at the beginning of the 1990s, we pointed out that two theoretical models of nuclear excitation predict the existence of relatively stable states with deformed shapes in the nuclei of light elements. Shortly, a third model appeared which also led to similar conclusions. Our attention was drawn to nickel-66, because it was present in the predictions of all three models," recalls Prof. Fornal.

The possibility of experimentally searching for relatively stable states with deformed shapes in the Ni-66 nucleus has, however, only emerged recently. The new experimental method, proposed by Prof. Silvia Leoni (UniMi), combined with the computationally extremely sophisticated Monte Carlo shell model developed by the Tokyo University theorists, enabled the design of appropriate, accurate measurements. The experiment was carried out at the 9 MV FN Pelletron Tandem accelerator operating in the Romanian National Institute of Physics and Nuclear Engineering (IFIN-HH).

In the experiment in Bucharest, a target of nickel-64 was fired with nuclei of oxygen-18. Relative to oxygen-16, which is the main (99.76%) isotope of atmospheric oxygen, these nuclei contain two additional neutrons. During the collisions, both the excess neutrons can be transferred to the nickel nuclei, resulting in the creation of nickel-66, the basic shape of which is almost an ideal sphere. With properly selected collision energies, a small portion of the Ni-66 nuclei thus formed achieve a certain state with a deformed shape which, as measurements showed, proved to be slightly more stable than all other excited states associated with significant deformation. In other words, the nucleus was in a local, deep minimum of potential.

"The extension of life span measured by us of the deformed shape of the Ni-66 nucleus is not as spectacular as that of the actinides, where it reached tens of millions of times. We recorded only five-fold growth. Nevertheless, the measurement was exceptional, because it was the first observation of its kind in light nuclei," concludes Prof. Fornal and stresses that the measured delay times of return to the basic state correspond to an acceptable extent with the values provided by the new theoretical model, which further enhances the attainment of the achievement. None of the earlier models of nuclear structure allowed for such detailed predictions. This suggests that the new theoretical approach should be helpful in describing several thousand nuclei that have not yet been discovered.

On the Polish side the research was financed by the National Science Centre.

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The Henryk Niewodniczański
Institute of Nuclear Physics
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Kraków, 14 grudnia 2016

NUCLEAR SURFING: PROTONS HAVE BEEN OBSERVED 'CATCHING A WAVE' ON THE SURFACE OF AN ATOMIC NUCLEUS

For surfers, it's not enough just to wait for the right wave: they still have to know how to catch it. As it turns out, one challenge faced by surfers also applies to protons. An experiment recently conducted by physicists from Poland, Italy and France provided new information on surfing taken to its absolute extreme: protons synchronizing their movement with the vibrations of atomic nuclei.

We can say a lot of things about atomic nuclei that are more or less certain, but we know this much for sure: nothing about their nature is boring, despite how we were taught about it in high school. As proof of this we can look at a recent experiment which studied how protons in atomic nuclei can, in their own way, take part in a popular sport. A team of researchers from the Italian Universita' degli Studi di Milano (UniMi), and the Institute of Nuclear Physics, Polish Academy of Sciences (IFJ PAN) in Kraków along with broad international cooperation, measured, for the first time, the time needed for a single proton in a nucleus to synchronize with the oscillations of the nucleus. The achievement can be illustrated with an analogy: some protons can 'surf' on top of a nucleus, and we finally know how long they have to wait to catch the wave.

Atomic nuclei contain from one proton to more than 200 protons and neutrons, and, like atoms, they can absorb and emit certain amounts of energy. In atoms, these processes are accompanied by the transitions of electrons between orbitals, lying further or closer to the nucleus and grouping in the electron shells. Like the electrons around the nucleus, protons and neutrons of the same nuclei are in constant motion. Although they do not revolve around the highlighted point, it turns out that we can talk about the existence in the nuclei of certain shells with well-defined energies. On the whole, the space in these shells may be occupied by both protons and neutrons. Some shells, however, are reserved for protons, and others only for neutrons.

To jump to an adjacent layer may sometimes require absorbing or emitting a large amount of energy (this occurs particularly when the shells are full). If the available energy is less, the nucleus can still change its energy state, but in a more sophisticated way: it starts to vibrate. It is known that in such situation the proton or neutron may couple with the oscillation of the nucleus. At first glance, the phenomenon seems very abstract. Meanwhile, a similar mechanism plays a major role in a popular, iconic sport. That is, as we already mentioned, surfing.

"Surfers can wait a long time for the right wave. But when it does come along, it doesn't always mean a good time is guaranteed! If the surfer just gawks at it, it will pass, and he just pops up on the surface

Like a surfer on a wave, a proton can be coupled with the vibrations of an atomic nucleus. Pictured in the role of proton is a bubble of air graphically pulled out from under the surface. (Source: IFJ PAN, jch).

like a cork. The real fun only comes if he can time his jump onto the wave. Good surfing depends on a precise harmonization between surfer and wave. In a similar way, under appropriate conditions protons 'jump' on the surface oscillations of the atomic nucleus and travel with them. And I think they're more natural surfers than people are: after all, they do it under extreme conditions and they don't need a board...", explains Prof. Bogdan Fornal (IFJ PAN).

Coupling of the proton with the vibration of the nucleus is difficult to study because there must be a system where a single proton is outside a shell which is completely filled with numerous protons and neutrons. To observe the 'proton surfers', the Italian-Polish team conducted an experiment in the laboratory of the Institut Laue-Langevin in Grenoble, in which millimeter-sized lumps of uranium ^{235}U and plutonium ^{241}Pu were irradiated with neutrons. In order to increase the chance of capture by atomic nuclei, the neutrons were slowed considerably. When a neutron joined the nucleus of the target, the system became unstable and fell apart in different ways. Among the decay products were excited nuclei of antimony ^{133}Sb.

"The nucleus of antimony ^{133}Sb is basically the nucleus of tin ^{132}Sn with an extra proton. Tin ^{132}Sn is special: it contains 50 protons and 82 neutrons, exactly enough to completely fill the neutron and proton shells. In this nucleus – what we call a doubly magic nucleus – a jump from shell to shell requires emission or absorption of large amounts of energy. Antimony ^{133}Sb was so interesting for us, because it gives us a loosely bound proton and a compact core which is prone to fall into vibrations, and that's an ideal system for testing coupling," explains Prof. Fornal.

The nuclei of antimony ^{133}Sb rid themselves of excess energy by emitting gamma quanta of several specific energies. In the experiment the radiation was recorded, and the results were compared to theoretical predictions. In this way, it was established through which energy states the nucleus of ^{133}Sb returned to the ground state. The scientists found that the decay path consists of two parts: one with an uncoupled proton and the other with a proton coupled with the oscillations of the nucleus. The collected data show that when it comes to coupling, the nucleus loses energy quickly, and the same coupling is retained for all subsequent steps down the ladder of energy.

"We first measured the time required for the proton to couple with the core oscillations. As a result, we know that when the proton jumps on the wave, it behaves like a champion surfer: it stays on till the wave crashes, that is, until the nucleus reaches the ground state. What gives the proton the most difficulty are the transitions between uncoupled and coupled states, that is, getting on the wave," says Prof. Fornal.

Interestingly, several protons can join together and couple to the oscillation of the shells. They then form a kind of group, one that acts in a very intricate manner, engaging not only with the waves but also among themselves.

The results of the experiment (on the Polish side funded by grants from the National Science Centre) are important in the context of further research into neutron-rich nuclei. Science now knows of 258 stable nuclei and approximately 3,000 unstable ones – roughly as many as all the known exoplanets. It is predicted that the atomic nuclei number in total 7 to 9 thousand. So at least twice as many nuclei as we have come to know throughout the entire history of nuclear physics are still waiting to be discovered and explored. A single, consistent model of the atomic nucleus would be extremely helpful in that search, but interactions in atomic nuclei are so complicated that even after decades of ongoing concerted efforts, such a model has yet to be created.

It's very easy for a schoolteacher to describe, for example, electrostatic interaction between two bodies with electrical charges, because there are only two charges, and the force between them depends only on their mutual distance. Protons and neutrons in the nucleus are bound by strong interaction, but strong interaction depends not only on the distance between each pair of interacting nuclear particles, but also on the constantly changing mutual orientation of their spins (angular momentum). In addition, nuclei are heavy elements incorporating not only two particles but a significant number of protons and neutrons, all interacting with each other and each moving in a field produced by the others. The entire system is so complicated that so far only approximate models have been built, each of which describes only some aspects of nuclear reality reasonably well. In this situation, any qualitatively new experimental measurements are extremely important.

"Our joint experiment at the ILL has provided my group with data which have made it possible to construct a new model to better describe the coupling of the protons with the oscillating nucleus.

For the first time, we can, for example, calculate in this case the probabilities in which excited nuclei de-excite individual energy states. As a result, we can better predict the properties of nuclei with a greater excess of neutrons, including those which are just waiting to be discovered," concludes Prof. Silvia Leoni (UniMi).

The model, built and designed based on the experience of physicists from UniMi and IFJ PAN, is a significant step towards (among other matters) a better understanding of the mechanisms responsible for the formation of elements heavier than iron in the Universe (i.e., elements formed in the process initiated by the rapid capture of neutrons emitted in large amounts during supernova explosions). Another potential area of application of the model is nuclear power. Its use here could help to better predict how the nuclei formed by the reactions in reactors decay, and thus contribute to further ensuring their safety.

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MATERIALS AND TECHNOLOGIES WITH A FUTURE

Kraków, 5 September 2017

A REVOLUTION IN LITHIUM-ION BATTERIES IS BECOMING MORE REALISTIC

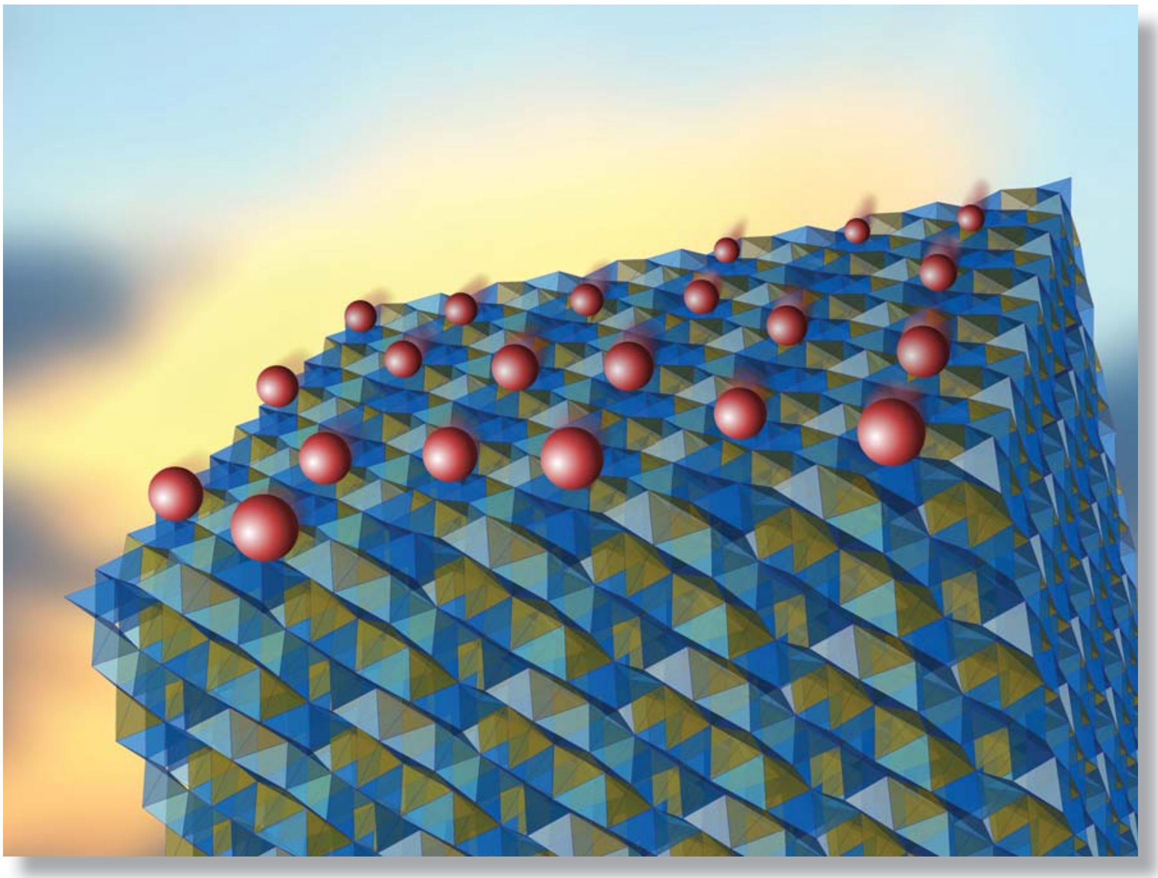
The modern world relies on portable electronic devices such as smartphones, tablets, laptops, cameras or camcorders. Many of these devices are powered by lithium-ion batteries, which could be smaller, lighter, safer and more efficient if the liquid electrolytes they contain were replaced by solids. A promising candidate for a solid-state electrolyte is a new class of materials based on lithium compounds, presented by physicists from Switzerland and Poland.

Commercially available lithium-ion batteries consist of two electrodes connected by a liquid electrolyte. This electrolyte makes it difficult for engineers to reduce the size and weight of the battery, in addition, it is subjected to leakage; the lithium in the exposed electrodes then comes into contact with oxygen in the air and undergoes self-ignition. Boeing's troubles, which for many months caused a full grounding of Dreamliner flights, are a spectacular example of the problems brought about by the use of modern lithium-ion batteries.

Laboratories have been searching for solid materials capable of replacing liquid electrolytes for years. The most popular candidates include compounds in which lithium ions are surrounded by sulphur or oxygen ions. However, in the journal Advanced Energy Materials, a Swiss-Polish team of scientists has presented a new class of ionic compounds where the charge carriers are lithium ions moving in an environment of amine (NH_2) and tetrahydroborate (BH_4) ions. The experimental part of the research project was carried out at Empa, the Swiss Federal Laboratories for Materials Science and Technology in Dübendorf, and at the University of Geneva (UG). The person responsible for the theoretical description of the mechanisms leading to the exceptionally high ionic conductivity of the new material was Prof. Zbigniew Łodziana from the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Kraków.

“We were dealing with lithium amide-borohydride, a substance previously regarded as not being too good an ionic conductor. This compound is made by milling two constituents in a ratio of 1 to 3. To date, nobody has ever tested what happens to ionic conductivity when the proportions between these constituents are changed. We were the first to do so and suddenly it turned out that by reducing the number of NH_2 groups to a certain limit we could significantly improve the conductivity. It increases so much that it becomes comparable to the conductivity of liquid electrolytes!” says Prof. Łodziana.

The several dozen-fold boost in ionic conductivity of the new material – the effect of a change in the proportion of its constituents – opens up a new, unexplored direction in the search for a candidate for a solid-state electrolyte. Previously, throughout the world, the focus was almost exclusively on changes in the composition of the chemical substance. It has now become apparent that, at the stage of



Lithium amide-borohydride is a promising candidate for a solid electrolyte. The crystalline structure of this material consists of two sub-lattices, shown in different colors. Under appropriate conditions, lithium ions (red), normally found in the elementary cells of only one sub-lattice (yellow), move to the empty cells of the second sub-lattice (blue) where they can freely propagate. (Source: IFJ PAN).

production of the compound, a key role can be played by the proportions themselves of the ingredients used to manufacture them.

"Our lithium amide-borohydride is a representative of a promising new class of solid-state electrolyte materials. However, it will be some time before batteries built on such compounds come into use. For example, there should be no chemical reactions between the electrolyte and the electrodes leading to their degradation. This problem is still waiting for an optimal solution", comments Prof. Łodziana.

The research prospects are promising. The scientists from Empa, UG and IFJ PAN did not confine themselves to just characterizing the physico-chemical properties of the new material. The compound was used as an electrolyte in a typical $Li_4Ti_5O_{12}$ half-cell. The half-cell performed well, in tests of running down and recharging 400 times it proved to be stable. Promising steps have also been taken towards resolving another important issue. The lithium amide-borohydride described in the publication exhibited excellent ionic conductivity only at about 40 °C. In the most recent experiments this has already been lowered to below room temperature.

Theoretically, however, the new material remains a challenge. Hitherto models have been constructed for substances in which the lithium ions move in an atomic environment. In the new material, ions move among light molecules that adjust their orientation to ease the lithium movement.

"In the proposed model, the excellent ionic conductivity is a consequence of the specific construction of the crystalline lattice of the tested material. This network in fact consists of two sub-lattices. It turns out that the lithium ions are present here in the elementary cells of only one sub-lattice. However, the diffusion barrier between the sub-lattices is low. Under appropriate conditions, the ions thus travel to the second, empty sub-lattice, where they can move quite freely," explains Prof. Łodziana.

The theoretical description presented here explains only some of the observed features of the new material. The mechanisms responsible for its high conductivity are certainly more complex. Their better understanding should significantly accelerate the search for optimal compounds for a solid-state electrolyte and consequently shorten the process of commercialization of new power sources that are most likely to revolutionize portable electronics.

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Kraków, 8 March 2017

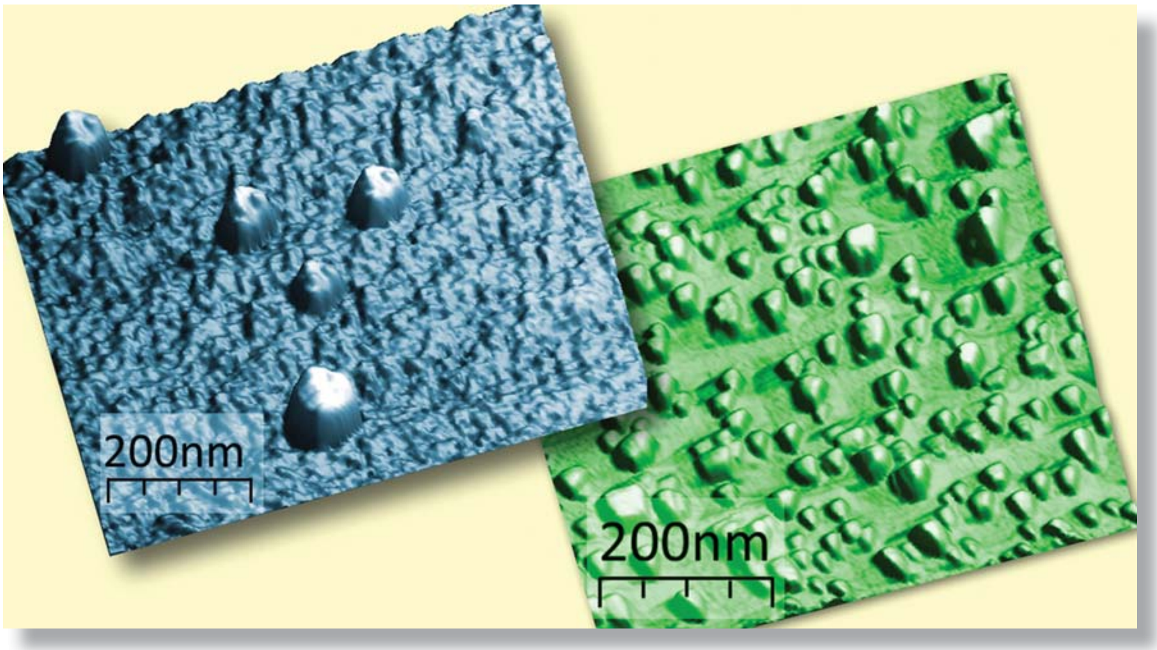
PHONON NANOENGINEERING: VIBRATIONS OF NANOISLANDS DISSIPATE HEAT MORE EFFECTIVELY

Europium silicide has for some time attracted the attention of scientists. Recognized as being promising for electronics and spintronics, this material has recently been submitted by a team of physicists from Poland, Germany and France to comprehensive studies of the vibrations of its crystal lattice. The results yielded a surprise: deposited on a substrate of silicon, some structures of europium silicide appear to vibrate in a way that clearly broadens the possibilities of designing nanomaterials with tailored thermal properties.

The vibrations of atoms in the crystal lattices of materials, known as phonons, are not chaotic. Instead, they are governed by the lattice symmetry, atomic mass and other factors. For instance, the atoms deep in the solid oscillate differently than on its surface, and still differently when the material forms, for example, nanoislands i.e. small atomic clusters on a substrate. An international team of physicists, composed of scientists from the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Kraków, the Karlsruhe Institute of Technology (KIT) and the European Synchrotron (ESRF) in Grenoble, have for the first time comprehensively examined how the vibrations of the crystal lattice of europium silicide ($EuSi_2$) change depending upon the nanostructures arrangement on a substrate of silicon. The study yielded remarkable results: a new type of vibration was observed in the sample in which the $EuSi_2$ nanoislands were in contact with each other.

“Usually nanoengineering means modifying material on a scale of nanometres, or billionths of a metre. The research on europium silicide in which we participated allows us to offer something more: phonon nanoengineering, i.e. engineering in which not so much the structure of the material is carefully designed as the vibrations of atoms in its crystal lattice,” says Dr. Przemyslaw Piekarz (IFJ PAN).

Europium silicide forms a crystal, in which each europium atom is surrounded by 12 silicon atoms. The system exhibits what is known as tetragonal symmetry: the distance between atoms in one direction is different than in the two remaining directions. This metallic compound readily binds to silicon, and also has a record-breakingly low so-called Schottky barrier (i.e. the barrier of potential energy electrons encounter on their transition from the metal to silicon). Such materials are of interest today in view of their potential application in nanoelectronic systems, for example, in MOSFET technology used in the production of modern processors. However, at low temperatures $EuSi_2$ also exhibits interesting magnetic properties, which makes it attractive for the successor of electronics – spintronics.



Microscopic images of the europium silicide nanoislands on the silicon surface. The nanoislands are completely isolated (left) or adjoining each other (right). (Source: IFJ PAN).

Although compounds of rare earth metals and silicon play a fundamental role in heat transport, among others, their lattice vibrations have not to date been comprehensively studied. Meanwhile, in nanoelectronic systems where heat is generated in large amounts, thermal properties of a material became as important as the magnetic or electric properties.

A group led by Dr. Svetoslav Stankov (KIT, Germany) has developed a procedure for the preparation of epitaxial $EuSi_2$ nanostructures by depositing, in ultrahigh vacuum conditions, small amounts of europium atoms on a heated substrate of single crystalline silicon. Moreover, by careful adjustment of the temperature of the substrate and the amount of europium atoms they were able to tailor the morphology of the prepared EuSi2 nanostructures on the silicon surface.

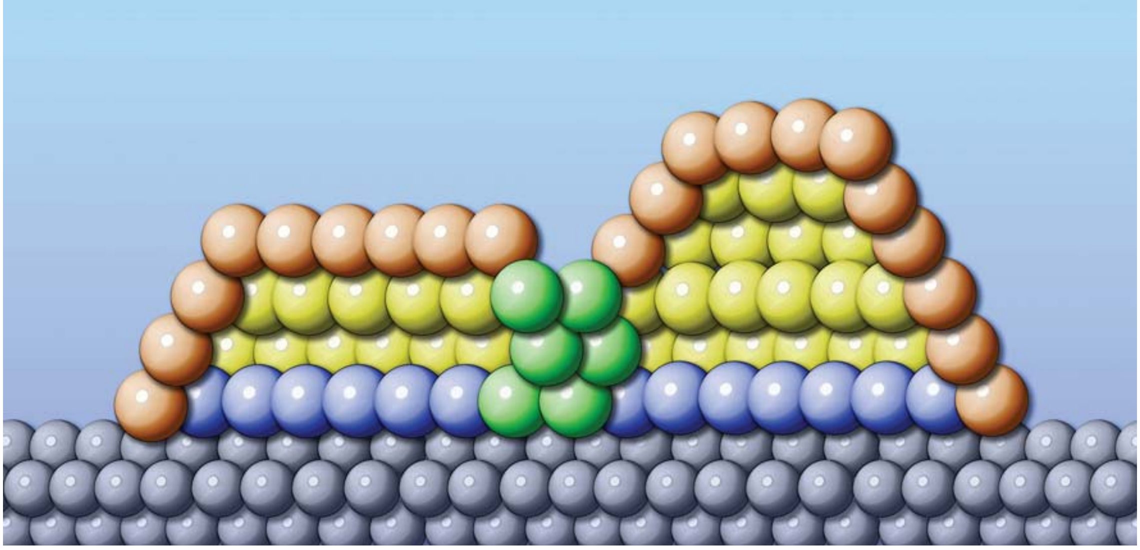
“In this experiment we focused our attention on four europium silicide samples forming: a uniform film, which could be regarded as a solid crystal, a tightly pleated film, and two different assemblies of nanoislands,” explains Dr. Stankov and adds: “A nanoisland is a discrete cluster of self-organized atoms on a surface reaching sizes of several tens of nanometres with a height of a dozen or so nanometres. It turned out that especially interesting are the samples in which the $EuSi_2$ nanoislands are completely isolated from each other and those where the nanoislands are in close contact with each other.”

The samples were prepared in the ultra-high vacuum system at the nuclear resonance beamline of the ESRF synchrotron in Grenoble by the KIT group and investigated in situ by nuclear inelastic scattering (NIS).

“NIS is a state-of-the-art method for direct measurement of the energy spectrum of atomic vibrations of nanomaterials with very high resolution. In this experimental technique the sample is illuminated with high energy photons, selected so that their absorption by atomic nuclei excites or annihilates lattice vibrations of a certain kind, yielding the element-specific phonon density of states,” adds Dr. Stankov.

Theoretical studies at the IFJ PAN were carried out ab initio, based on the fundamental laws of quantum mechanics and statistical physics, using PHONON software written by Prof. Krzysztof Parliński (IFJ PAN). The Kraków group dealt not only with modelling the vibrations of the crystal lattice of structures of europium silicide, but also determining the conditions for conducting experiments in the ESRF synchrotron.

“In Grenoble only the vibration energies of europium atoms were recorded. The curves obtained from the measurements agreed very well with our calculations for the solid crystal and the surface. We could supplement these data with our predictions for the movements of silicon atoms, which helped to better interpret the results,” says Prof. Parliński.



A structure of europium silicide nanoislands. The surface of nanoislands is marked in brown, solid $EuSi_2$ crystals in yellow, and the silicon surface in black. Two interfaces are visible: between the nanoislands and the silicon surface (blue), and the source of new vibrations – the interface between two nanoislands (green). (Source: IFJ PAN).

Particularly interesting results were obtained for the samples with nanoislands. In the case of a substrate coated with discrete nanoislands a significant increase of the amplitude of vibration of europium atoms was observed, up to 70% relative to the vibrations in the crystal. Such a large increase translates into significantly greater possibilities in the field of heat transfer. The most interesting effect appeared, however, in the sample with nanoislands adjoining each other. Namely, additional vibrations with a characteristic energy were found at the interfaces between the nanoislands. Although theoretically predicted earlier on, their existence was confirmed experimentally for the first time. They constitute another 'gateway' through which material can discharge heat into the environment. By means of the adjoining nanoislands a significant increase in the efficiency of heat transfer in nanostructures becomes a reality.

"In the analysis of materials scientists usually look at the properties of a sample of fixed morphology. We have described a whole spectrum of possible surface morphologies of $EuSi_2$. An advanced theoretical model and precise measurements have allowed us for the first time to exactly trace how the vibrations of the crystal lattice of a nanomaterial change depending on its arrangement on the substrate," stressed Dr. Piekarz.

The research on europium silicide nanostructures, funded by the Helmholtz Association, the Karlsruhe Institute of Technology (project VH-NG-625) and on the Polish side by the HARMONIA grant from the Polish National Science Centre, is of a basic nature. However, the knowledge gained, especially with regard to the crystal lattice vibrations occurring at the interface between adjacent nanoislands and the related drastic changes in the heat transport, is universal. After suitable adaptation, this phenomenon will allow researchers to design nanomaterials other than europium silicide with tailored thermal properties.

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Kraków, 12 December 2018

WHEN HEAT CEASES TO BE A MYSTERY, SPINTRONICS BECOMES MORE REAL

The development of spintronics depends on materials that guarantee control over the flow of magnetically polarized currents. However, it is hard to talk about control when the details of heat transport through the interfaces between materials are unknown. This "thermal" gap in our material knowledge has just been filled thanks to the Polish-German team of physicists, who for the first time described in detail the dynamic phenomena occurring at the interface between a ferromagnetic metal and a semiconductor.

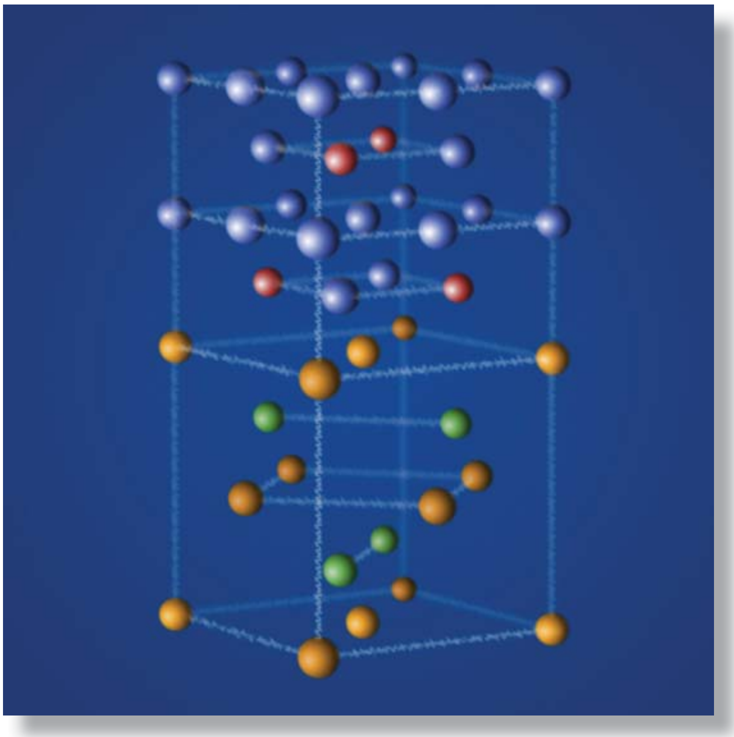
Spintronics has been proposed as a successor of the omnipresent electronics. In spintronic devices, electric currents are being replaced by spin currents. One promising material for this type of application seems to be a gallium arsenide/iron silicide heterostructure: for every four electrons passing through this interface, as many as three carry information about the direction of the magnetic moment. So far, however, little was known about the dynamic properties of the interface, which determine the heat flow. A cooperation between the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Kraków, the Karlsruhe Institute of Technology (KIT), the Paul Drude Institut für Festkörperelektronik in Berlin and the DESY research Centre in Hamburg has finally helped to close this gap.

"The systems of Fe_3Si iron silicide and GaAs gallium arsenide are special. Both materials differ significantly in properties: the first is a very good ferromagnetic material, the other is a semiconductor. On the other hand, the lattice constants, i.e. characteristic distances between atoms, differ only by 0.2% in both materials, so they are almost identical. As a result, these materials combine well, and there are no defects or significant stresses near the interface," says Dr. Przemyslaw Piekarz (IFJ PAN).

The Polish group focused on the preparation of a theoretical model of crystal lattice vibrations in the tested structure. The PHONON computer program, created and developed over the last 20 years by Prof. Krzysztof Parliński (IFJ PAN), played an important role here. Using the basic laws of quantum mechanics, the forces of interactions between atoms were calculated, and this allowed to solve equations describing the motion of atoms in crystal networks.

Dr. Malgorzata Sternik (IFJ PAN), who performed most of the calculations, explains: "In our model, the substrate is gallium arsenide, and its outermost layer consists of arsenic atoms. Above it there are alternately arranged iron-silicon and iron layers. Atomic vibrations are different for a solid crystal, and near the interface. This is why we studied how the spectrum of vibrations changes depending on the distance from the interface".

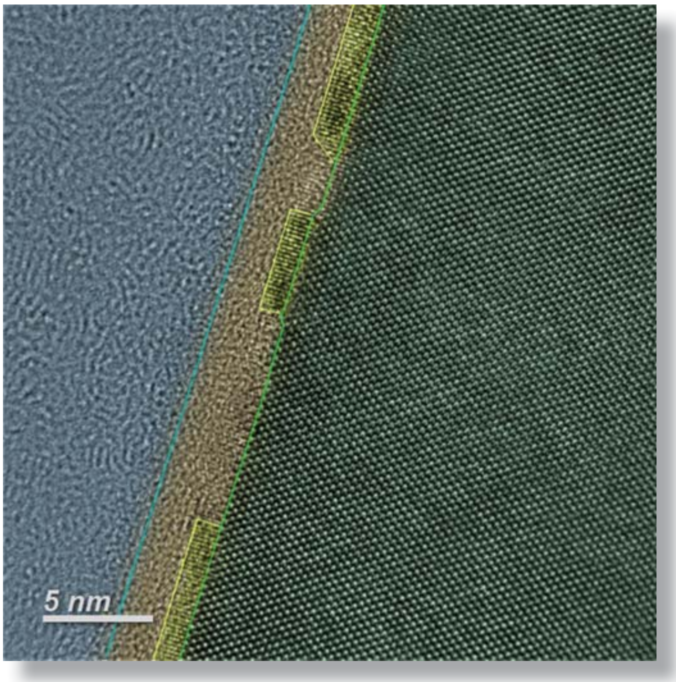
The dynamics of atoms in crystals is not random. Crystalline materials are characterized by a long-range order. As a consequence, the motion of atoms is not chaotic here, but it follows certain, sometimes



The GaAs/Fe_3Si interface model. Arsen atoms marked in orange, gallium – green, silicon – red, iron – blue (Source: IFJ PAN).

very complex, patterns. Transverse acoustic waves are mainly responsible for heat transfer. This means that when analyzing the lattice dynamics, the researchers had to pay special attention to the atomic vibrations occurring in the plane parallel to the interface. If the vibration waves of the atoms in both materials were matched to each other, heat would effectively flow through the interface.

“Measuring the spectrum of atomic vibrations in ultrathin layers is one of the grand challenges in the experimental solid state physics,” explains the leading scientist Dr. Svetoslav Stankov (KIT) and adds: “Thanks to the outstanding performance of the synchrotron radiation sources we are able nowadays, by nuclear inelastic scattering, to directly measure the energy spectrum of atomic vibrations in nanomaterials with very high resolution. In our experiment the synchrotron beam was oriented parallel



Microscopic image of the GaAs/Fe_3Si interface (GaAs marked in green, Fe_3Si in yellow; the protective germanium layer in brown) (Source: IFJ PAN).

to the plane of the interface. In this way we were able to observe atomic vibrations parallel to the Fe_3Si/GaAs interface. Furthermore, the experimental method is element specific implying that the obtained data are practically free from background, or other artefacts."

Ge/Fe_3Si/GaAs samples containing various numbers of Fe_3Si monolayers (3, 6, 8 and 36) were prepared at the Paul Drude Institut für Festkörperelektronik by Jochen Kalt, a PhD student at the Karlsruhe Institute of Technology. The experiment was carried out at the Dynamics Beamline P01 of the synchrotron radiation source Petra III in Hamburg.

It turned out that despite the similar lattice parameters of both materials, the vibrations of the interface atoms differ drastically from those in the bulk. The first principles calculations were perfectly in line with the experimental observations, reproducing the novel features in the energy spectrum of interface atomic vibrations.

"The almost perfect match between theory and experiment paves the way towards interface phonon nanoengineering that will lead to the design of more efficient thermoelectric heterostructures and will stimulate further progress in thermal management and nanophononics," concludes Dr. Stankov.

The Fe3Si/GaAs interface has proven to be a perfect model system for studying dynamic and spintronic interface phenomena. In the future the research team plans to extend this work to better understanding the electronic and magnetic properties of this promising material. The research is funded by the Helmholtz Association (HGF, VH-NG-625), German Ministry for Research and Education (BMBF, 05K16VK4) and the Polish National Science Center (2017/25/B/ST3/02586).

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Krakow, 20 April 2016

ANTIMATTER HELPS TO UNVEIL THE SECRETS OF LIQUID CRYSTALS

The chaos typical of liquid molecules, and the ordering characteristics of crystals. There are states of matter connecting such contradictory features: liquid crystals. Thanks to an innovative application of antimatter, it has been demonstrated at the Institute of Nuclear Physics of the Polish Academy of Sciences in Krakow that the structures formed by certain molecules of liquid crystals must in fact be different than previously thought.

Liquid crystals are found in many areas of technology, and in future, their use will likely grow, for example, as organic semiconductors. But to make this possible, we still need to conduct basic research using a variety of experimental techniques in order to reveal the structure of these compounds and their dynamics. To this end, new experiments have been conducted on the quenched smectic-E (Sm-E) phase of liquid crystals at the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Krakow. Smectics of this type are composed of well-ordered particles separated into layers. Up until now it was thought that the distance between the individual layers of particles was very small. Research conducted by the Krakow physicists helped to verify the correctness of current models and precisely determine the crystal-like phase structure.

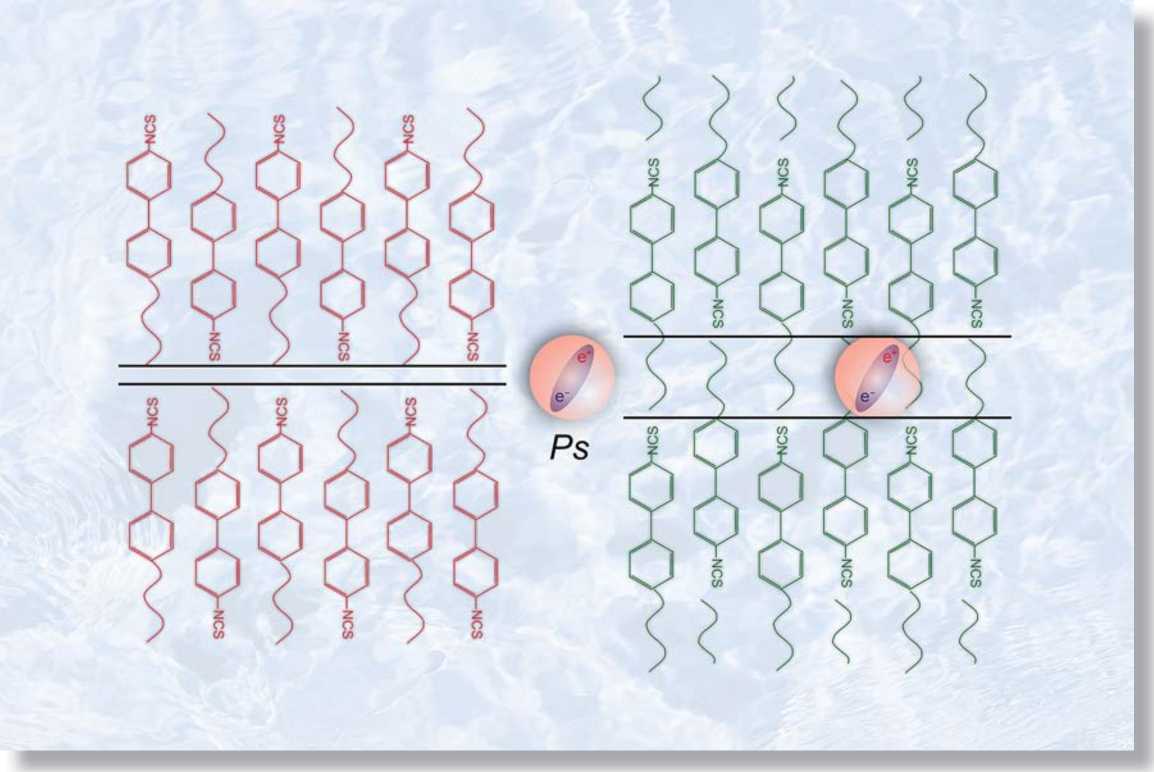
"We have employed an interesting measurement technique rarely used in the case of liquid crystals. The method uses the specific characteristics of positrons, which are antimatter counterparts of ordinary electrons," explains Dr. Ewa Dryzek (IFJ PAN).

A positron as the antiparticle of an electron has a positive charge. When a positron meets an electron it may lead to annihilation, where the mass of both particles converts into electromagnetic radiation with a characteristic energy.

"In the world of ordinary matter, antimatter is produced by physical processes only in trace amounts. In the course of our measurements we used positrons created in radioactive decay of the isotope sodium 22," says Dr. Ewa Juszyńska-Gałązka (IFJ PAN).

Positrons of a radioactive source penetrated the test material, in which they encountered electrons. Before the annihilation of a positron and an electron pair, an exotic atom called positronium can form. In soft matter such as liquid crystals or polymers positronium may be formed in nanopores, which are small voids between molecules. Measuring its lifetime, that is, the time between the emission of a positron from a radioactive source and its annihilation, allows us to determine the size of the nanopores. The smaller the nanopores, the faster the annihilation occurs.

Research at IFJ PAN (made possible thanks to previous cooperation, among other endeavours, with Dr. Bożena Jasińska's group from the Institute of Physics of the University of Maria Curie-Skłodowska



Liquid-crystal SMEs have a different structure than previously expected, as shown by measurements using antimatter particles conducted at the Institute of Nuclear Physics of the Polish Academy of Sciences in Krakow. On the left is the current model of Sm-E, and on the right is the new model, with a distinct gap between the layers, large enough to be able to accommodate positronium (Source: IFJ PAN).

University in Lublin) concerned positron irradiation of a compound called 4TCB, which unlike many other substances does not crystallize with a decrease in temperature, but with an increase. The results showed that in the material positronium is formed. However, given the existing model arrangement of molecules in the Sm-E phase, it was difficult to identify the place where it could be accommodated.

"Our measurements show that positronium's nanopores are the size of approximately six angstroms, that is, six 10-billionths of a meter. These results were consistent with one of the variants of the new model of Sm-E, which only recently has been proposed by Prof. Kazuya Saito's group from Japan," says Dr. Dryzek.

Measurements have confirmed that the alkyl chains – 'tail' of molecules – are in a liquid state, and so have freedom of movement like in an isotropic liquid. It is worth mentioning that in liquids, as a result of interaction with the surrounding molecules, the positronium repulses the neighbouring molecules or their parts to produce a small empty space around itself. Such an arrangement can be imagined as a bubble with positronium in its center.

The Japanese Sm-E model, proposed on the basis of calorimetric tests and the diffraction, assumed that the liquid crystal molecules are arranged in two layers: the first comprised of rigid phenyl rings, the other of alkyl chains.

"At this point all the information began to fit together! Positronium can produce a bubble in the layer containing the alkyl tails, as they are in the liquid state. The size of the resulting bubble corresponds to the width of the layer," says Dr. Dryzek.

Temperature measurements of the positronium lifetime confirmed that at low temperatures (liquid nitrogen) quenched 4TCB creates glass, wherein the positronium cannot form. The movements of the alkyl tails are frozen and positronium cannot produce a bubble. With an increase in temperature the glass softens, which can be described as the formation of liquid-like domains. It is in these domains that positronium begins to form.

Positron annihilation spectroscopy is used in the material testing of metals, semiconductors and polymers. The results of IFJ PAN prove that skilfully applied, this method can be a source of intriguing and detailed information about the structure of liquid crystals.

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UBIQUITOUS PHYSICS

Kraków, 18 October 2017

CHAOS REIGNS EVEN IN SIMPLE ELECTRONICS

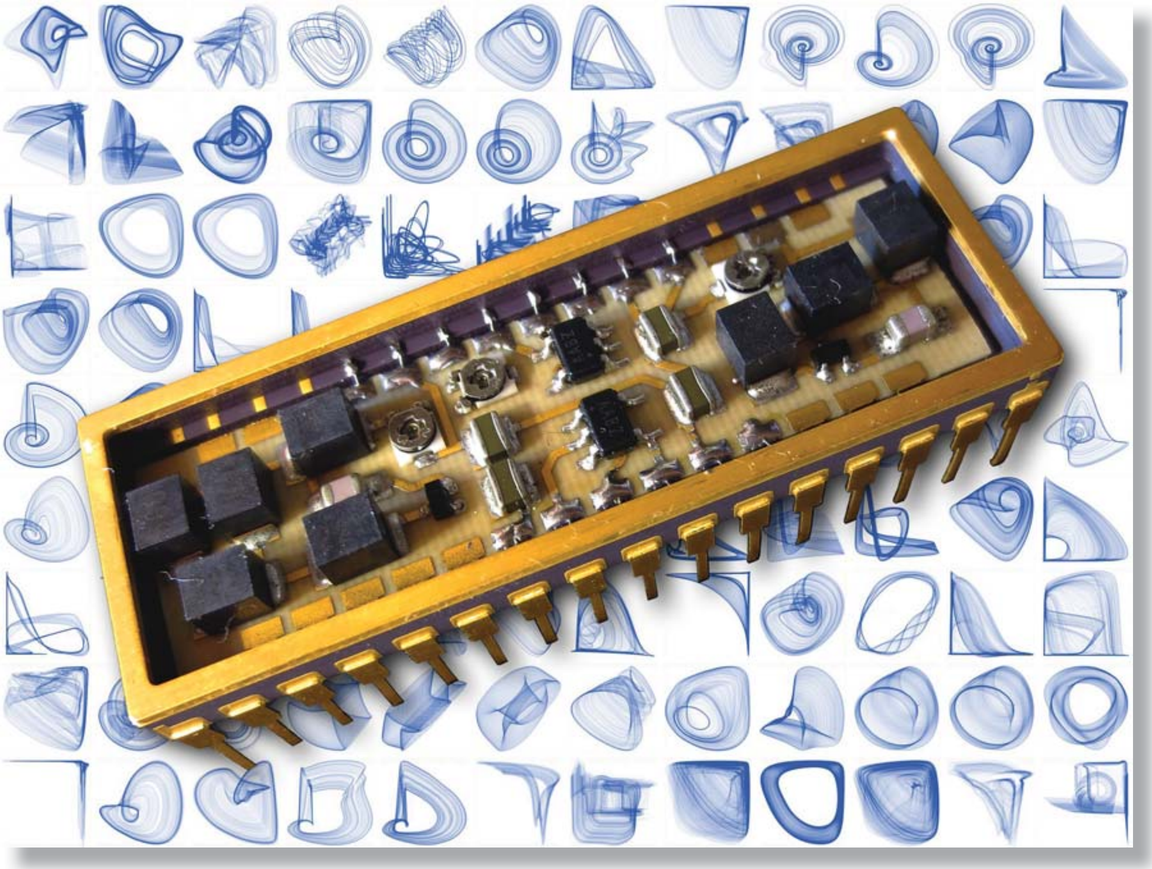
It's really surprising: it turns out that among simple electronic circuits, built of just a few components, many of them behave chaotically, in an extremely complicated, practically unpredictable manner. Physicists from the Institute of Nuclear Physics Polish Academy of Sciences in Kraków have discovered, examined and described dozens of new, unusual circuits of this type. What is especially interesting is that one of the circuits generates voltage pulses very similar to those produced by neurons, only it does so a thousand times faster.

Just a few transistors, resistors, capacitors and induction coils are enough to build electronic circuits that behave in a virtually unpredictable way. Even in such simple systems chaotic oscillations of a complex nature turn out to be not the exception but the norm, according to researchers from the Institute of Nuclear Physics Polish Academy of Sciences (IFJ PAN) in Kraków. In a paper published in the journal Chaos, they have presented 49 new, unusual chaotic electronic oscillators – not designed but discovered by computer simulations.

"Electronics is usually associated with devices that work precisely and always according to expectations. Our research shows a completely different picture. Even in electronic circuits containing only one or two transistors, chaos is ubiquitous! The predictable and always the same reactions of electronic devices that we all use on an everyday basis do not reflect the nature of electronics but the efforts of designers," says the first author of the paper, Dr. Ludovico Minati (IFJ PAN).

By chaos we generally mean lack of order. In physics, this concept works a little differently: circuits are said to behave chaotically when even very small changes in input parameters result in large changes in output. Since various types of fluctuations are a natural feature of the world, in practice chaotic systems show an enormous wealth of behaviour – so great that precise prediction of their reactions is very difficult, and often impossible. The circuit can thus seem to be behaving quite randomly, even though in fact its evolution follows a certain complicated pattern.

Chaotic behavior is so complex that to this day there are no methods to effectively design electronic circuits of this type, so physicists from the IFJ PAN approached the problem differently. Instead of building chaotic oscillators from scratch, they decided to... discover them. The structure of the circuits, made up of commercially available components, was mapped as a sequence of 85 bits. In the maximum configuration the modelled circuits consisted of a power source, two transistors, a resistor and six capacitors or induction coils, connected in a circuit containing eight nodes. The strings of bits thus prepared were then subjected to random modifications. The simulations were made on the Cray XD1 supercomputer.



Many simple electronic systems can behave in a difficult to foresee, chaotic manner, as shown by researchers from the Institute of Nuclear Physics Polish Academy of Sciences in Kraków. The image shows a device built from two recently discovered oscillators. In the background are so-called attractors, illustrating the diversity and richness of behaviour of the new circuits (Source: IFJ PAN).

"Our search was blind, in a gigantic space offering 2 to a power of 85 possible combinations. During the simulation we analyzed more or less two million circuits, so an extremely small area of the available space. Of these, about 2,500 circuits exhibited interesting behaviour," says Dr. Minati, and emphasizes that chaotic electronic oscillators were known about previously. Up to now, however, it seemed that they occurred in only a few variants, and that their construction required some effort and an appropriately complex system.

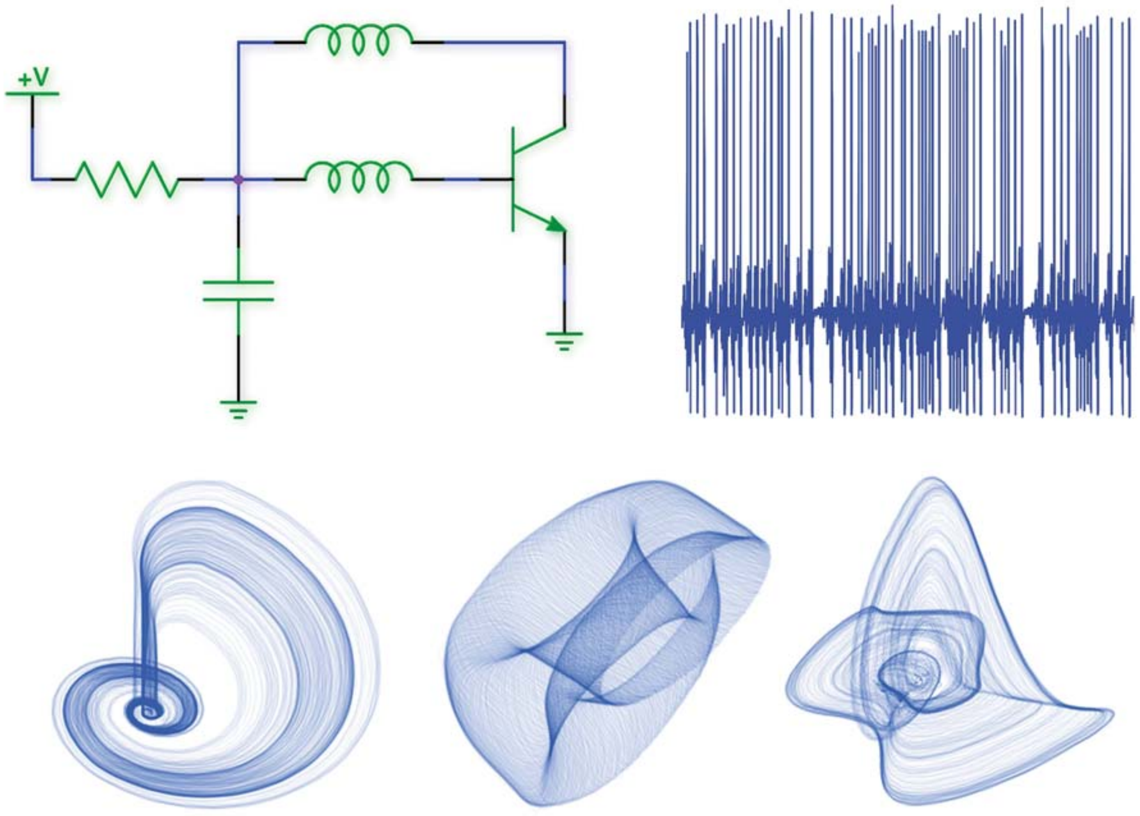
Physicists from the IFJ PAN analyzed the behavior of the new circuits using the SPICE program, commonly used in the design of electronic circuits. However, in the case of chaotic behaviour, SPICE's simulation capabilities turned out to be insufficient. So the 100 most interesting circuits were physically built and tested in the laboratory. In order to improve the quality of the signals generated during the tests, delicate tuning of the component parameters was often performed. Eventually the number of interesting circuits was reduced to 49. The smallest chaotic oscillator consisted of one transistor, one capacitor, one resistor and two induction coils. Most of the circuits found showed non-trivial, chaotic behaviour with a sometimes astonishing scale of complexity. This complexity can be visualized using special graphs – attractors, geometrically reflecting the nature of changes in the circuit over time. Statistical analyses of the signals generated by the new oscillators did not, however, reveal any traces of two important features found in many self-organizing systems: criticality and multi-fractality.

"We could talk about multi-fractality if different portions of the voltage variation diagram, magnified in different places in different ways, revealed changes similar to the original characteristics. In turn, we would be dealing with criticality if the circuit was in a state in which it could at any moment switch from regular to chaotic mode or vice versa. We did not notice these phenomena in the examined oscillators," explains Prof. Stanisław Drożdż (IFJ PAN, Kraków University of Technology) and adds: "Critical systems generally have more opportunities for reacting to changes in their own environment. So it is no wonder that criticality is a phenomenon quite often encountered in nature. A lot points to the fact that a system operating in a critical condition is, for example, the human brain."

Of particular interest was one of the found oscillators, which generated voltage spikes resembling stimuli typical for neurons. The similarity of impulses was striking here, but not complete.

"Our artificial neuron analogue proved to be much faster than its biological counterpart: pulses were produced thousands of times more often! If it were not for the lack of criticality and multi-fractality, the speed of operation of this circuit would justify talking about an electronic super-neuron. Perhaps such a circuit exists, only we have not found it yet. At the moment, we have to be satisfied with our 'almost super-neuron,'" comments Dr. Minati, with a smile.

The Kraków-based physicists have also demonstrated that as a result of combining the found circuits in pairs, behaviours of even greater complexity appear. Coupled circuits in some situations worked perfectly synchronously, like musicians playing in unison, in some one of the circuits took over the role of leader and in still others the mutual inter-dependence of the oscillators was so complicated that it was revealed only after careful analysis of statistics.



Chaotic voltage changes are common even for electronic circuits made up of only several elements. In the top left corner is a diagram of the simplest chaotic oscillator found by physicists from IFJ PAN in Kraków. On the right, a series of pulses showing a great resemblance to neural activity, generated by one of the newly discovered circuits. In the lower row several so-called attractors, illustrating the complexity of behaviour of the new circuits. (Source: IFJ PAN).

In order to accelerate the development of research into electronic systems that simulate the behaviour of the human brain, the diagrams of all the circuits found by physicists from the IFJ PAN have been made public. Anyone interested can download them from: ftp://ftp.aip.org/epaps/chaos/E-CHAOEH-27-012707.

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The Henryk Niewodniczański
Institute of Nuclear Physics
Polish Academy of Sciences

Kraków, 13 December 2018

FROM CATHEDRAL FLOORS TO TRANSISTOR CIRCUITS: THE SPLENDID GENERATIVE POTENTIAL OF THE SIERPINSKI TRIANGLE

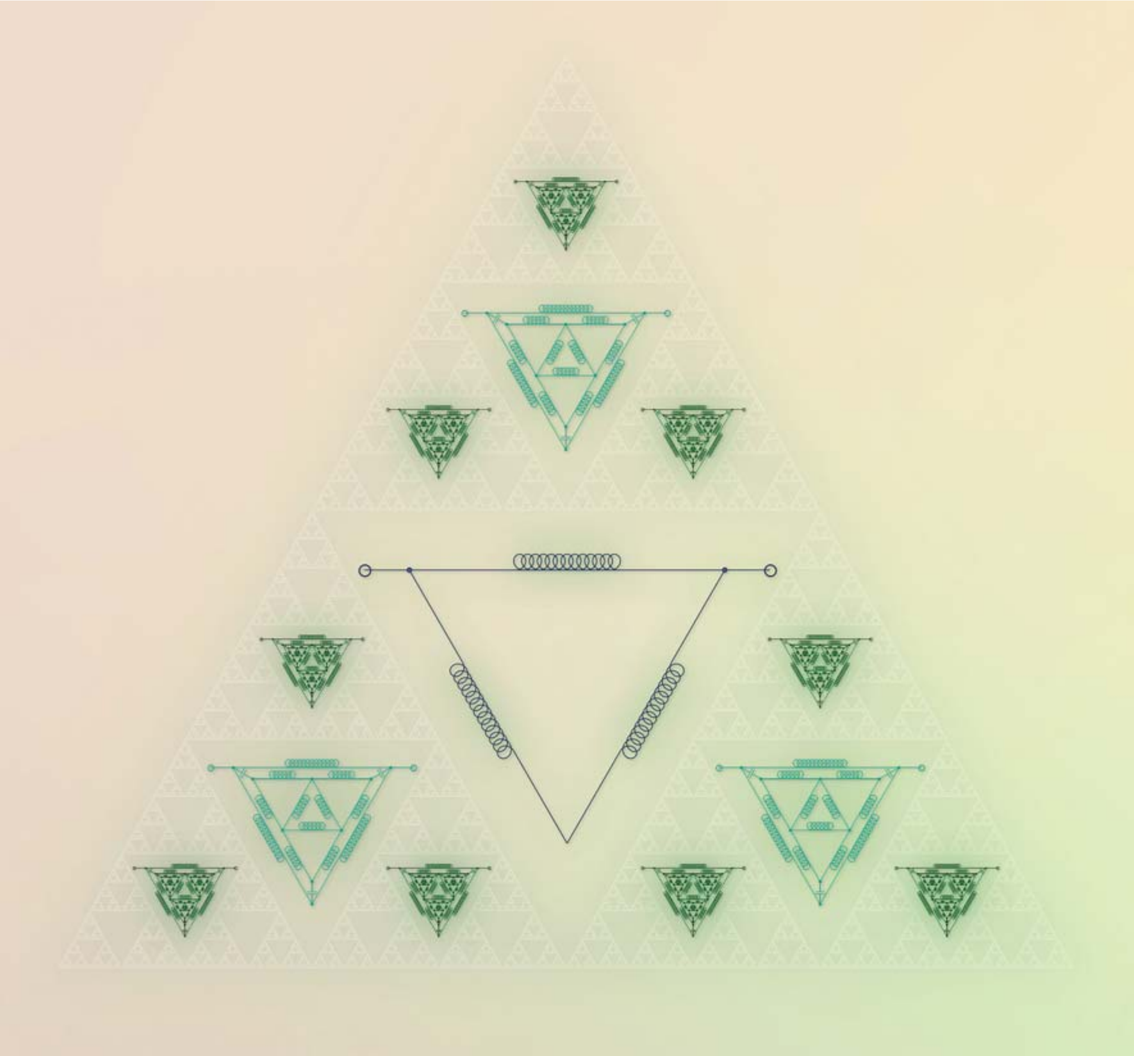
One transistor, just a pair of inductors and capacitors. Such a simple electronic circuit can become an oscillator with a surprising richness of behavior. However, even more interesting effects become visible if the structure of connections is fractal and shows some... imperfections. Could similar rules explain the diversity and complexity of the human brain dynamics?

Intuition suggests that self-similarity appears only in systems as complex as neural networks in the brain, or in fascinating shapes of nature, for example in the famous Romanesco broccoli buds. At the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Kraków a discovery was made that in some ways challenges this belief. In close collaboration with colleagues from the University of Catania and the University of Trento in Italy, the researchers constructed an elementary electronic oscillator based on just one transistor. As it turns out, when it contains fractal arrangements of inductors and capacitors, these generate amazingly rich characteristics of the electrical signals.

Even when we may not pay attention to it, we are surrounded by objects whose shape has a remarkable property: it is similar regardless of how close or far we look. The whole is sometimes similar to its parts! This extraordinary feature, known as self-similarity, is a distinguishing property of mathematical fractals. Self-similarity, however, is not only the domain of mathematics. It is readily detectable, for example, in the shapes of clouds, coastlines, in the structure of plants or even in ourselves. Fractal properties are visible in the arrangement of the bronchi in the lungs, blood vessels in the brain, and, at a smaller scale, in the layout of dendrites and in the connections between neurons in the brain.

Why fractals seem to arise so pervasively? Scientists from all disciplines have long been fascinated by this profound question. But it is only more recently that engineers have started taking an interest in them for practical applications. What they like is that fractals can fold very long lines into small areas, helping the miniaturisation of antennas. Notwithstanding, it is possible to build fractal circuits quite simply, just by connecting together standard inductors and capacitors according to a fractal pattern. Regardless of their physical size, such circuits would always have a self-similar shape – and interesting properties. But so far nobody has examined how they could perform when inserted into an oscillator.

“In our latest research, we started off from an extremely simple circuit that we had discovered last year. It is really tiny, as it only includes one transistor, two inductors, one capacitor and one resistor. Nevertheless, depending on the geometry of the connections and parameters of the inductors and capacitors, the circuit exhibits various, sometimes very complex activities. We wondered what would happen



Three iterations of simple electronic oscillators. The Sierpinski triangle is visible in the background. (Source: IFJ PAN).

if we replaced the inductors with smaller and smaller self-similar circuits" says Dr. Ludovico Minati (IFJ PAN), the main author of the paper in the renowned scientific journal Chaos.

There are many patterns which can be repeated to generate fractals. One of the simplest ones starts off drawing a triangle, then taking the mid-points of its sides and connecting them. In this way, four smaller triangles are formed: three at the vertices and one in the middle. Then, the triangle in the middle should be ignored, and the algorithm should be iterated in the other triangles. A large number of these iterations leads to the formation of the Sierpinski triangle, from the name of a Polish mathematician who studied its remarkable properties. However, it has, in fact, been well known for centuries as a decorative element and appears quite frequently in the floors of churches in the Lazio region of Italy, realised in the medieval period by the Marmorari Romani.

Intrigued by the idea of transforming the analyzed circuit into a fractal, the Kraków researchers attempted to recreate patterns of the Sierpinski triangle with inductors and capacitors. And here a surprise awaited them. Although the circuits for laboratory tests were realized with the highest precision, the generated patterns failed to reach the same heights of complexity and aesthetic beauty that was observed in simulations!

As one considers just a triangle of inductors, the generated signals are not so complex. But as one inscribes more and more triangles, increasing the depth of the fractal (meaning, how many nested levels, or iterations, are present), what is found is that the signals become more and more intricate, delineating a motion in as many as... ten dimensions! However, when one goes from numerical simulations to building the real circuits, at first the reality seems more bleak, since such a level of dynamical richness is not reached, and the number of dimensions decreases. It turns out that this is due to the fact that real components are not "ideal", effectively making the fractal more blurred.

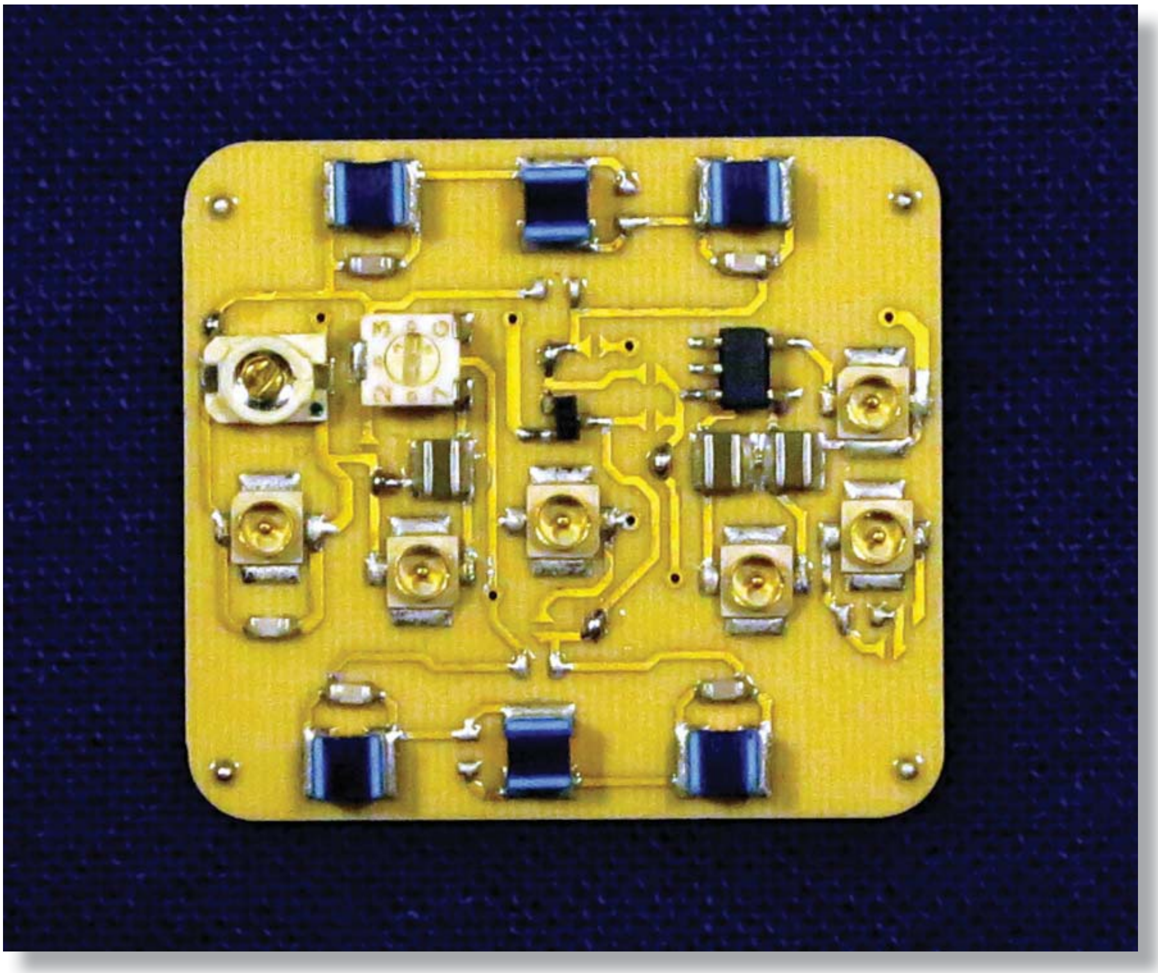
"At first, we were quite disappointed. Later, we discovered something even more interesting than what we had initially planned to study. The key to remove the hindreance caused by the non-ideal elements was not to unblur the fractal structure, but to... damage it!" adds Dr. Minati, still looking somewhat surprised.

Like artists of all walks like to say, there is beauty in imperfection, and the study of Kraków researchers seems to firm up this statement. By damaging the fractals slightly, for example, by removing some components or inserting some short-circuits, it is possible to obtain much more complex resonances, which are readily confirmed by the experiment. In fact, it turns out that these are rather similar to what would be obtained by reshuffling all components in a completely random manner. In a real, physically-built circuit, these more complex resonances give back what was lost due to the non-ideal components, offering new ways of obtaining complex signals.

"Perfection belongs to mathematics, and neither to biology nor physics. Most of the fractals we observe in nature are not perfect at all, and we usually take this fact as an obvious flaw. Meanwhile, our understanding of the consequences of imperfections may be quite limited," notes Prof. Stanisław Drożdż (IFJ PAN, Kraków University of Technology).

The latest research shows that in simple, fractal electronic oscillators, imperfections in the structure of connections radically increase the dynamics of behavior. This result of Kraków physicists even provokes some speculations related to the structure and functions of the human brain.

"We might be tempted to assume that imperfections in the layout of neural connections arise accidentally in a process of brain growth from a structure that would otherwise be ideal by definition.



Real electronic oscillators generate more complex dynamics as a result of imperfections in fractal connections. (Source: IFJ PAN).

In fact, this is probably not the case and their presence may serve a specific purpose and be a result of long-term natural selection. Neural networks with defects will manifest more complex dynamics! Who knows, then, if inspired by this observation, one day we will even intentionally build imperfect computers?" sums up Prof. Drożdż.

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Kraków, 23 August 2018

ON THE GENESIS OF SHAPE: THERE IS NO MAGIC IN REMOTE SYNCHRONIZATION

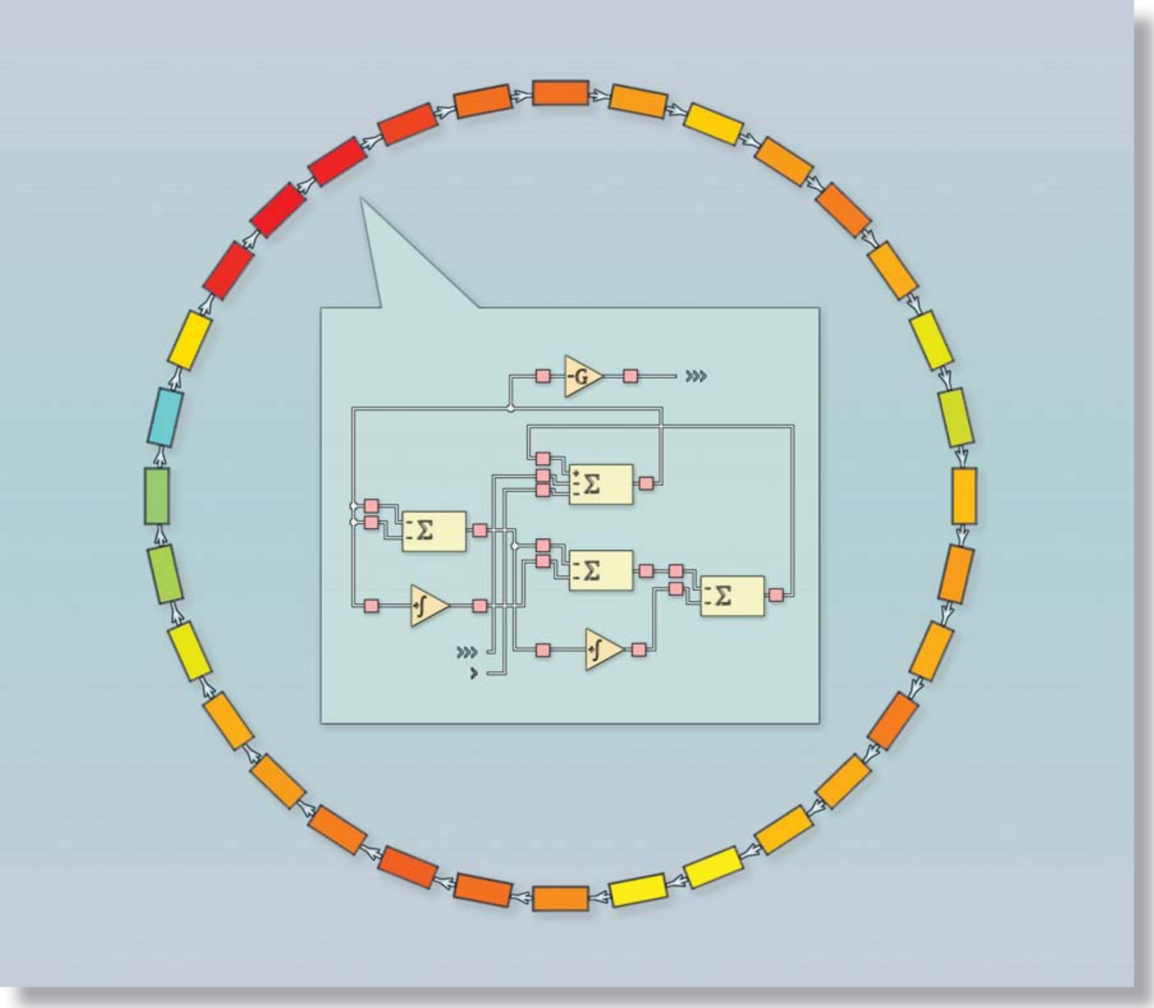
In some physical systems, even elements quite distant from one another are able to synchronize their actions. At a first glance, the phenomenon looks rather mysterious. Using a network of simple electronic oscillators interconnected as a ring, researchers from the Institute of Nuclear Physics of the Polish Academy of Sciences in Kraków have shown that, in fact, remote synchronization can, at least in certain cases, be explained quite clearly.

The most fascinating physical, chemical and biological processes are probably those in which "something" comes from "nothing". For example, why do concentric rings suddenly appear in a seemingly homogeneous layer of liquid, as in the case of the Belousov-Zhabotinsky reaction? Why can a hydra have many tentacles, always arranged so regularly? Why in a network of a dozen or so simple electronic oscillators connected in a ring, do some remote elements suddenly start to operate in the same rhythm? At the root of similar phenomena across such different systems there are universal, though still poorly understood, mechanisms of synchronizing the activity of a system's components. The nuances of one of these mechanisms have just been explained by scientists from the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Kraków, in close collaboration with colleagues from the University of Palermo and the University of Catania in Italy.

Synchronization leading to the birth of shape (representing a form of morphogenesis) can occur in systems of diverse nature, and various mechanisms may be responsible for its occurrence. A metaphor of a representative situation is that in a fairly uniform group of guests who do not know one another at a large party, clearly visible groups of similar interests form quickly, within which the people spend most of the time talking to each other. This type of phenomenon – the result of specific features of certain elements or arising from accidental events – is referred to as cluster synchronization. It is present in many physical systems, for example between neurons in the human brain.

"In our latest research, we have been dealing with an instance of a related type of synchronization: remote synchronization. This is when elements or groups of elements that are not directly connected with each other synchronize their activity, but do so without entraining the other elements through which the synchronization information is propagated. It resembles a situation where two people exchange information with each other through a courier, but the courier not only cannot read the contents of the messages, but is often quite oblivious to the existence of a hidden message," explains Dr. Ludovico Minati (IFJ PAN), the main author of the publication in the well-known scientific journal Chaos.

Various occurrences of remote synchronization have been described to date, and remote synchronization is deemed to occur for instance between areas of the brain distant from one another, between



Remote synchronization in a network of simple electronic oscillators connected in a ring. Periodic fluctuation of the low frequency component driving the effect, resembling a diffraction pattern, is represented by the colors of the oscillators. (Source: IFJ PAN).

meteorological phenomena over different continents, and even between elements of electronic circuits. In 2015, Dr. Minati, then at the University of Trento, described an instance of this sort of synchronization in networks built out of just a dozen or so simple electronic oscillators connected in series as a ring. It was noticed then that individual oscillators tried to synchronize not only with their closest neighbors on the ring, but also with some more distant ones, at the same time remaining less desynchronized with the others located at an intermediate distance.

"We observed this effect with real fascination because it occurred in a device much smaller, but above all, radically simpler than the brain. The phenomenon was described in detail, unfortunately we were not able to fully understand its nature. We have only presented a satisfactory explanation in our latest publication," says Dr. Minati.

Researchers from the IFJ PAN studied rings of oscillators experimentally and with the use of computer simulations. The observation that information has to propagate in the rings using not one but three frequencies turned out to be a breakthrough (in this respect, the phenomenon resembles the amplitude modulation used in radio technology). Each oscillator not only generated its own signal of a chaotic nature, but also reacted to signals coming from nearby oscillators, and transferred them to the other two bands. Depending on their phase in a given oscillator, these signals were amplified or weakened in a manner resembling an interference effect. The researchers accordingly observed patterns reminiscent of the diffraction bands well known from optics. Fluctuations of synchronization intensity giving rise to "remoteness" appeared between oscillators wherein constructive or destructive interference occurred.

In order to better understand the nature of the observed synchronization, the Kraków-based physicists subjected the oscillator rings to additional tests. The sensitivity of synchronization to high-intensity noise introduced at various sites of the systems was tested, varying numbers of oscillators in the ring were simulated together with the effects appearing on its opening. Analysis of the results made it possible to determine that in the studied oscillator rings remote synchronization is not so much a global characteristic of the whole system, as it is the result of the local interactions of individual oscillators with their surroundings. At the same time, it was also investigated whether remote synchronization could be used to transfer a signal introduced into the system from the outside. The result, however, was negative.

"Understanding the mechanisms associated with the occurrence of complex interdependencies between elements in systems of diverse nature is a great challenge in non-linear science. We still have limited understanding of the mechanisms responsible for most types of remote synchronization. A more complete knowledge of similar processes would have considerable theoretical and practical significance. Who knows, maybe we would be able to better predict, for example, collective behaviours in various social networks or even financial markets?" sums up Prof. Stanisław Drożdż (IFJ PAN, Kraków University of Technology).

Those interested in conducting their own research on synchronizing electronic oscillators can download supplementary materials from the following website, including experimental time-series: ftp://ftp.aip.org/epaps/chaos/E-CHAOEH-27-012707.

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Kraków, 22 November 2018

IT'S TIME FOR A HYPER-CRASH, SAY MULTIFRACTAL ANALYSES OF THE MAIN STOCK MARKET INDEX

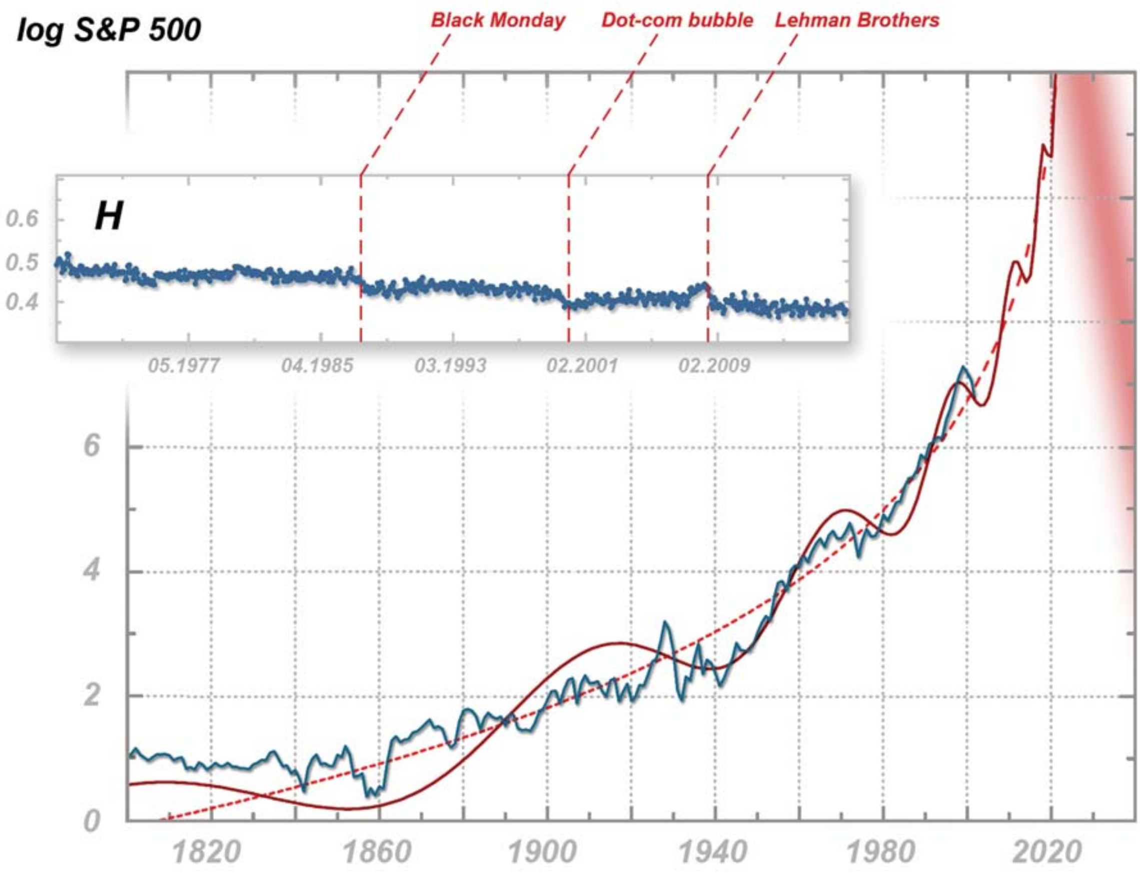
The near future of the global economy looks extremely bleak. This pessimistic forecast comes from advanced statistical analysis of the S&P 500 stock market index, recently published by scientists from the Institute of Nuclear Physics of the Polish Academy of Sciences in Kraków. Based on their analysis, the researchers explain why, in up to a dozen or so years, we can expect a financial meltdown such as never before – and explain why you have the chance to save the world by reading this text.

Black Monday, the bursting of the dot-com bubble, the bankruptcy of the Lehman Brothers. These events shook up the global economy. Soon, however, we may have to deal with such a gigantic collapse of financial markets that all previous crashes will appear as minor stumbling blocks in comparison. This catastrophic vision emerges from the multifractal analysis of financial markets presented in the pages of the highly valued magazine Complexity by scientists from the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Kraków – and it coincides with their previous forecasts from a dozen or so years ago.

"The data is, unfortunately, quite unambiguous. It seems that since the mid-2020s, a global financial crash of a previously unprecedented scale is highly probable. This time the change will be qualitative. Indeed radical!" says Prof. Stanisław Drożdż (IFJ PAN, Kraków University of Technology).

In their latest publication, scientists from the IFJ PAN looked at various economic data, including the daily listing of Standard & Poor's 500 index in the period from January 1950 to December 2016 (the S&P 500 is the largest global stock market index and includes the largest 500 companies, largely of a worldwide nature). The main goal of the Kraków researchers' article was not to make catastrophic forecasts, but to credibly present issues related to the occurrence of multifractal effects (i.e. those in which in order to see self-similarity, different fragments of the structure under investigation have to be increased at different rates) in the financial time series (i.e. prices or stock market indices). The scientists' attention was especially drawn to a graph showing changes in the Hurst exponent, calculated for the S&P 500 based on multifractal spectra obtained during the analysis.

The Hurst exponent can assume values from 0 to 1 and reflects the degree of susceptibility of a system to a change in trend. A value equal to 0.5 means that in the next measurement the fluctuating tested value has the same probability of changing up as of changing down. Values below 0.5 indicate a greater tendency to alternation in the directions of fluctuation: a rise in value increases the probability of a decrease or vice versa, which in the context of finances can be interpreted as a symptom of nervousness.



Multifractal and fractal manifestations of nervousness in the world economy. Top: changes in the Hurst exponent for the S&P 500 index in the last half-century, with the moments of financial crashes marked. Below: oscillations of the S&P 500 in the years 1800-2003 with extrapolation (made in 2003) to 2025. (Source: IFJ PAN).

Values above 0.5 indicate the persistent nature of the changes and the tendency for the system to build a trend. After an increase, there is then a higher probability of another increase, and after a decrease – a greater subsequent fall.

Stable, mature markets are recognized as being those whose Hurst exponent is equal to 0.5 or shows only slight deviations from this value. The Hurst graph for the S&P 500 does actually start at 0.5. On October 19, 1987, however, there was a crash – the famous Black Monday. The exponent then slightly decreased, but for more than a decade it remained relatively stable again. At the turn of the century there was a clear fall, and by March 2000, the dot-com bubble had burst. Just as before, the Hurst exponent again stabilized, but for a shorter period. Already at the end of the first decade, it suddenly began to grow rapidly, only to fall after the bankruptcy of Lehman Brothers in September 2008. From that moment, the Hurst exponent not only did not return to the value of 0.5, but in the last decade it has quite clearly and systematically fallen below the particularly worrying value of 0.4.

"What is also striking in the changes in the Hurst exponent for the S&P 500 is the shortening time intervals between consecutive crashes and the fact that after each collapse the indicator never returns to its original level. We have a clear signal here that the nervousness of the world market is growing all the time, for decades, regardless of changing people, business entities or technology," notes Prof. Drożdż.

This observed dependence corresponds with another detected by Prof. Drożdż and his colleagues already in 2003. In their publication in Physica A: Statistical Mechanics and its Applications, one of the graphs shows the changes of the logarithm from the S&P 500 index starting from 1800 (values from before the introduction of the S&P 500 were reconstructed on the basis of historical data). The zig-zag curve bends along a sinusoid of increasing frequency, ever more dynamically ascending to the asymptote located around 2025. Each subsequent crash is preceded by smaller swings, quasi-mini-crashes, which have been called precursors. Many of the precursors have their own still smaller precursors, thus showing some self-similarity.

"The thing is that analogous self-similar dependence can also work on larger time scales. In which case, all previous crashes would only be precursors of a much larger and more dangerous event. When we come across a process with similar dynamics in physics, we talk about phase transition of the second type, such as the appearance or disappearance of magnetic properties in magnetic material around the Curie temperature," says Prof. Drożdż.

The question concerning the credibility of such a pessimistic forecast remains open. If financial markets do not change qualitatively in the coming years, the worst-case scenario of the development of events has the chance of becoming a reality. However, one must bear in mind the significant difference between the worlds of mathematics or physics and the world of finance. Mathematical laws and models constructed within physics are effective and relatively uncomplicated, among others due to the internal simplicity and immutability of the objects they concern. Financial markets are much more complex. Their participants are changeable: they remember, they learn, they can react both logically and emotionally. There is no shortage of examples proving that when knowledge about a law with the power to forecast is disseminated among a significant number of market participants, the market changes rapidly and the detected regularity disappears. Will the same happen in the case of the impending hyper-crash?

The problem is that we do not know what or how something would have to affect the global market to prevent the impending collapse. One remedy may be, for example, the emerging markets of cryptocurrencies, but will they really become one? Nobody knows. It is not even certain whether, knowing about the changes that are necessary, it would be possible to introduce them in just a few years – and it does not look like we have a longer period at our disposal. The future of the world economy from the mid-2020s thus appears very gloomy.

"Probably, we are the only ones who can't lose on this forecast. If the hyper-crash does occur, we will have shown the power of our multifractal statistical tools in a spectacular way. Personally, however, I would prefer for this not to happen. If this is the case and the hyper-crash does not occur, we will still have the quite acceptable interpretation that our forecast was... correct, but today's press release will have influenced the behaviour of market participants and, well, we have just saved the world!" notes Prof. Drożdż, slightly tongue-in-cheek.

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Kraków, 10 October 2018

BITCOIN BETTER THAN THE DOLLAR?

The name itself, cryptocurrency, does not inspire trust. Clusters of bits, considered by many as money of a doubtful nature. Advanced statistical analysis for the Bitcoin market carried out at the Institute of Nuclear Physics of the Polish Academy of Sciences in Kraków, however, has not shown any significant differences between its basic statistical parameters and their equivalents for respected financial markets. All indications are that Bitcoin is a better currency than it might seem at first glance.

Bitcoin, the first and the most popular cryptocurrency, is still treated by many investors with a deal of mistrust. A detailed statistical analysis of the Bitcoin market (BTC), conducted at the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Kraków, contradicts this common opinion. The analysis, published in the renowned scientific journal Chaos: An Interdisciplinary Journal of Nonlinear Science, shows Bitcoin – and potentially other cryptocurrencies – in a surprisingly positive light.

The credibility of traditional currencies seems to be, to a significant degree, a psychological artefact resulting from the nature of their evolution. Subconsciously, we believe that since at one time there used to be specific material commodities behind money, this is still the case today. But from the physical point of view, traditional currencies have for quite some time now been the same as cryptocurrencies from their moment of birth: clusters of bits in the memory of bank computers. The real value of a currency is now determined not by what lies behind it, but first and foremost by what is happening to it – that is, the market.

“When new emerging financial markets started to appear in Central and Eastern Europe after the collapse of socialism, the question of their stability naturally arose. A number of statistical criteria were identified at that time, making it easier to assess the maturity of the market. We were curious about the results we would get if we used them to look at the Bitcoin market, currently valued at hundreds of billions of dollars,” says Prof. Stanisław Drożdż (IFJ PAN, Kraków University of Technology).

An analysis was carried out for changes of the Bitcoin price in the period from 2012 to April 2018, posted in one-minute sequences. Rates of return were first in line. There is good quantitative evidence that in a mature market and in sufficiently short time scales their probability distributions are subject to inverse cubic law. Behind this dangerously sounding name there is a simple dependency: the distribution is described by the inversion of the third power of the examined quantity.

“Initially, the graphs we got were a bit crooked, which did not augur anything promising. But when we took a closer look at the data, suddenly it turned out that this crookedness originated from the first two years of the analysed period, that is, from the time when the market was just starting to shape itself. Later on, the rates of return fluctuated according to the inverse cubic law,” says Prof. Drożdż.

Will bitcoin topple the dollar of its pedestal? (Source: IFJ PAN).

The researchers' magnifying glass then focused on the volatility of rates of return. In mature global markets, the signs of returns (indicating whether we are earning or losing) are not correlated – and this is exactly what the Bitcoin market shows. However, time correlations in the dynamics of finance may appear in more subtle dependencies, for example in various forms of volatility clustering. We talk about this type of effect when the range of variability of the studied size is set at a more or less constant level for a certain period of time determining the size of the cluster, after which the range changes to sizes significantly smaller or larger than the previous one – and this type of variability evolves over time.

Volatility clustering is associated with another feature: the reluctance of the system to change trend. This reluctance is described by a parameter known as the Hurst exponent. It assumes values from 0 to 1. A value equal to 0.5 means that in the next measurement the tested value has the same probability of changing up as of changing down. Values below 0.5 indicate a tendency to fluctuate and correspond to situations where a rise in value increases the probability of a decrease (or vice versa). Values above 0.5 indicate the persistent nature of the changes: after an increase we have a higher probability of another increase, after a decrease we have a higher probability of a further fall. It turns out that for the Bitcoin market, the Hurst exponent approaches 0.5, which is characteristic of markets with a high reputation.

"One of the more sophisticated features signalling the maturity of a market is the multifractal nature of its characteristics. Multifractals are fractals of fractals, i.e. structures in which, in order to see self-similarity, various fractal fragments have to be magnified at different speeds. Multifractal analyses reveal dependencies existing in many scales. In the case of Bitcoin, we detected multifractality in the functions of fluctuations in rates of return, particularly evident in the last six months of the examined period. This was of the same type as for regular, mature markets, such as the stock, dollar, oil or bond markets," says Prof. Drożdż and concludes: "The most important statistical parameters of the Bitcoin market indicate very clearly that for many months now it has met all the important criteria of financial maturity. It seems that in the case of other cryptocurrencies it will be possible to expect a similar transformation. If this happens, the world's largest market, the Forex market, can look forward to very real competition."

Taken in a broader context, these statements lead to an intriguing observation. The real foreign exchange market matures with the help of a central bank or a government. Bitcoin, on the other hand, has matured on its own, solely due to its own characteristics, integrally incorporated in the foundations of its own market. So which of these currencies should we consider structurally better?

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Kraków, 10 January 2018

WHAT SORT OF STREAM NETWORKS DO SCIENTIFIC IDEAS FLOW ALONG?

When scientists have an interesting idea, the result is usually a joint publication. At the Institute of Nuclear Physics of the Polish Academy of Sciences in Kraków, it has been shown that tracking the dependencies between co-authors, one can not only see the paths along which scientific ideas flow, but also reconstruct the structure of scientific cooperation and detect emerging communities. Interestingly, the proposed method of analysis can be an effective tool to fight terrorists and... dishonest politicians.

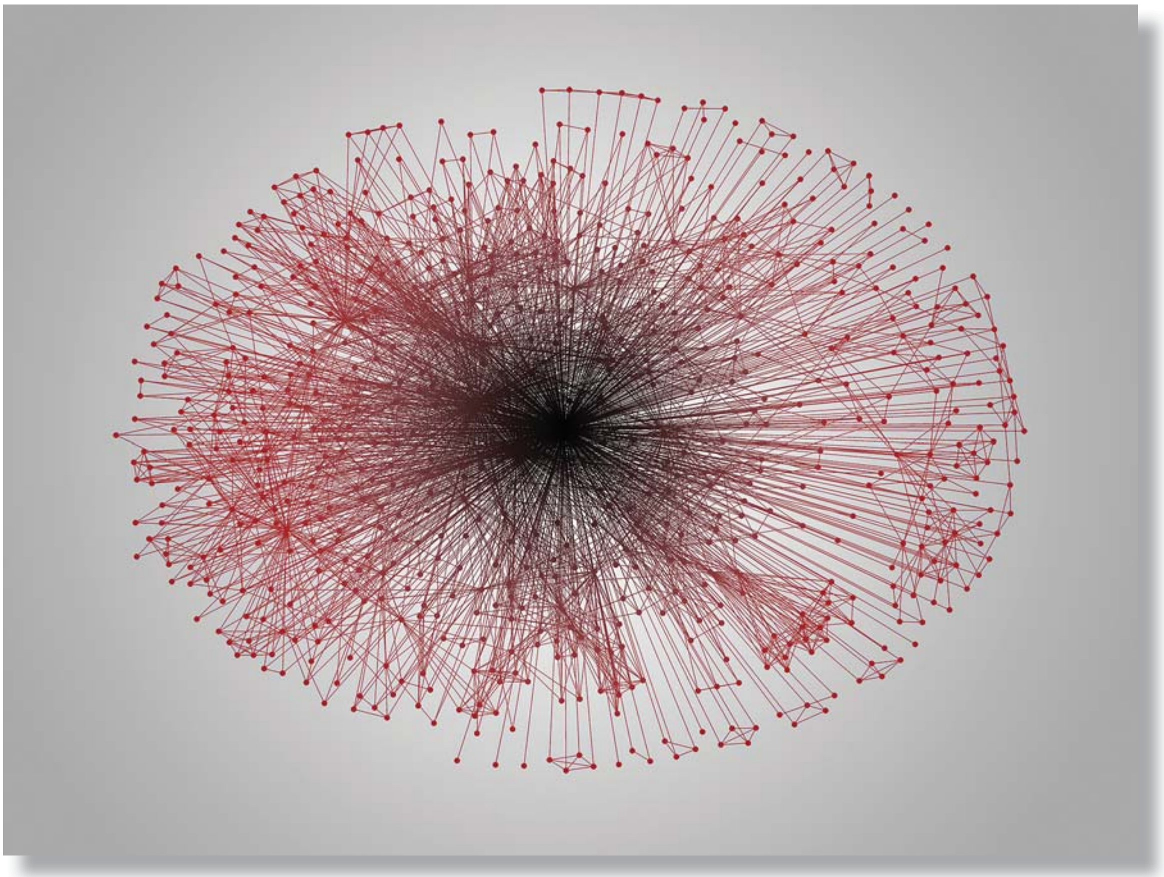
Panta rhei, everything flows. If Heraclitus of Ephesus was correct, not only rivers, but also ideas should flow. Tracking the flow of ordinary ideas can be difficult. In the case of scientific ideas, it is much easier: the researchers exchanging them usually produce joint publications. A group of researchers from the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Kraków, headed by Prof. Stanisław Drożdż (IFJ PAN, Kraków University of Technology), has analyzed the structures of links between the coauthors of scientific works forming around such eminent figures of modern science as Harry Eugene Stanley or Edward Witten. Illustrated in the form of graphs, the research results give a unique insight into the various forms of modern scientific cooperation.

“More and more people are now participating in scientific projects, and science itself is becoming more and more interdisciplinary. The scale of difficulty of the scientific issues under research is increasing, and we are also dealing with the rapid development of modern methods of communication. All this means that the links between scientists today have not only a significant complexity, but also constantly growing dynamics”, says Prof. Drożdż.

When starting to analyze the structures of scientific cooperation, the Kraków researchers made use of an idea connected with the figure of Paul Erdos, one of the greatest mathematicians of the twentieth century. Erdos was the author and co-author of approx. 1500 publications, with a total of over 500 people working together. Erdos’ exceptional scientific activity provoked mathematicians to invent Erdos numbers, reflecting the scientific ‘kinship’ of a given person with Erdos himself. According to the definition, Erdos was assigned the number 0, the scientist who wrote the publication with him – 1, the scientist who wrote a publication with a person having an Erdos number of 1 – the number 2, etc.

“Our idea was to analyze the scientific connections of several contemporary outstanding scholars in a similar way and to present them in the form of graphs, or sets of nodes and lines connecting them. Naturally, the central node of each graph was a scientist chosen by us; the remaining nodes corresponded to his next, closer or further associates. In this approach, the connections between nodes can be interpreted as flows of ideas resulting in writing a joint publication,” explains Prof. Drożdż.

The simplest graph produced according to the above principles would be a graph for Paul Dirac, an English physicist-theoretician who always published his works as the sole author. Dirac’s graph would



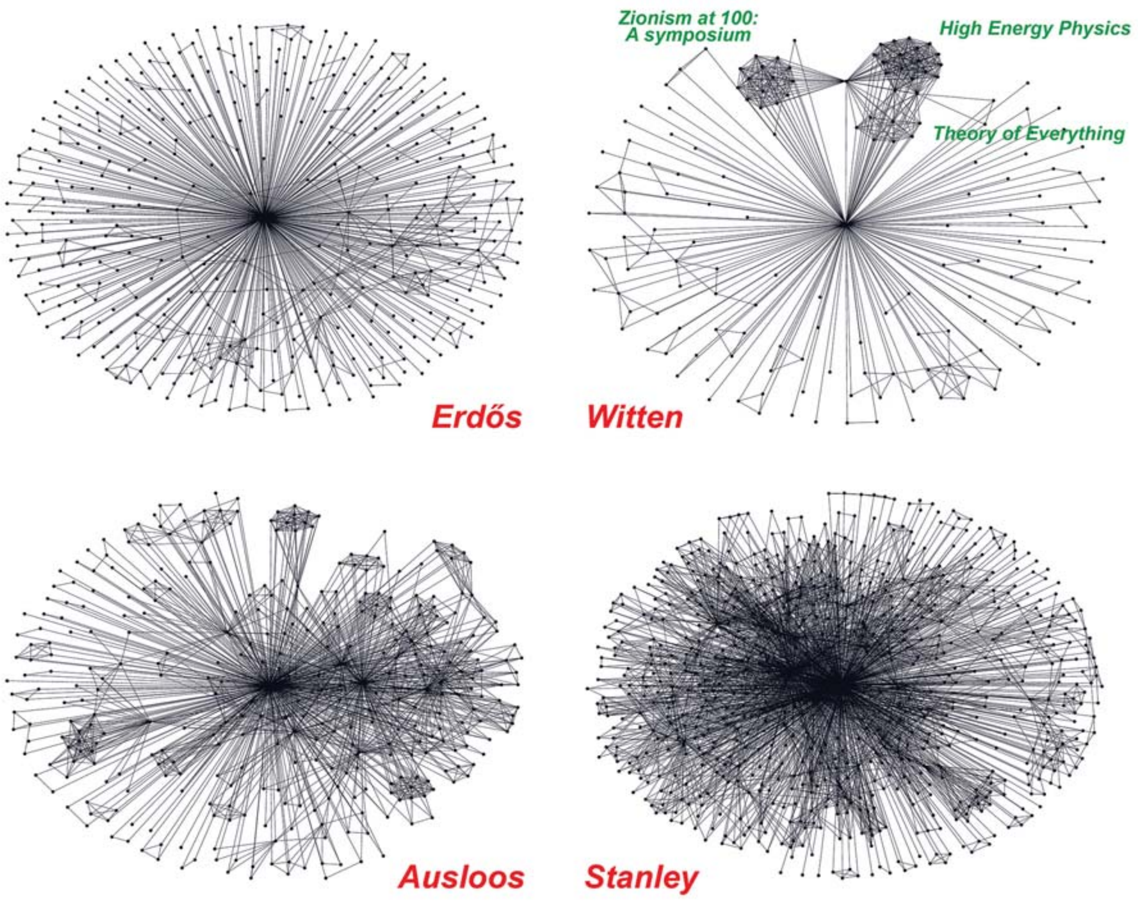
Graph showing the flow of ideas initiated by Prof. H. Eugene Stanley. Connections between collaborators show the existence of several clearly visible sub-networks, corresponding to scientific communities focusing on specific research topics. (Source: IFJ PAN).

therefore consist of just one node. There would be an equally uninteresting topology in graphs of modern scientific ventures in which hundreds of scientists participate, assigned to many subsequent publications in an often purely administrative manner (this is a common situation in the case of complex, long-term experiments, such as LHC and LIGO gravitational wave detectors). These graphs would consist of a large number of nodes, most of them connecting with all the others. The network of connections here is so dense that it is difficult to find any interesting dependencies.

The graph of Erdos himself also turned out to be moderately interesting: numerous links radiate from the central node to many neighboring nodes, and almost always ended there. Only some of the nodes symbolizing Erdos' associates were connected to each other. The shape of the structure was probably influenced here by the fact that the communication tools existing in the 20th century were much more poorly developed than at present and it was much more difficult for many scientists, especially the lesser known ones, to establish new contacts.

"When Erdos was dealing with the mathematical description of networks reflecting human interactions, he predicted that the connection structure would be quite democratic: most nodes would be in direct contact with a comparable, though not very large, number of other nodes. But at the turn of the century, for the first time, a large network was visualized: the Internet. Suddenly, it turned out that this network has a much less democratic structure: only 20% of nodes have access to 80% of connections. We discovered a self-organization resulting from the operation of a similar power law in the network of Professor Stanley", notes Prof. Drożdż.

Prof. H. Eugene Stanley is an interdisciplinary statistical physicist, co-author of several dozen publications a year. His Hirsch index, reflecting the number and response of scientific publications, is one of the highest in the natural and technical sciences. In the idea flow network surrounding Stanley there are many highlighted nodes, around which there are more nodes, representing scientists developing their own research, and inspired by Stanley's works. Some of them, corresponding



Graphs showing scientific connections initiated by Paul Erdos, Edward Witten, Marcel Ausloos and H. Eugene Stanley. In the case of Edward Witten there are three clearly visible sub-networks, corresponding to specific topics. (Source: IFJ PAN).

to such figures of science as Marcel Ausloos, Shlomo Havlin or Sergey Buldyrev, influenced their colleagues in a similarly creative way, focusing their own communities around themselves. As a result, the Stanley network acquired hierarchical features, in many places demonstrating the self-similarity characteristic of fractal objects.

The hierarchy of the ideas network is neither a universal feature nor is it characteristic of the outstanding figures of today's science. The graph illustrating the scientific connections of Edward Witten, a well-known mathematical physicist developing string theory, turned out to have a general outline resembling a simple star, as was so clearly visible in Erdos's graph. In Witten's, however, the presence of several distinct sub-structures separated from each other is visible. They correspond to communities dealing with specific topics, e.g. the theory of everything or the physics of high energies.

"The mathematical procedure proposed by us makes it possible to detect links between people which are not always perceived at first glance. The existence of some communities only became obvious when, constructing the graphs, we took into account the fact that connections between nodes can have different strengths. Some authors may, after all, publish joint works many times," notes Prof. Drożdż.

In networks of interpersonal contacts, mathematics enables the revealing of the presence of communities connected by common ideas. The methods of analysis proposed by the Kraków physicists could thus be used for other purposes, e.g. to follow the structures of terrorist organizations. But it is possible to imagine other, more peaceful applications. For example, who knows if modern democracies would not function more effectively if, before elections, each of us could see a graph illustrating the network of the candidate's connections with other people next to his or her photo?

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The Henryk Niewodniczański
Institute of Nuclear Physics
Polish Academy of Sciences

Kraków, 21 January 2016

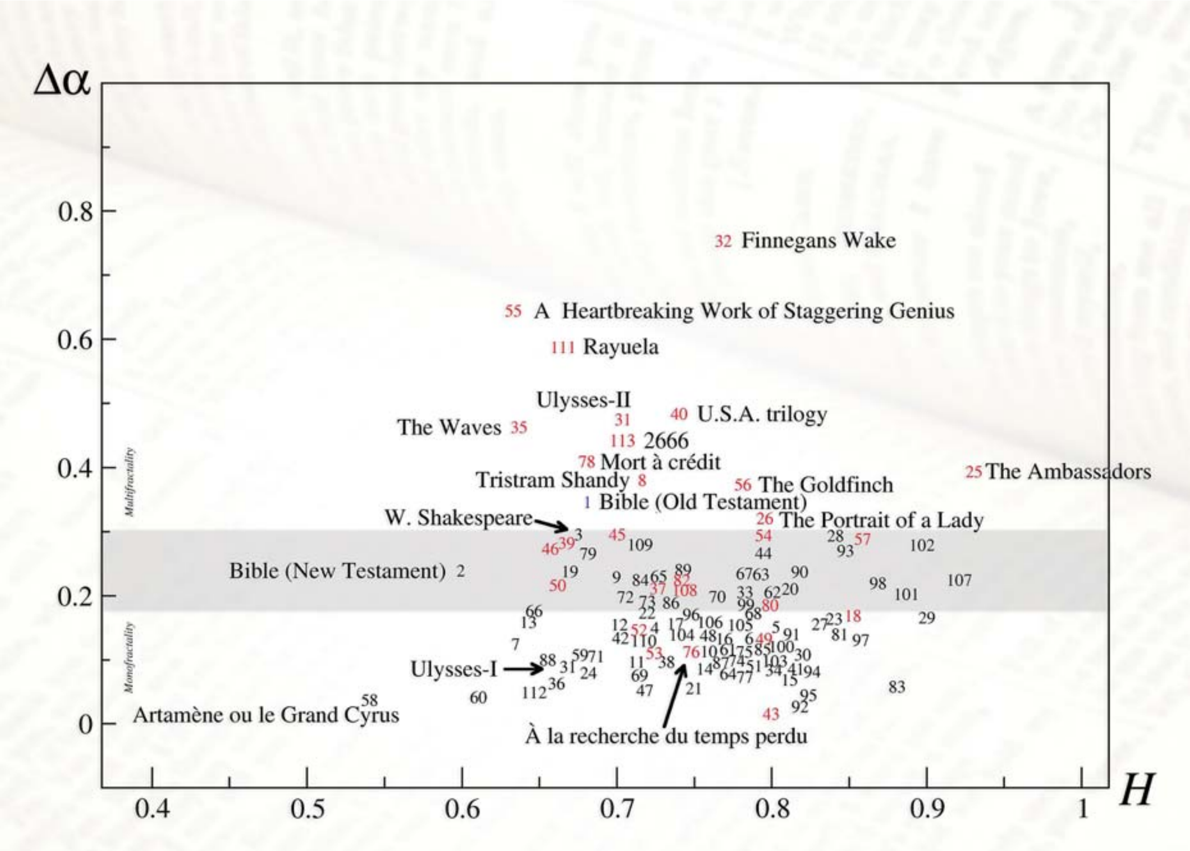
THE WORLD'S GREATEST LITERATURE REVEALS MULTIFRACTALS AND CASCADES OF CONSCIOUSNESS

James Joyce, Julio Cortazar, Marcel Proust, Henryk Sienkiewicz and Umberto Eco. Regardless of the language they were working in, some of the world's greatest writers appear to be, in some respects, constructing fractals. Statistical analysis carried out at the Institute of Nuclear Physics of the Polish Academy of Sciences, however, revealed something even more intriguing. The composition of works from within a particular genre was characterized by the exceptional dynamics of a cascading (avalanche) narrative structure. This type of narrative turns out to be multifractal. That is, fractals of fractals are created.

As far as many bookworms are concerned, advanced equations and graphs are the last things which would hold their interest, but there's no escape from the math. Physicists from the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ) in Kraków, Poland, performed a detailed statistical analysis of more than one hundred famous works of world literature, written in several languages and representing various literary genres. The books, tested for revealing correlations in variations of sentence length, proved to be governed by the dynamics of a cascade. This means that the construction of these books is in fact a fractal. In the case of several works their mathematical complexity proved to be exceptional, comparable to the structure of complex mathematical objects considered to be multifractal. Interestingly, in the analyzed pool of all the works, one genre turned out to be exceptionally multifractal in nature.

Fractals are self-similar mathematical objects: when we begin to expand one fragment or another, what eventually emerges is a structure that resembles the original object. Typical fractals, especially those widely known as the Sierpinski triangle and the Mandelbrot set, are monofractals, meaning that the pace of enlargement in any place of a fractal is the same, linear: if they at some point were rescaled x number of times to reveal a structure similar to the original, the same increase in another place would also reveal a similar structure.

Multifractals are more highly advanced mathematical structures: fractals of fractals. They arise from fractals 'interwoven' with each other in an appropriate manner and in appropriate proportions. Multifractals are not simply the sum of fractals and cannot be divided to return back to their original components, because the way they weave is fractal in nature. The result is that in order to see a structure



Multifractality in literature. The numbers correspond to the position of a given literary work in the pool (as in the detailed list available in the scientific publication). The color red indicates works traditionally belonging to the genre of stream of consciousness. On the vertical axis is the width of the multifractal spectrum – in those closer to unity, the text has a more multifractal structure. The horizontal axis is the degree of persistence H, in this case in the length of the sentences. A higher value of H means that there is a greater probability of a long sentence immediately following a long one, and a short one following another short. H = 0.5 means the lack of such a tendency. (Source: IFJ PAN).

similar to the original, different portions of a multifractal need to expand at different rates. A multifractal is therefore non-linear in nature.

"Analyses on multiple scales, carried out using fractals, allow us to neatly grasp information on correlations among data at various levels of complexity of tested systems. As a result, they point to the hierarchical organization of phenomena and structures found in nature. So we can expect natural language, which represents a major evolutionary leap of the natural world, to show such correlations as well. Their existence in literary works, however, had not yet been convincingly documented. Meanwhile, it turned out that when you look at these works from the proper perspective, these correlations appear to be not only common, but in some works they take on a particularly sophisticated mathematical complexity," says Prof. Stanisław Drożdż (IFJ PAN, Kraków University of Technology).

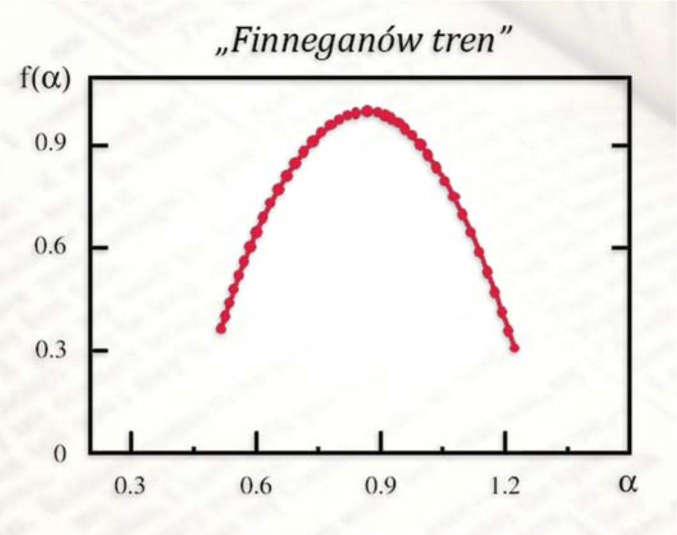
The study involved 113 literary works written in English, French, German, Italian, Polish, Russian and Spanish by such famous figures as Honore de Balzac, Arthur Conan Doyle, Julio Cortazar, Charles Dickens, Fyodor Dostoevsky, Alexandre Dumas, Umberto Eco, George Elliot, Victor Hugo, James Joyce, Thomas Mann, Marcel Proust, Wladyslaw Reymont, William Shakespeare, Henryk Sienkiewicz, JRR Tolkien, Leo Tolstoy and Virginia Woolf, among others. The selected works were no less than 5,000 sentences long, in order to ensure statistical reliability.

To convert the texts to numerical sequences, sentence length was measured by the number of words (an alternative method of counting characters in the sentence turned out to have no major impact on the conclusions). The dependences were then searched for in the data – beginning with the simplest, i.e. linear. This is the posited question: if a sentence of a given length is x times longer than the sentences of different lengths, is the same aspect ratio preserved when looking at sentences respectively longer or shorter?

"All of the examined works showed self-similarity in terms of organization of the lengths of sentences. Some were more expressive – here The Ambassadors by Henry James stood out – while others to far less of an extreme, as in the case of the French seventeenth-century romance Artamene ou le Grand Cyrus. However, correlations were evident, and therefore these texts were the construction of a fractal," comments Dr. Paweł Oświęcimka (IFJ PAN), who also noted that fractality of a literary text will in practice never be as perfect as in the world of mathematics. It is possible to magnify mathematical fractals up to infinity, while the number of sentences in each book is finite, and at a certain stage of scaling there will always be a cut-off in the form of the end of the dataset.

Things took a particularly interesting turn when physicists from the IFJ PAN began tracking nonlinear dependence, which in most of the studied works was present to a slight or moderate degree. However, more than a dozen works revealed a very clear multifractal structure, and almost all of these proved to be representative of one genre, that of stream of consciousness. The only exception was the Bible, specifically the Old Testament, which has so far never been associated with this literary genre.

"The absolute record in terms of multifractality turned out to be Finnegan's Wake by James Joyce. The results of our analysis of this text are virtually indistinguishable from ideal, purely mathematical multifractals," says Prof. Drożdż.

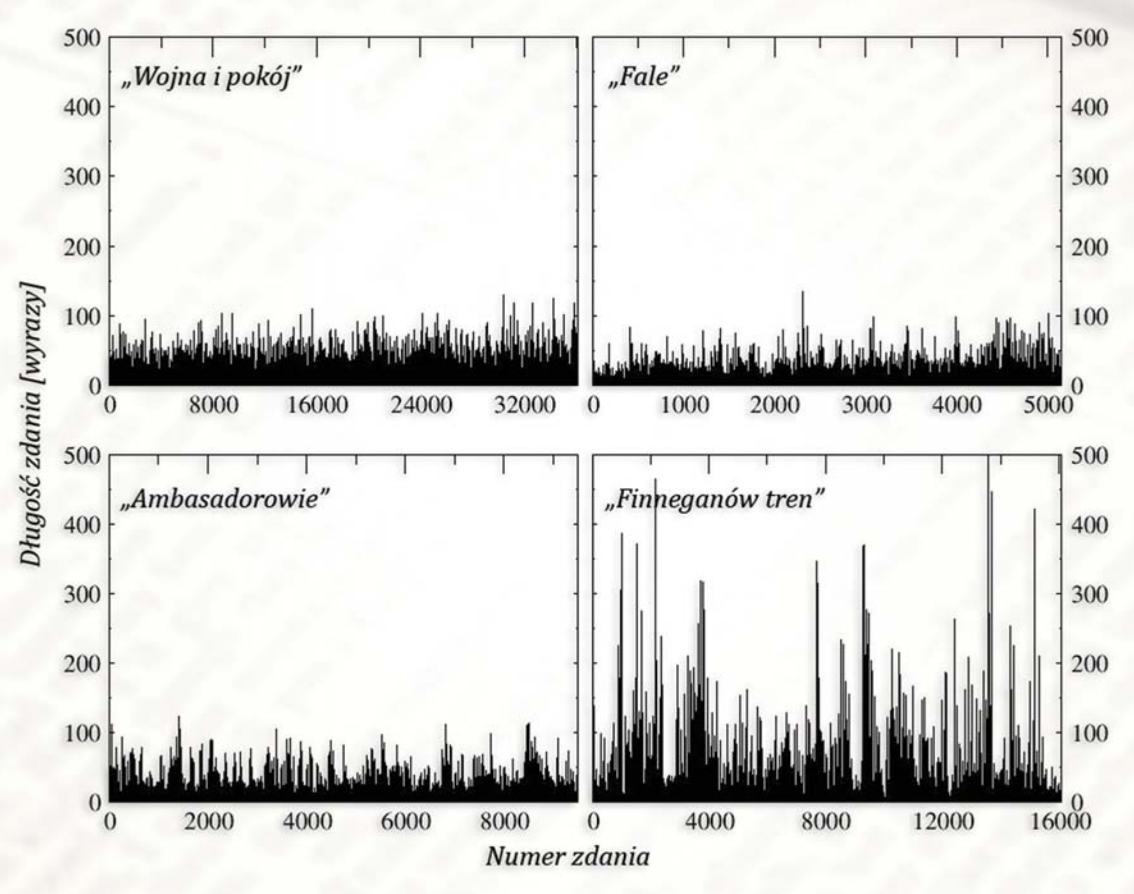


Multifractal analysis of Finnegan's Wake by James Joyce. The ideal shape of the graph is virtually indistinguishable from the results for purely mathematical multifractals. The horizontal axis represents the degree of singularity, and the vertical axis shows the spectrum of singularity. (Source: IFJ PAN).

The most multifractal works also included A Heartbreaking Work of Staggering Genius by Dave Eggers, Rayuela by Julio Cortazar, The US Trilogy by John Dos Passos, The Waves by Virginia Woolf, 2666 by Roberto Bolano, and Joyce's Ulysses. At the same time a lot of works usually regarded as stream of consciousness turned out to show little correlation to multifractality, as it was hardly noticeable in books such as Atlas Shrugged by Ayn Rand and A la recherche du temps perdu by Marcel Proust.

"It is not entirely clear whether stream of consciousness writing actually reveals the deeper qualities of our consciousness, or rather the imagination of the writers. It is hardly surprising that ascribing a work to a particular genre is, for whatever reason, sometimes subjective. We see, moreover, the possibility of an interesting application of our methodology: it may someday help in a more objective assignment of books to one genre or another," notes Prof. Drożdż.

Multifractal analyses of literary texts carried out by the IFJ PAN have been published in Information Sciences, the prestigious journal of computer science. The publication has undergone rigorous verification: given the interdisciplinary nature of the subject, editors immediately appointed up to six reviewers.



Sequences of sentence lengths (as measured by number of words) in four literary works representative of various degrees of cascading character. (Source: IFJ PAN).

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Kraków, 30 November 2016

OVERLOOKED ELEMENTS OF LANGUAGE AND LITERATURE PLAY A KEY ROLE

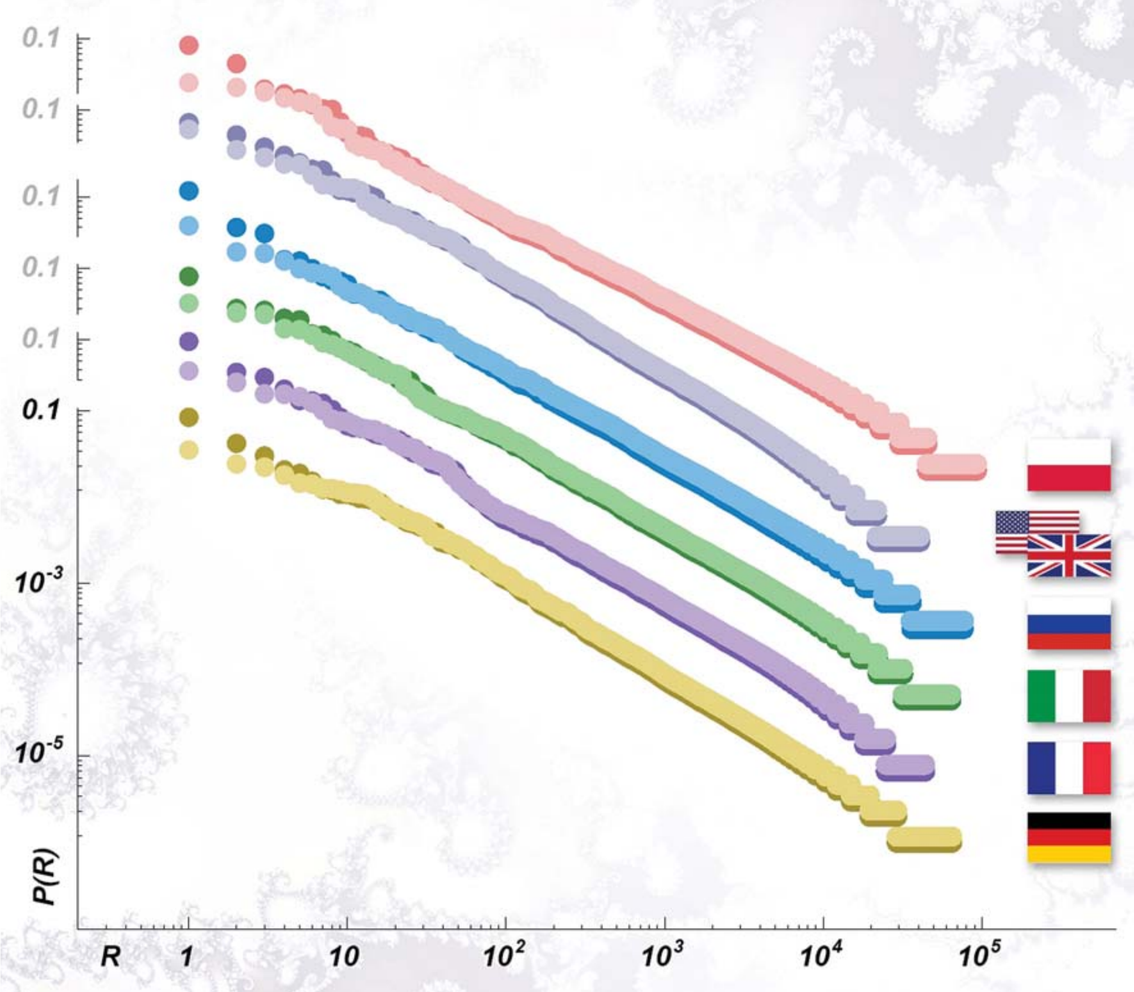
Everything is pointing towards success in unravelling the mysteries inherent in every human language, which for nearly 100 years have been an object of intrigue for mathematicians and linguists working on studies into statistics of literature. New analysis of the frequencies of word occurrence in the most famous works of literature, undertaken at the Institute of Nuclear Physics of the Polish Academy of Sciences in Kraków, have shown that our languages are structurally more complex and more exhaustive than they ever before seemed.

It's been said that 80% of a person's success is achieved from only 20% of their efforts. That famous ratio holds up over a surprising number of domains. For example, it is apparent that in every language, whether spoken or written, that 80% of all statements are made up of merely 20% of the most common words. One possible reason is that when we talk to each other we want to convey as much content as possible with the least effort (among other factors). This phenomenon of dependency was one of the earliest of the series of power laws to be discovered, and is known as Zipf's law. It has turned out that it is not as trivial as it might seem at first glance. Scientists from the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Kraków have established that certain puzzling features of Zipf's law, for decades a source of intrigue for those involved in the statistical analysis of literary texts, are a consequence of neglecting one of the basic components of language.

"A year ago, with the help of detailed multiscale analysis we showed that the length of sentences in literature – that is, the distance between the sentence-ending punctuation – shows a very complex dependency of a multifractal nature, especially evident in the works of the genre known as stream of consciousness. It was an intriguing result that prompted us to look with greater attention to the role of other punctuation marks, especially in the context of Zipf's law. The results have provided us with a new way to look at not only the role of punctuation among languages, but even within the same language," says Prof. Stanisław Drożdż (IFJ PAN, Kraków University of Technology).

Charts showing Zipf's law for literary texts are created with the use of an uncomplicated procedure. Each word is counted per how often it occurs in the text. Those which occur most often are assigned to rank 1, the next are placed in rank 2, etc. (in richer texts the ranks can even exceed ten thousand, and exotic words usually appear far above rank 1,000). Zipf's law states that the probability of a word is inversely proportional to its rank: the larger the rank, the lower the probability. Graphs showing the relationship are (on a logarithmic scale) on a straight line.

Ever since the American linguist George Zipf popularized his law, it never ceases to amaze. How can something as complex as a structure created using language be described by such a straightforward law? There were more puzzles. Quite early on it was noticed that the graphs relating to the frequency of words for ranks closer to unity curve slightly downward from a straight line. That deviation particularly intrigued Benoit Mandelbrot,



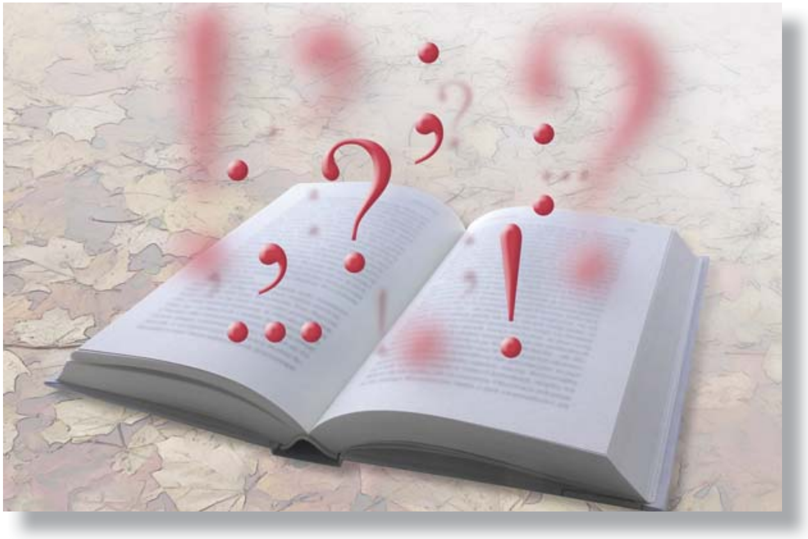
Recent research conducted at the Institute of Nuclear Physics of the Polish Academy of Sciences in Kraków reveals that in narrative texts punctuation plays as important role as words. (Source: IFJ PAN).

the great French mathematician of Polish origin, who worked on this issue for many years. He even suggested his own amendment to Zipf's original law, to better map deviation (it is worth mentioning at this point, that his work on Zipf's law, among other interests, helped guide him toward the concept of fractals).

In this latest study, the physicists at IFJ PAN analyzed texts written in six Indo-European languages, two of each belonging to these groups: Germanic (English and German), Romance (French and Italian) and Slavic (Polish and Russian). The selected literary works come from the archives of Project Gutenberg (www.gutenberg.org), and each is at least five thousand sentences long. For each of the languages at least five different texts were chosen, and merged to form one text totaling about a million words. All words unrelated to the transmitted content were removed, such as 'chapter', 'part' and 'epilogue', and for all language-specific abbreviations like 'Mr.' and 'Dr.' the dots were removed and they were treated as separate words. Also deleted were annotations and footnotes, page numbers, and punctuation marks of a more typographical nature: quotation marks and parentheses.

"The eventual punctuation marks considered for analysis were commas, colons, and semicolons, and those which end sentences: periods, exclamation marks, question marks, and ellipses," specifies Prof. Jaroslaw Kwapien (IFJ PAN), one of the co-authors of the scientific paper published in the renowned journal Information Sciences.

Among the studied works of literature are: 1984 by George Orwell, Moby Dick by Herman Melville, Ulysses by James Joyce, Gulliver's Travels by Jonathan Swift, Gone with the Wind by Margaret Mitchell, Thus Spake Zarathustra by Friedrich Nietzsche, The Trial by Franz Kafka, The Magic Mountain by Thomas Mann, Madame Bovary by Gustave Flaubert, The Phantom of the Opera by Gaston Leroux, Foucault's Pendulum by Umberto Eco, Giacinta by Luigi Capuana, The Spring to Come by



Probability of occurrence of words (vertical axis) versus their rank (horizontal axis) for corpora representing different European languages. The original puzzling downward departure from the straight line for ranks close to unity, observed for the ordinary words (brighter colors), disappears (corresponding darker colors) when the punctuation marks are also taken into account. (Source: IFJ PAN)

Stefan Zeromski, The Promised Land by Wladyslaw Reymont, The Doll by Boleslaw Prus, Anna Karenina and War and Peace by Leo Tolstoy, and The Brothers Karamazov by Fyodor Dostoevsky.

Including punctuation marks led a to highly significant result: the downward bend seen on the original Zipf's graph for ranks close to unity practically disappears. The 'new words' (the punctuation marks) fall into place almost exactly so that together with the 'real words' the rank-frequency distribution now fits into the straight line for all ranks, thus extending the original form of Zipf's law to all the scales. Mandelbrot's amendment turned out to be generally redundant.

"When we begin to treat punctuation marks like they are words they start occupying ranks closer to unity and with frequency relative to the ordinary words, so that the original Zipf departure from the straight line for small ranks basically disappears. Thus, upon considering punctuation, our language emerges as a more consistent composition! That's why it seems well-founded to say that punctuation is just as important to a language as its words, and language without it is basically incomplete," says Prof. Drożdż.

New graphs reveal several novel and significant features. For example, considering punctuation in Slavic languages the thus generalized Zipf rank-frequency distribution falls almost perfectly along one line for all ranks. Some trace of the original Zipf's deviation remains for Romance and Germanic languages, and this is especially apparent with the English language.

"What if while analyzing non-Slavic languages we didn't consider their additional specific features?" wonders Prof. Drożdż, being mindful of other interesting interpretations: "Might it also be that the cause of incomplete reduction of curvature is rooted in the language itself? For instance, in English there might be a source of easily discernable tendencies of authors to limit the number of punctuation marks. If this last cause holds true, it might be worth asking the question: can we be sure that excessive reduction of punctuation is a beneficial action that doesn't harm the integrity of the language?"

The latest discovery from the IFJ PAN could potentially have implications beyond linguistic research. Zipfian deviation for ranks closer to unity is being observed in many areas and has diverse origins, which are often not fully understood. In the graphs prepared based on literary works the deviation disappears after accounting for the common factor, but so far this has been considered negligible. Perhaps in other cases it could also be eliminated by including elements which have thus far been deprived of a greater role.

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EXPLORING THE FOUNDATIONS OF PHYSICAL REALITY

Kraków, 8 November 2018

SPACETIME – A CREATION OF WELL-KNOWN ACTORS?

Most physicists believe that the structure of spacetime is formed in an unknown way in the vicinity of the Planck scale, i.e. at distances close to one trillionth of a trillionth of a metre. However, careful considerations undermine the unambiguity of this prediction. There are quite a few arguments in favour of the fact that the emergence of spacetime may occur as a result of processes taking place much "closer" to our reality: at the level of quarks and their conglomerates.

What is spacetime? The absolute, unchanging, ever- and omni-present arena of events? Or perhaps it is a dynamic creation, emerging in some way on a certain scale of distance, time or energy? References to the absolute are not welcome in today's physics. It is widely believed that spacetime is emergent. It is not clear, however, where the process of its emergence takes place. The majority of physicists tend to suppose that spacetime is created on the Planck scale, at distances close to one trillionth of a trillionth of a metre ($\sim 10^{-35}$ m). In his article in Foundations of Science, Professor Piotr Żenczykowski from the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Kraków systematizes the observations of various authors on the formation of spacetime, and argues that the hypothesis about its formation at the scale of quarks and hadrons (or quark aggregates) is quite sensible for a number of reasons.

Questions about the nature of space and time have puzzled humanity since at least antiquity. Are space and time separated from matter, creating a "container" for motions and events occurring with the participation of particles, as Democrit proposed in the 5th century BC? Or perhaps they are attributes of matter and could not exist without it, as Aristotle suggested a century later? Despite the passage of millennia, these issues have not been resolved yet. Moreover, both approaches – albeit so contradictory! – are deeply ingrained into the pillars of modern physics. In quantum mechanics, events take place in a rigid arena with uniformly flowing time. Meanwhile, in the general theory of relativity, matter deforms elastic spacetime (stretching and twisting it), and spacetime tells particles how to move. In other words, in one theory the actors enter an already prepared stage to play their roles, while in the other they create the scenography during the performance, which in turn influences their behaviour.

In 1899, German physicist Max Planck noticed that with certain combinations of some constants of nature, very fundamental units of measurement could be obtained. Only three constants – the speed of light c, the gravitational constant G and Planck's constant h – were sufficient to create units of distance, time and mass, equal (respectively) to $1.62 \cdot 10^{-35}$ m, $5.39 \cdot 10^{-44}$ s oraz $2.18 \cdot 10^{-5}$ g. According to today's mainstream belief, spacetime would be created at Planck's length. In fact, there are no substantive arguments for the rationality of this hypothesis.

Both our most sophisticated experiments and theoretical descriptions reach the scale of quarks, i.e. the level of 10^{-18} m. So how do we know that along the way to Planck's length – over a dozen

Just as the interactions between sand grains form a smooth surface on the beach, the spacetime known to us could be the result of relations between quarks and their conglomerates. (Source: IFJ PAN).

consecutive, ever smaller orders of magnitude – spacetime retains its structure? In fact, we are not even sure if the concept of spacetime is rational at the level of hadrons! Divisions cannot be carried out indefinitely, because at some stage the question of the next smaller part simply ceases to make sense. A perfect example here is temperature. This concept works very well on a macro scale, but when, after subsequent divisions of matter, we reach the scale of individual particles, it loses its raison d'etre.

"At present, we first seek to construct a quantized, discrete spacetime, and then 'populate' it with discrete matter. However, if spacetime was a product of quarks and hadrons, the dependence would be reversed: the discrete character of matter should then enforce the discreteness of spacetime!" says Prof. Żenczykowski, and adds: "Planck was guided by mathematics. He wanted to create units from the fewest constants possible. But mathematics is one thing, and the relationship with the real world is another. For example, the value of Planck's mass seems suspicious. One would expect it to have a value rather more characteristic for the world of quanta. In the meantime, it corresponds to approximately 1/10 of the mass of a flea, which is most certainly a classical object."

Since we want to describe the physical world, we should lean towards physical rather than mathematical arguments. And so, when using Einstein's equations we describe the Universe at large scales, and it becomes necessary to introduce an additional gravitational constant, known as the cosmological constant Lambda. If, therefore, while constructing fundamental units, we expand the original set of three constants by Lambda, in the case of masses we obtain not one but three fundamental values: $1.39 \cdot 10^{-65}$ g, 2.14 · 1056 g, and $0.35 \cdot 10^{-24}$ g. The first of these could be interpreted as a quantum of mass, the second is at the level of the mass of the observable Universe, and the third is similar to the masses of hadrons (for example, the mass of a neutron is $1.67 \cdot 10^{-24}$ g). Similarly, after taking Lambda into account, a unit of distance of $6.37 \cdot 10^{-15}$ m appears, very close to the size of hadrons.

"Playing games with constants, however, can be risky because a lot depends on which constants we choose. For example, if spacetime was indeed a product of quarks and hadrons, then its properties, including the velocity of light, should also be emergent. This in turn means that the velocity of light should not be among the basic constants," notices Prof. Żenczykowski.

Another factor in favour of the formation of spacetime at the scale of quarks and hadrons are the properties of the elementary particles themselves. For example, the Standard Model does not explain why there are three generations of particles, where their masses come from, or why there are so-called internal quantum numbers, which include isospin, hypercharge and colour. In the picture presented by Prof. Żenczykowski these values can be linked to a certain six-dimensional space created by the positions of particles and their momenta. The space thus constructed assigns the same importance to the positions of particles (matter) and their movements (processes). It turns out that the properties of masses or internal quantum numbers can then be a consequence of the algebraic properties of 6D space. What's more, these properties would also explain the inability to observe free quarks.

"The emergence of spacetime may be associated with changes in the organization of matter occurring at a scale of quarks and hadrons in the more primary, six-dimensional phase space. However, it is not very clear what to do next with this picture. Each subsequent step would require going beyond what we know. And we do not even know the rules of the game that Nature is playing with us, we still have to guess them! However, it seems very reasonable that all constructions begin with matter, because it is something physical and experimentally available. In this approach, spacetime would only be our idealization of relations among elements of matter," sums up Prof. Żenczykowski.

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The Henryk Niewodniczański
Institute of Nuclear Physics
Polish Academy of Sciences

Kraków, 14 February 2019

BOTH QUANTUM AND CLASSICAL – STATES FROM THE BORDERLAND OF WORLDS

There is a reason why quantum properties seem extremely exotic: our senses simply cannot see them in the world around us. It turns out, however, that the boundary between exotic quantum reality and classical reality does not have to be as strict as it may seem. Researchers from Kraków, Poland, have shown that there can be quantum states that on one hand exhibit the most characteristic of quantum features, whilst being as close to classical states as is possible in quantum mechanics.

The everyday, classical world is dramatically different from the world of quantum mechanics. In the former, in principle, everything can be precisely measured and predicted. All classical objects exist here in a specific place in space, in a particular state, and they are not able to react immediately to what is happening to other objects that are distant from them. Meanwhile, in the world of quantum mechanics, instead of certainty, we have only probability. Objects can be in different places and states at the same time and due to the phenomenon of quantum entanglement, they seem to react immediately to what has happened to their partners that can be any distance away from them.

Theoreticians from the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Kraków collaborating with mathematicians from the Institute of Mathematics of the Jagiellonian University (IM UJ), however, have shown that both worlds may have more in common with each other than one would suppose. In a publication in Coherent States and Their Applications: A Contemporary Panorama, they describe the unique quantum states of a two-particle system simultaneously exhibiting both classical and quantum features.

It is widely believed that in the classical world quantum effects are imperceptible and in describing the classical system they can safely be omitted. Such thinking leads to the naive view that if something behaves classically, it does not behave in a quantum manner – and vice versa. This is not so in reality. The classical world is a world of systems composed of a huge number of quantum objects, and its everyday observable properties are, as the principle of correspondence would suggest, a borderline case of the properties of the latter. Understanding the nature of this borderline is not easy, and physicists still have much to do in this field.

"In our deliberations, we addressed a problem posed over 80 years ago by one of the co-founders of quantum mechanics, Erwin Schrödinger. It deals with the possibility of the co-existence in a single quantum system of properties that are separately considered to be quantum or classical. We tried to find the answer to the question of whether they can occur simultaneously or whether they are mutually exclusive. Together with Prof. Franciszek Szafraniec from the Jagiellonian University's Institute of Mathematics we showed that in a system of two quantum particles certain classical and quantum features can indeed coexist amicably," says Dr. Katarzyna Górska (IFJ PAN).

Under certain conditions, some quantum states (represented by rotating coins) and classical states (coins lying on the table) may coexist amicably, as demonstrated by scientists from the Institute of Nuclear Physics of the Polish Academy of Sciences and the Jagiellonian University (Source: IFJ PAN).

The flagship illustration of the non-intuitiveness of the world of quanta is the famous Heisenberg uncertainty principle. It states that for any particle (for simplicity with a fixed mass) it is not possible to simultaneously measure, with any precision, its position or velocity. If we know the exact position of the particle, we will not know anything about its velocity; if we know the exact velocity, we will not be able to indicate the position. Moreover, the uncertainty of the measurements depends on the state in which the particle is, and since quantum particles can be in various states, the uncertainties can be different. States in which the Heisenberg uncertainty principle is minimized are called coherent and are highly similar to states observed in classical systems.

The basic – and at the same time extremely interesting – property of quantum systems is their capability of superposition, that is, being in a state that is a mixture (combination) of certain particular (and at the same time observable) states called base states. In the classical world, such quantum superposition does not exist, but we can try to imagine it with a rather intuitive example: a coin spinning on a table. Here the coin is in a state reminiscent of the superposition of two base states: heads or tails. We can even carry out a "measurement", that is, press the spinning coin to the table top (or wait for gravity to do this for us). We then destroy the superposition and the coin shifts to one of two, most classical, states: it lies with either heads or tails on top.

"The above analogy is far from complete. The coin is a classical object, and when it spins, heads and tails remain unchanged all the time, and the coin cannot choose between them. So we really have three significantly different states in this system," explains Dr. Andrzej Horzela (IFJ PAN). "Meanwhile, in quantum superposition there is only one state. Recalling the analogy of the spinning coin, we should see in it some form of head-tails or maybe tails-heads. Something that escapes our imaginations, our classical intuition or maybe even our common sense. And what if our quantum state is additionally a coherent state, and therefore one regarded as closest to the classical states in which we always have either heads or tails?"

Entanglement is considered as being the most important sign of the quantum nature of a system, coherence – as a feature signalling closeness to the classical state. The states found by the Kraków-based physicists are, at least in the mathematical sense, simultaneously coherent and entangled in relation to the entire system of both particles.

"Quantum states of a similar nature have already been considered in the past. They have even been produced experimentally, starting from two coherent states, which were then entangled. The state thus obtained is entangled, but as a whole it does not have to be coherent. Our states are constructed in a way that ensures that they remain simultaneously coherent (i.e. they minimize the uncertainty principle) and entangled. Thus, they can be interpreted as objects that exhibit properties on the one hand close to classical and on the other considered as typically quantum. The manifestation of their quantum nature is that they describe a system of two particles, which cannot be separated even when these particles do not interact with each other," explains Dr. Horzela.

The result of the Kraków scientists is mathematical in nature. The question remains whether the discovered states can be created in the laboratory. It seems that there are no contraindications preventing their existence. The final answer, however, will only come from experience. The experimentalists, especially scientists dealing with quantum optics, thus have a great scope of activity ahead of them.

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POPULARIZING ACTIVITY AND PRESENCE OF IFJ PAN IN THE MEDIA

POPULARIZING ACTIVITY

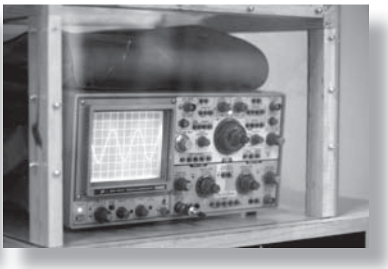
The Henryk Niewodniczański Institute of Nuclear Physics the Polish Academy of Sciences actively participates in regular public large-scale popularization events. Some of these events are organized together with other scientific institutions every year. The most important of them are, among others:

FESTIVAL OF SCIENCE AND THE ARTS IN KRAKÓW

Among the numerous stands presented by Kraków universities and scientific institutions, each year during the festival there are exhibitions prepared by the staff and Ph.D. students of the Institute. Visitors to the IFJ PAN stand can participate, for example, in a "journey to the beginning of the Universe", find out what it is made of and what its fate will be, and learn about the research carried out at the European Centre for Nuclear Research CERN. Those interested can explore the secrets of proton radiotherapy of cancer, in particular get to know the operation of the cyclotron and therapeutic stations at the Cyclotron Centre Bronowice (CCB). In addition, scientists from the Institute explain to those interested what gravitational waves, dark matter and black holes are, and what it is about "catching" cosmic ray particles, using an application downloaded on their smartphones, i.e. what is the international project CREDO (Cosmic-Ray Extremely Distributed Observatory), initiated at the Institute in 2016.

LESSER POLAND RESEARCHERS' NIGHT

The organization of the Lesser Poland Researchers' Night is every year the largest science-promoting undertaking of the Institute. In tents located in the green areas of the Institute, research staff and Ph.D. students show the research and achievements of six scientific divisions of IFJ PAN, through presentations and experiments with the participation of the public. The Constructor's Tent is also set up, in which everyone can build simple models of various devices (such as: spectroscope, hovercraft, periscope, kaleidoscope). These models can be taken home later. All visitors to the Institute at that time can visit the most interesting laboratories on the "In the labyrinth of science" trail. As part of the "Scientific cinema", popular science films are regularly shown, including: "The Secret World of Atomic Nuclei", "We study the secrets of DNA", "Chronicle of Bronowice", created by an employee of the Institute: Dr. hab. Jerzy Grębosz, as well as the film "Shifting Horizons" by Wiktor Niedzicki. Every year, this event is accompanied by interesting events, such as "Physics Tricks" – a demonstration of experiments in which nature reveals its magic face, "Physics for adults" – demonstrations of physical experiments permitted for the 18+ audience, or "Where is the limit of serious physics?", an interactive lecture combined with a demonstration of simple experiments that can become the beginning of amateur research projects. For younger participants, there is an additional attraction – Scientific hare and hounds – a task game referring to the laws of physics and physical phenomena encountered in everyday life. The participants, equipped with a map of the territory of the Institute, solve their non-trivial tasks. From 2018, another attraction of the Lesser Poland Researchers' Night is an exhibition of old experimental instruments showing how physics was once practiced – the so-called Lamusownia (a junk room). Every year on this day, the Institute is visited by over a thousand science enthusiasts.



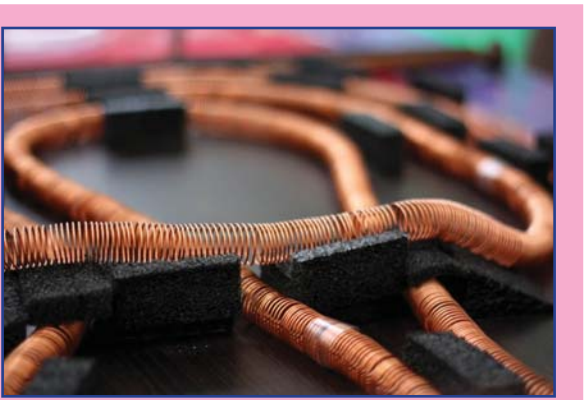
SCIENTIFIC PICNIC OF THE POLISH RADIO AND COPERNICUS SCIENCE CENTRE

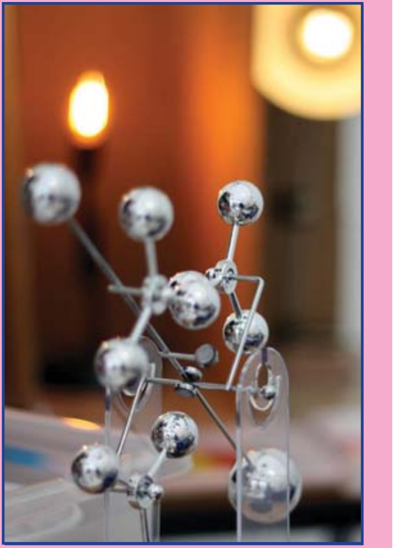
A regular open-air event popularizing science is organized every year in Warsaw at the National Stadium. Through the experiments carried out, the popularizers of science from the Institute aim to arouse curiosity and inspire people to expand their knowledge on their own. They present, among others how to use home-kitchen methods to illustrate the greenhouse effect, or liquid chromatography, and show the effect of soil type on the absorption of various substances. Picnic participants can learn about the methods of measuring radon concentration, about anti-radon protection used in buildings and various possibilities of detecting nuclear radiation, as well as learn about the use of magnets in therapeutic treatment, or broaden their knowledge about radiation and its impact on human health. The shows presented by IFJ PAN include "Ionizing radiation and its propagation in the environment", "Transport of contaminants in the environment", "Accelerate the particle in the accelerator", "A breakthrough in science? Now your move – explore the universe with your smartphone!".

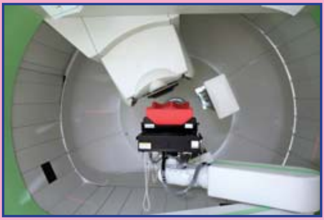
THE INSTITUTE OF NUCLEAR PHYSICS PAN ORGANIZES OR CONTRIBUTES TO OTHER EVENTS POPULARIZING SCIENCE

In cooperation with the International Particle Physics Outreach Group (IPPOG) and CERN, researchers of the Institute annually organize the **International Particle Physics Workshops** for high school students (as part of the "International Masterclasses – Hands on Particle Physics"). Every year, there are also student internships – **Particle Physics Laboratory** – IFJ PAN Particle Physics Summer Student Program. These events are intended to encourage students of physics and related sciences to become involved in particle physics research by enabling them to independently analyse the latest experimental data from ATLAS, ALICE, Belle, LHCb, NA61 / SHINE and T2K experiments.

As part of popularizing science, it is possible to **visit selected laboratories of the Institute** in small groups. These tours may choose a sightseeing program from among the laboratories provided, where scientists present half-hour lectures on research conducted in a given laboratory. Since 2018, an **Open Day** has been organized, during which scientists present to students the current offers of student internships and diploma theses, but also present research laboratories, sample preparation labs, and experimental





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equipment, as well as discuss and explain the research conducted in these laboratories. This gives a chance for individual meetings with potential tutors of student internships or diploma theses. Information about this event is disseminated at universities all over Poland and among national research groups.

The Institute also hosts **science shows**, which are very popular among primary and secondary school children and teenagers, conducted by Wiktor Niedzicki – a well-known physics promoter, and dr Dominika Kuźma from IFJ PAN. These events are attended by nearly a thousand primary and secondary school students from Krakow and its vicinity with great applause. On the occasion of the series of popular science shows, in 2018, the Institute published a booklet with descriptions and photos illustrating selected simple physical experiments for children, entitled "The Fourth Wiktor's Laboratory".

The Institute supports **competitions in the field of physics**, including the Lesser Poland Competition in Physics and Astronomy for primary and secondary school students and the nationwide competition "Chain Experiment", organized on the initiative of students of the Faculty of Physics, Astronomy and Applied Computer Science of the Jagiellonian University in Kraków. The employees of the Institute also prepare interesting projects themselves – incl. a competition for a washable tattoo design, entitled Tattoo with physics in the background or Particle Hunter, consisting in team detection of secondary cosmic radiation particles and local radioactivity using smartphones equipped with the CREDO Detector application. The aim of the competition is to create a network of users of the CREDO Detector application, to promote the idea of co-creating science by non-professional researchers, to enable children and adolescents to participate in scientific research and co-author scientific discoveries. Several hundred students from several dozen schools in the country are involved in the campaign.

INFORMATION AND SOCIAL MEDIA

Institute of Nuclear Physics Polish Academy of Sciences is not only a great environment for creative research work, but above all it is a community of scientists, engineers and the entire staff. It is an institution well known in the region, in Poland and abroad. Various forms of electronic social communication serve to bring these relationships closer.

Every year, the Institute publishes on the global scientific press service: EurekAlert!, notes on major scientific achievements attained with the significant participation of researchers from IFJ PAN, which were published in renowned journals. Press reports on this website had from several to several thousand openings a month. Press releases on these achievements also appeared in a number of professional news services in Poland, including Polish Press Agency Science in Poland https://scienceinpoland.pap.pl (PAP Science in Poland). EurekAlert! (www.eurekalert.org) is run by the American Association for the Advancement of Science.

The Institute is also active on **Facebook**, **Twitter** and **YouTube**, posting information and videos on its activities and the ongoing popularization events undertaken by the Institute. The laboratories and scientific departments of the Institute also run their Facebook profiles, including Laboratory of Individual and Environmental Dosimetry, Department of Magnetic Materials and Nanostructures. There are also profiles: IFJ PAN Particle Physics Summer Student Program, the CREDO project and the Epiphany conference.

IFJ PAN employees are often invited by various scientific and cultural institutions to deliver popularizing lectures, participate in discussion panels and conduct laboratory exercises. They also collaborate with the media by publishing their texts on popular science blogs, such as Crazy Nauka, or appearing on television, e.g. in the TVP Sonda 2 program or in radio broadcasts.

PHYSICS IN HOT PURSUIT

The materials presented herein are based on the scientific achievements that we have made available to the media in the form of press releases.

The same were also posted on the EurekAlert! Website, with delivers news from various fields of science. The content of the book has been divided into six chapters, arranged thematically in such a way as to increase its readability. However, this is only a brief report of a fraction of the research work carried out at the Institute – other discoveries and another publication are still ahead of us.

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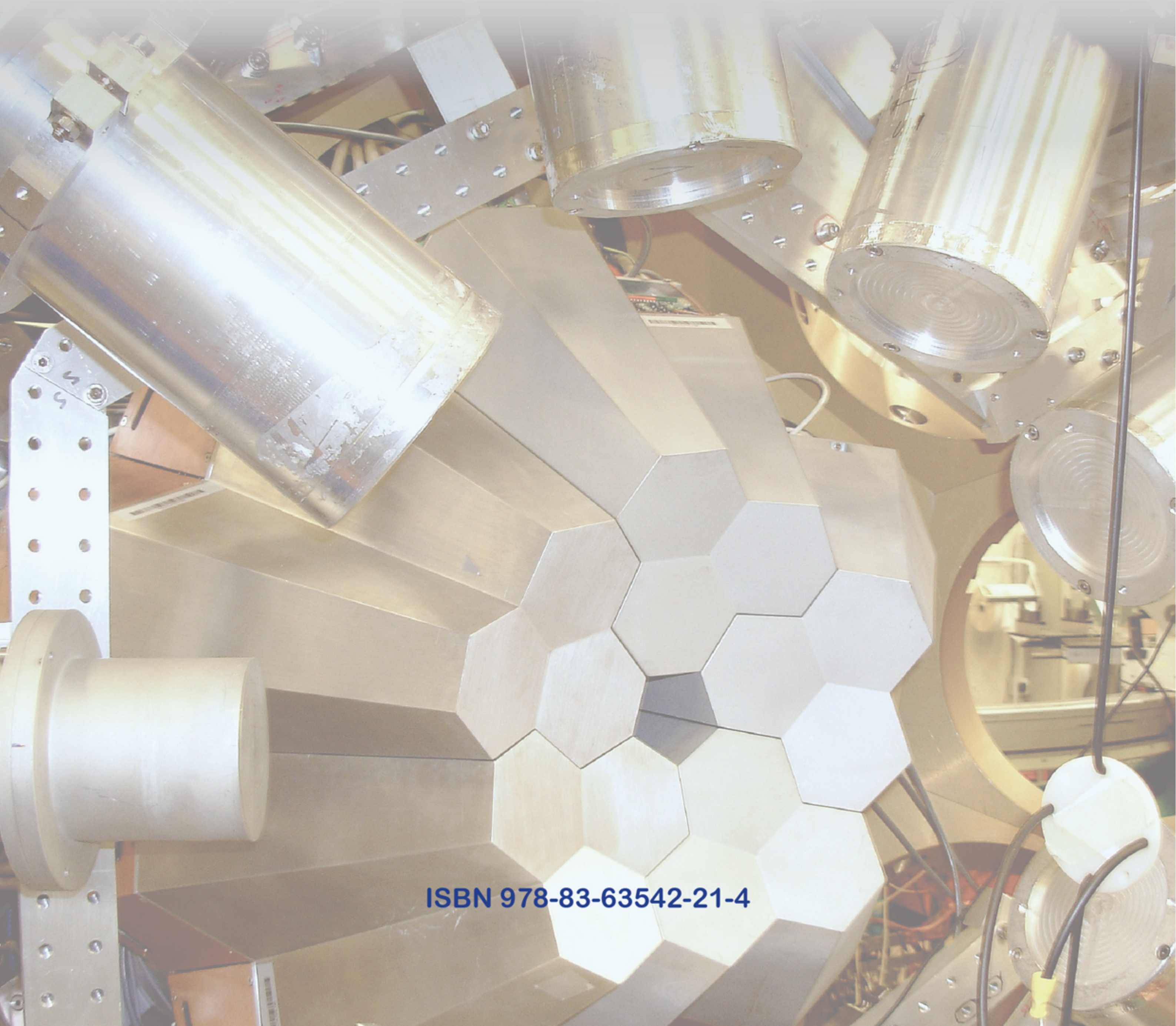

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