



Cracow, 17 March 2022

## Interior of protons is maximally entangled

*Fragments of the interior of a proton have been shown by scientists from Mexico and Poland to exhibit maximum quantum entanglement. The discovery, already confronted with experimental data, allows us to suppose that in some respects the physics of the inside of a proton may have much in common not only with well-known thermodynamic phenomena, but even with the physics of... black holes.*

Various fragments of the inside of a proton must be maximally entangled with each other, otherwise theoretical predictions would not agree with the data collected in experiments, it was shown in *European Physical Journal C*. The theoretical model (which extends the original proposal by physicists Dimitri Kharzeev and Eugene Levin) makes it possible to suppose that, contrary to current belief, the physics operating inside protons may be related to such concepts as entropy or temperature, which in turn may relate it to such exotic objects as black holes. The authors of the discovery are Dr. Martin Hentschinski from the Universidad de las Americas Puebla in Mexico and Dr. Krzysztof Kutak from the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Cracow, Poland.

The Mexican-Polish theorists analysed the situation in which electrons are fired at protons. When an incoming electron carrying a negative electric charge approaches a positively charged proton, it interacts with it electromagnetically and deflects its path. Electromagnetic interaction means that a photon has been exchanged between the electron and the proton. The stronger the interaction, the greater the change in momentum of the photon and therefore the shorter the associated electromagnetic wave.

*"If a photon is 'short' enough to 'fits' inside a proton, it begins to 'resolve' details of its internal structure. The result of interacting with this sort of photon can be the decay of the proton into particles. We have shown that there is entanglement between the two situations. If the observation by the photon of the interior part of the proton leads to its decay into a number of particles, let's say three, then the number of particles originating from the unobserved part of the proton is determined by the number of particles seen in the observed part of the proton,"* explains Dr. Kutak.

We can speak of quantum entanglement of various quantum objects, if certain characteristic of the objects are related to each other in a particular way. The classical analogy of the phenomenon can be represented by the toss of a coin. Let's assume that one object is one side of the coin, and the other object is its other side. When we flip a coin, there is the same probability that the coin will land heads or tails facing up. If it lands heads up, we know for sure that the other side is tails. We can then speak of maximum entanglement since the probability which determines the value of an object's characteristic does not favour any possible value: we have a 50% chance of heads and the same for tails. A smaller than maximum entanglement occurs when the probability starts to favour one of the possible outcomes to a greater or lesser extent.

*"Our study shows that the interior of a proton seen by a passing photon must be entangled with the unseen part in just this maximal manner, as suggested by Kharzeev and Levin. In practice, this*

*means that we have no chance of predicting whether, due to interaction with the photon, the proton will decay into three, four or any other number of particles,”* explains Dr. Hentschinski.

The new theoretical predictions have already been verified. If entanglement inside the proton were not maximal, there would be discrepancies between theoretical calculations and the results of the H1 experiment at the HERA accelerator at the DESY centre in Hamburg, where positrons (i.e. antiparticles of the electrons) were collided with protons until 2007. Such discrepancies were not observed.

The success of the Polish-Mexican tandem is due to the fact that the researchers managed to correctly identify the factors responsible for the maximum entanglement of the proton interior.

In the naive schoolbook view, the proton is a system of three elementary particles: two up quarks and one down quark. However, the strong interactions between these quarks, carried by gluons, can be so strong that they lead to the creation of virtual particle-antiparticle pairs. These can be not only pairs of virtual gluons (which are their own antiparticles), but also pairs made up of any quark and its corresponding antiparticle (even one as massive as charm). All this means that inside the proton, apart from three valence quarks, there are constantly 'boiling' seas of virtual gluons and virtual quarks and antiquarks.

*“In earlier publications, physicists dealing with the subject assumed that the source of entanglement should be a sea of gluons. Later, attempts were made to show that quarks and antiquarks are the dominant source of entanglement, but even here the proposed methods of description did not stand the test of time. Meanwhile, according to our model, verified by confrontation with experimental data, the sea of virtual gluons is responsible for about 80% of the entanglement, while the sea of virtual quarks and antiquarks is responsible for the remaining 20%,”* emphasizes Dr. Kutak.

Most recently, quantum physicists have been associating entropy with the state inside a proton. This is a quantity well known from classical thermodynamics, where it is used to measure the degree of disordered motion of particles in an analysed system. It is assumed that when a system is disordered, it has high entropy, whereas an ordered system has low entropy. It has recently been shown that in the case of the proton, we can successfully talk about entanglement entropy. However, many physicists have considered the proton to be a pure quantum state in which one should not speak of entropy at all. The consistency of the Mexican-Polish model with experiment is a strong argument for the fact that the concept of entanglement inside the proton as proposed by Kharzeev and Levin has a point. Last but not least, since entanglement entropy is also related to concepts such as the surface area of black holes, the latest result opens an interesting field for further research.

*The Henryk Niewodniczański Institute of Nuclear Physics (IFJ PAN) is currently one of the largest research institutes of the Polish Academy of Sciences. A wide range of research carried out at IFJ PAN covers basic and applied studies, from particle physics and astrophysics, through hadron physics, high-, medium-, and low-energy nuclear physics, condensed matter physics (including materials engineering), to various applications of nuclear physics in interdisciplinary research, covering medical physics, dosimetry, radiation and environmental biology, environmental protection, and other related disciplines. The average yearly publication output of IFJ PAN includes over 600 scientific papers in high-impact international journals. Each year the Institute hosts about 20 international and national scientific conferences. One of the most important facilities of the Institute is the Cyclotron Centre Bronowice (CCB), which is an infrastructure unique in Central Europe, serving as a clinical and research centre in the field of medical and nuclear physics. In addition, IFJ PAN runs four accredited research and measurement laboratories. IFJ PAN is a member of the Marian Smoluchowski Kraków Research Consortium: "Matter-Energy-Future", which in the years 2012-2017 enjoyed the status of the Leading National Research Centre (KNOW) in physics. In 2017, the European Commission granted the Institute the HR Excellence in Research award. The Institute holds A+ category (the highest scientific category in Poland) in the field of sciences and engineering.*

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## **SCIENTIFIC PUBLICATIONS:**

“Evidence for the maximally entangled low  $x$  proton in Deep Inelastic Scattering from H1 data”  
M. Hentschinski, K. Kutak  
*European Physical Journal C*, 82, 111 (2022)  
DOI: <https://doi.org/10.1140/epjc/s10052-022-10056-y>

## **LINKS:**

<http://www.ifj.edu.pl/>

The website of the Institute of Nuclear Physics, Polish Academy of Sciences.

<http://press.ifj.edu.pl/>

Press releases of the Institute of Nuclear Physics, Polish Academy of Sciences.

## **IMAGES:**

**IFJ220317b\_fot01s.jpg**

**HR:** [http://press.ifj.edu.pl/news/2022/03/17/IFJ220317b\\_fot01.jpg](http://press.ifj.edu.pl/news/2022/03/17/IFJ220317b_fot01.jpg)

If a photon carries too little energy, it does not fit inside a proton (left). A photon with sufficiently high energy is so small that it flies into the interior of a proton, where it 'sees' part of the proton (right). Maximum entanglement then becomes visible between the 'seen' and 'unseen' areas. (Source: IFJ PAN)