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Flavor symmetry of the high-energy world does not work as expected

In collisions of argon and scandium atomic nuclei, scientists from the international NA61/SHINE experiment have observed a clear anomaly indicative of a violation of one of the most important symmetries of the quark world: the approximate flavor symmetry between up and down quarks. The existence of the anomaly may be due to hitherto unknown inadequacies in current nuclear collision models, but the potential connection to the long sought-after 'new physics' cannot be ruled out.

If we were to assemble a structure using the same number of wooden and plastic blocks, we would expect the proportions between the blocks of the two types not to alter after it has been dismantled. Physicists have so far lived in the belief that a similar symmetry of the initial and final states, called flavor symmetry, occurs in collisions between particles containing up and down quarks. However, a different picture of reality emerges from a paper just published in the prestigious journal *Nature Communications*. An intriguing observation, with far-reaching consequences, was made by the NA61/SHINE experiment group, a significant part of which are physicists from Poland, including those from the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Cracow. The team studied collisions between argon and scandium nuclei accelerated by the Super Proton Synchrotron (SPS) – the same accelerator that is also responsible for the final phase of accelerating protons before injecting them inside the Large Hadron Collider (LHC) at CERN near Geneva.

"According to the current state of knowledge, the world of matter we perceive is mainly made up of elementary particles called quarks. They come in six types, each having its antimatter counterpart. Protons and neutrons, the basic constituents of atomic nuclei, are composed of triplets of – always mixed – up and down quarks, while quark-antiquark pairs are called mesons," Prof. Andrzej Rybicki (IFJ PAN) introduces us to the subject.

The factor responsible for the gluing together of quarks into protons, neutrons or mesons is the strong interaction, described by a theory called quantum chromodynamics. From its equations, it follows that if quarks of all types had the same masses, the strong interaction would not distinguish any of them. In fact, quarks of different varieties (flavors) differ significantly in their masses, which breaks this symmetry. What becomes crucial, however, is that the two lightest types of quarks – the previously mentioned up and down quarks – differ little in their masses. Strong interactions therefore do not treat them in exactly the same manner, but similarly enough to speak of the existence of an approximate flavor symmetry. In nuclear research, the importance of this symmetry is significant. It is what makes it known that if a high-energy collision involving up quarks produces some secondary particles with a given probability, then with almost the same probability other corresponding secondary particles would be produced in a collision in which down quarks would be present (and *vice versa*).

The NA61/SHINE experiment team was involved in the study of *K* mesons (kaons), which appear in various types during high-energy collisions of argon and scandium atomic nuclei. Originally, the group planned to measure only electrically charged kaons. Admittedly, it was known that short-lived neutral kaons, with no electric charge, are also produced in collisions, but measuring them did not seem worthwhile. After all, it was clear from the flavor symmetry that, when negative kaons and positive kaons were added, the result should correspond with the number of neutral kaons to a good approximation. In the end, however, the group decided to carry out measurements of kaons of all types – and this was a great success.

“The results published by our team turn out to be statistically significantly different from previous theoretical predictions. It is usually assumed that discrepancies in experimental data, due to the approximate nature of the flavor symmetry, do not exceed 3% in this energy range. We, on the other hand, report an overproduction of charged kaons reaching as high as 18%!”, says Prof. Rybicki.

When looked at more closely, the observed effect becomes even more intriguing. A stable isotope of argon has 18 protons and 22 neutrons, whereas in the case of scandium, there are three more neutrons in a stable nucleus than there are protons. Protons are conglomerates of two up quarks and one down quark, neutrons *vice versa*, so simple arithmetic proves that there were slightly more down quarks in the systems studied before the collisions.

“Since we started off with more down quarks than up quarks, we would intuitively expect that if there is a disruption of the flavor symmetry, we should observe more down quarks after the collision as a result. Meanwhile, our analyses show unequivocally: the flavor symmetry is disrupted in the other direction and, in the end, it is the up quarks that are more abundant!”, says the initiator of the measurement of neutral kaons, Prof. Katarzyna Grebieszkow from the Warsaw University of Technology.

The reasons for the observed symmetry breaking in collisions between argon and scandium atomic nuclei are currently unknown. Perhaps the theoretical calculations inspired by quantum chromodynamics have not taken into account some important property of these collisions. However, another, more spectacular possibility cannot be ruled out: that the observed effect goes beyond the existing theory of strong interactions and the Standard Model built with it, which would mean that it is a manifestation of the long sought-after ‘new physics’. Regardless of further developments, the discovery already carries significant implications for scientists involved in studies of high-energy collisions between particles and atomic nuclei. Indeed, the assumption of the existence of the symmetry in question has been widely used for decades in modelling the course of many nuclear experiments and interpreting their results.

“The point is that we have discovered flavor symmetry breaking in collisions between atomic nuclei. Today, we are not yet able to say whether this is a universal phenomenon, affecting all interactions with the presence of quarks, or whether it occurs, for example, only for nuclei of specific mass or for some, but not other, collision energies,” stresses Prof. Rybicki and adds: *“In practice, this implies the need of a careful re-evaluation of virtually all models of particle production in high-energy collisions, and of numerous experimental results.”*

In the coming months, scientists from the NA61/SHINE team will begin work to confirm flavor symmetry breaking in collisions characterized by initially equal numbers of up and down quarks.

“The first focus will be on the tens of millions of already recorded collisions of pi+ and pi- mesons with carbon nuclei, where it is possible to speak of full flavor symmetry prior to the collision. The next step will be to study the course of oxygen-oxygen and magnesium-magnesium collisions, with the latter system seeming particularly promising due to the complexity of atomic nuclei similar to argon and scandium, whose collisions made it possible to discover the phenomenon in question,” says Dr. Seweryn Kowalski, professor at the University of Silesia, who – together with Prof. Eric Zimmerman of the University of Colorado Boulder – heads the NA61/SHINE experiment.

Unfortunately, we will still need to wait for the most interesting results: the collisions of magnesium nuclei will only be possible after the soon-to-be-commenced three-year upgrade of the LHC.

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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 establishments of the Institute is the Bronowice Cyclotron Centre (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 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. As a result of the categorization of the Ministry of Education and Science, the Institute has been classified into the A+ category (the highest scientific category in Poland) in the field of physical sciences.

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SCIENTIFIC PUBLICATIONS:

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LINKS:

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

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IMAGES:

IFJ250507b_fot01s.jpg **HR:** http://press.ifj.edu.pl/news/2025/05/07/IFJ250507b_fot01.jpg
Interior of the Projectile Spectator Detector (PSD) used in the NA61/SHINE experiment at CERN. (Source: Julien Marius Ordan, CERN-PHOTO-202011-147-2 / License: CC-BY-4.0)