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Matter–antimatter asymmetry still provides no evidence of new physics

The Universe's dominance by ordinary matter is compelling evidence that matter and antimatter are not perfect reflections of each other. However, known differences do not explain the scale of this imbalance, leaving open the possibility that unknown physics is responsible. A new analysis of meson decays, conducted by the LHCb collaboration, has narrowed the scope of the search for such a scenario while paving the way for more precise measurements in the future.

Over the past decade, scientists working at the Large Hadron Collider have focused their efforts on searching for differences between particles of matter and antimatter produced in proton-proton collisions. The latest and exceptionally thorough analysis of data collected between 2016 and 2018 as part of the LHCb experiment was carried out by a team of physicists from the universities of Warwick, Manchester and Oxford in the UK, TU Dortmund University in Germany, and the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Cracow.

The motivation behind this research lies in what is arguably the most astonishing feature of our world: the fact that it... simply exists. Why is this so surprising? Because, in its present form, it should not exist – at least according to our current understanding of physics. Cosmological models suggest that, shortly after the Big Bang, equal amounts of matter and antimatter must have been produced in the Universe. Yet when a particle meets its antiparticle, both are converted into energy in a process known as annihilation. Meanwhile, our reality is clearly dominated by particles of matter that have escaped annihilation. The worlds of matter and antimatter particles therefore cannot have been – and still are not – perfectly symmetrical.

"In many physical processes, simultaneously replacing all particles with their antiparticles and inverting all spatial coordinates leaves the laws governing these phenomena unchanged. This principle is known as charge-parity symmetry, or CP symmetry. We have been searching for processes that violate this symmetry in the decays of particles produced in proton–proton collisions at the LHC, specifically in the decays of mesons containing beauty and strange quarks and antiquarks," explains Dr. Agnieszka Dziurda (IFJ PAN), an expert in the physics of these decays.

The Standard Model, a theoretical framework developed in the 1970s, describes the elementary particles and their interactions. According to this model, matter is made up of elementary particles known as fermions. These include quarks (down, up, strange, charm, beauty and top) and leptons (electrons, muons, tau leptons and their associated neutrinos). In addition, every type of matter particle has a corresponding antiparticle.

Each proton–proton collision at the LHC produces a large number of massive, short-lived particles. In earlier studies of CP violation, physicists have observed asymmetries in certain decay processes involving particles and antiparticles. However, these phenomena alone cannot account for the present-day dominance of matter. Now, in a paper published in the renowned journal *Physical Review Letters*, researchers have presented an analysis of the decays of B_s^0 mesons. These mesons decay into lighter particles, and the Standard Model allows scientists to calculate the expected frequency of a given decay process and compare these predictions with experimental data.

“Interestingly, we chose to investigate a process in which the Standard Model predicts no asymmetry at all. So why study it at all?” asks Dr. Dziurda. She explains: *“Because if an asymmetry were nevertheless observed, it could be a signal that previously unknown physics was at work. We also know that current theoretical predictions for the probabilities of certain beauty-meson decay channels differ significantly from the values obtained experimentally. This discrepancy could, for example, stem from theoretical effects that have not yet been fully accounted for in our calculations. At this stage, however, we cannot rule out the possibility that it points to physics beyond the Standard Model.”*

Beauty mesons were exceptionally well suited to the search for CP symmetry breaking for another reason. They possess a remarkable property: they oscillate extremely rapidly between states corresponding to matter (a strange quark paired with a beauty antiquark) and antimatter (a beauty quark paired with a strange antiquark). One of the earlier measurements by the LHCb experiment showed that these oscillations can occur several trillion times per second. Thanks to such fast oscillations, the analysis could be carried out without having to determine the initial state of each meson.

A particular challenge for researchers was to thoroughly understand and characterise detector asymmetries, that is, differences in the detection of particles and antiparticles arising from the detector itself. This is because positively and negatively charged particles curve in opposite directions as they travel through the detector's magnetic field. Because detection efficiencies vary across the detector, this can affect the numbers of recorded particles and antiparticles. Such effects can produce an apparent asymmetry in the data even when the process being studied occurs with equal probability for particles and antiparticles. To account for these effects, the researchers used extensive calibration samples and computer simulations, and regularly reversed the direction of the detector's magnetic field. Corrections for differences in particle and antiparticle detection efficiencies were also applied when determining the final asymmetry in beauty-meson decays.

“We had to make sure that any asymmetry observed in the data, however small, was not caused by the detector itself. This was a crucial aspect of the entire analysis because, given the precision of our measurement, detector-related effects could have been of the same magnitude as the asymmetry we were looking for,” says Dr. Dziurda.

The data from the LHCb experiment analysed in this study revealed a difference of approximately one to two cases per thousand decays. However, since the measurement uncertainty was larger than the observed effect, the result is consistent with the predictions of the Standard Model. Although the finding does not solve the mystery of the missing antimatter or rule out the existence of new physics, it narrows down the range of possibilities in which new phenomena might be hiding. In the decays studied, any unknown process that would cause an asymmetry greater than about 2% would almost certainly have been detected.

Future research, using the larger datasets already collected with the upgraded LHCb detector, will allow scientists to investigate even more subtle effects in the discussed meson decays. Should a new source of CP violation be hidden therein, the analysis presented here provides physicists with a clearer understanding of where – and precisely how – the search should be conducted.

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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:

http://www.ifj.edu.pl/
The website of the Institute of Nuclear Physics, Polish Academy of Sciences.

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

IMAGES:

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Proton–proton collisions at the LHC produce, among other particles, mesons containing beauty and strange quarks and antiquarks. Differences between matter and antimatter were investigated in their decays into secondary particles. (Source: IFJ PAN)