New experimental evidence of the restoration of chiral symmetry at high matter density

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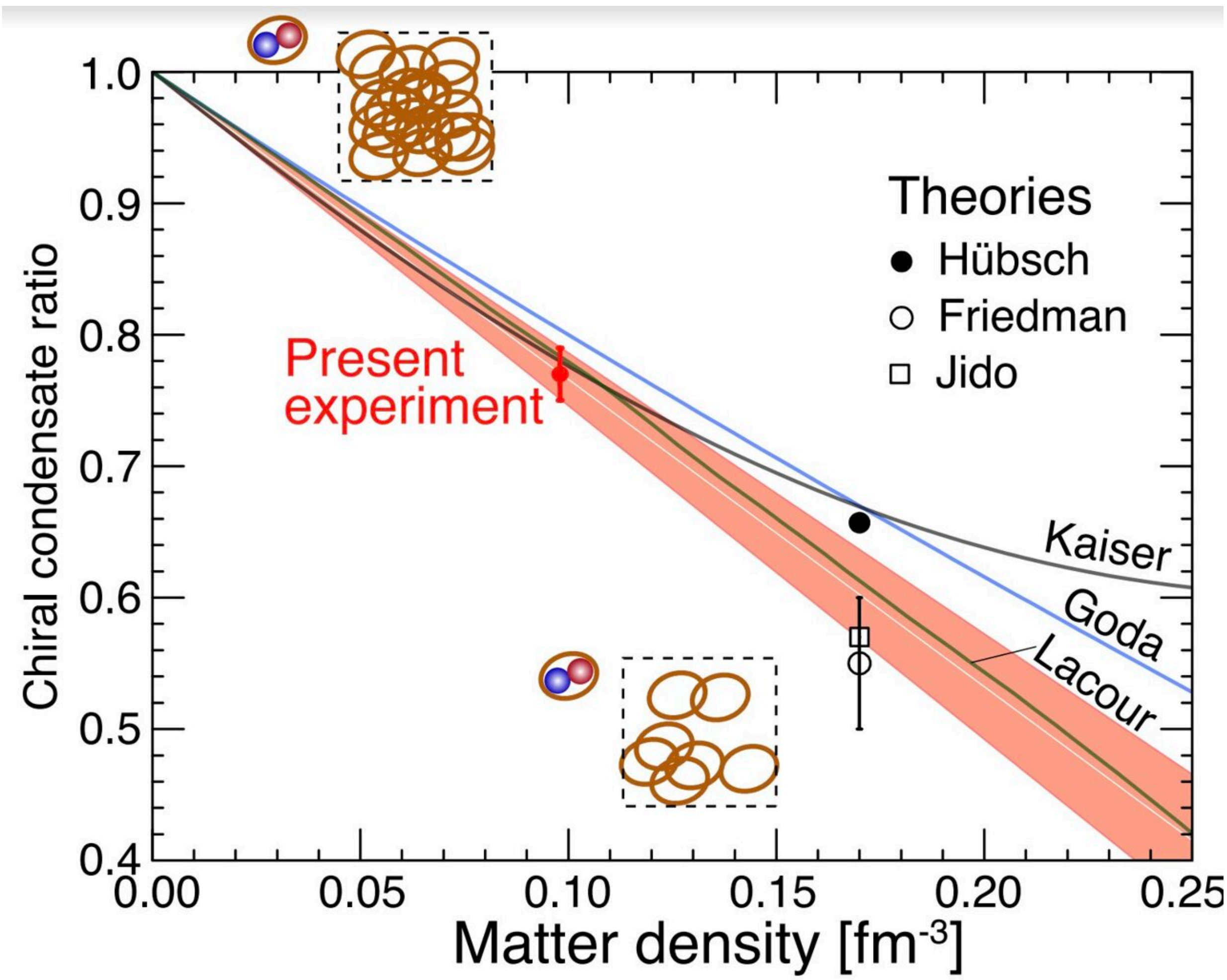

Reduction of chiral condensate at high matter density taken from press release in RIKEN by Nishi et al. The present experiment deduced the chiral condensate at the nuclear density of ~0.10 fm-3 to be reduced by a factor of 77+- 2% as shown by the red circle with error bars. The obtained result is compared with theoretical calculations. Credit: RIKEN by Nishi et al.

https://www.riken.jp/press/2023/20230327_1/index.html

The QCD vacuum (i.e., the ground state of vacuum in the quantum chromodynamics regime) is theoretically characterized by the presence of non-zero expectation values of condensates, such as gluons and quark–antiquark pairs. Instead of being associated with a lack of particles and interactions in an empty space, physics theory regards this state as filled with the so-called condensates, which have the same quantum numbers as the vacuum and cannot be directly observed.

While many theoretical physicists have discussed the properties of the QCD vacuum, experimentally validating these theoretical predictions has so far proved challenging, simply because the condensates in this state are elusive and cannot be directly detected. A hint of experimental "observation" can be found in the theoretical predictions of the properties of the QCD vacuum.

Theories predict that the condensate may decrease in the high temperature and/or at a high matter density due to the partial restoration of the so-called chiral symmetry. To prove these theories, some researchers collected measurements during ultra-relativistic, head-on collisions of heavy ions at particularly high temperatures. Other efforts in this area tried to probe properties of the QCD vacuum by measuring so-called "medium effects." These are essentially effects that alter the QCD vacuum and its structure, prompted by the presence of high matter density such as nuclear matter.

Researchers at the RIKEN Nishina Center for Accelerator-Based Science, Nara Women's University, the German Heavy Ion Research Institute, and other institutes worldwide have recently set out to gather experimental insights of the medium effects in nuclei at lower temperatures. In their experiments, outlined in a *Nature Physics* paper, they used spectroscopy techniques to measure the states of in (Sn) pionic atoms, bound systems consisting of a pion and atomic nucleus.

"The existence of the hidden structure of vacuum is one of the most important physics questions of the modern era," Kenta Itahashi, one of the researchers who carried out the study, told Phys.org. "The 'non-trivial' structure of the vacuum has been theoretically discussed for a long time. For instance, Nambu described the spontaneous symmetry breakdown of the vacuum. Despite the many related theories, experimental evidence in this area has so far been limited."

The primary objective of the recent work by Itahashi and his colleagues was to further elucidate the hidden structure of the QCD vacuum and its evolution over the history of the universe. According to theoretical predictions, the condensation of quark–antiquark pairs (i.e., chiral condensates) in this vacuum state would break the vacuum's chiral symmetry.

At high temperatures and/or high matter densities the chiral symmetry would be partially restored, which should thus theoretically reduce the expected value of chiral condensates. In their new experiments, the team set out to deduce the expected value of quark–antiquark pairs in the QCD vacuum by measuring pionic atoms at high densities and lower temperatures with high-precision spectroscopy techniques.

"We measured pion-nuclear bound systems in a spectroscopic way" Itahashi explained. "Our spectroscopy thus provides complementary information that can be analyzed in conjunction with past experimental findings focusing head-on collisions. Like drawing a phase diagram of water or superconducting materials, we wished to draw a phase diagram of the vacuum on a plane of temperature and density. In a sense, nuclear matter behaves as an impurity loaded into the vacuum."

The researchers found that their measurements were consistent with the spontaneous breakdown of the QCD vacuum's chiral symmetry described by Nambu's theory. Combined with the results of a pioneering study they conducted almost two decades ago, this work advances the present understanding of the QCD vacuum, the breaking and restoration of chiral symmetry, and how this affects the expected value of chiral condensates at high temperatures and/or high matter densities.

"As far as we know, there is currently no information on the order parameter at a high-matter density that was as accurately determined as ours," Itahashi said. "In our next studies, we wish to investigate the density dependence of the chiral symmetry. We already plotted the first point of the chiral order parameter on the density axis and we now plan to study the density derivative by making a systematic measurement. In addition, we also wish to develop a new pionic atom spectroscopy technique to reach higher precision and to enable the study of pionic atom formation with radioisotopes."

More information: Takahiro Nishi et al, Chiral symmetry restoration at high matter density observed in pionic atoms, *Nature Physics* (2023). DOI: 10.1038/s41567-023-02001-x