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CERN team solves decades-old mystery of light nuclei formation

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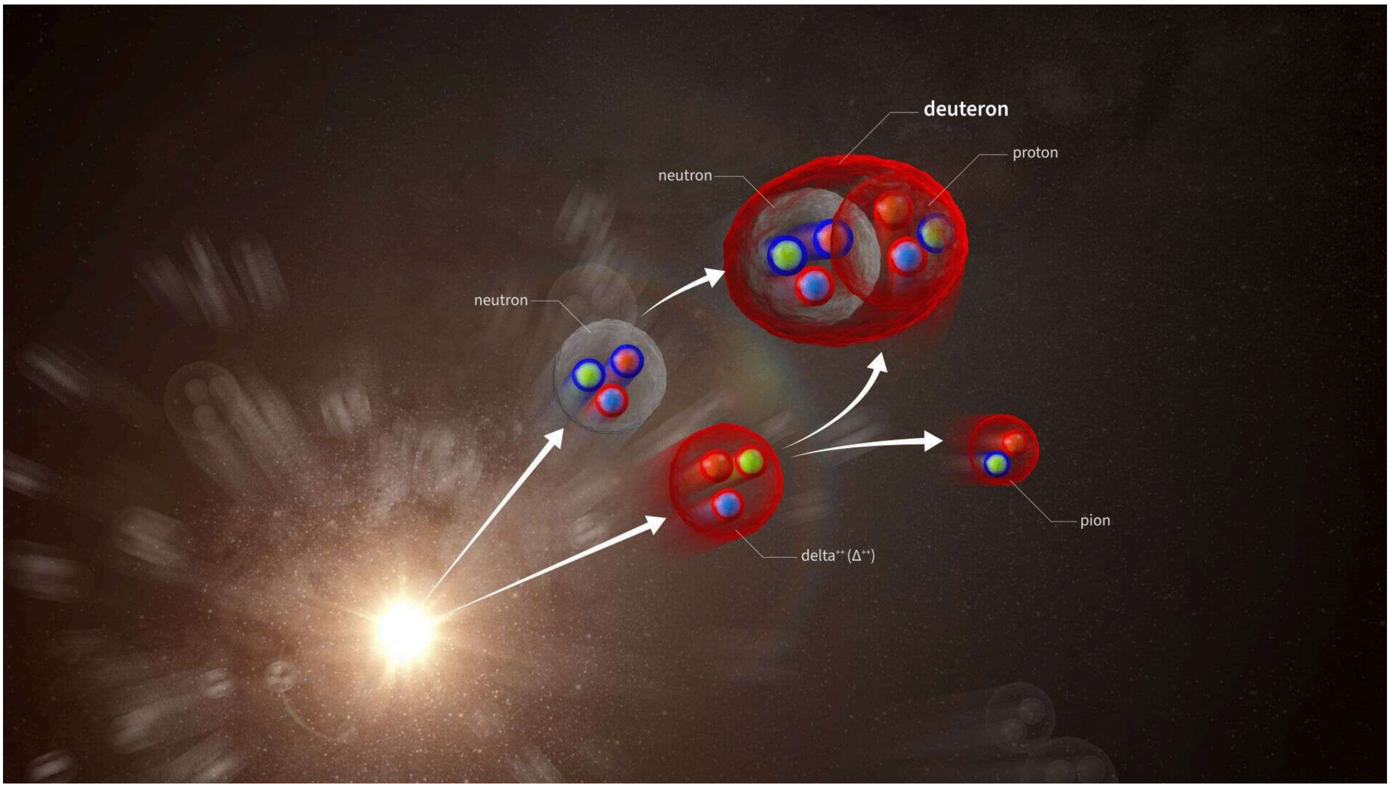

Light nuclei: Illustration of how deuterons can be produced from a high-energy collision. A delta particle emerging from the collision decays into a proton and a pion. The proton then undergoes nuclear fusion with a neutron to form deuteron. (Courtesy: CERN)

When particle colliders smash particles into each other, the resulting debris cloud sometimes contains a puzzling ingredient: light atomic nuclei. Such nuclei have relatively low binding energies, and they would normally break down at temperatures far below those found in high-energy collisions. Somehow, though, their signature remains. This mystery has stumped physicists for decades, but researchers in the ALICE collaboration at CERN have now figured it out. Their experiments showed that light nuclei form via a process called resonance-decay formation – a result that could pave the way towards searches for physics beyond the Standard Model.

Baryon resonance

The ALICE team studied deuterons (a bound proton and neutron) and antideuterons (a bound antiproton and antineutron) that form in experiments at CERN's Large Hadron Collider. Both deuterons and antideuterons are fragile, and their binding energies of 2.2 MeV would seemingly make it hard for them to form in collisions with energies that can exceed 100 MeV – 100 000 times hotter than the centre of the Sun.

The collaboration found that roughly 90% of the deuterons seen after such collisions form in a three-phase process. In the first phase, an initial collision creates a so-called baryon resonance, which is an excited state of a particle made of three quarks (such as a proton or neutron). This particle is called a Δ baryon and is highly unstable, so it rapidly decays into a pion and a nucleon (a proton or a neutron) during the second phase of the process. Then, in the third (and, crucially, much later) phase, the nucleon cools down to a point where its energy properties allow it to bind with another nucleon to form a deuteron.

Smoking gun

Measuring such a complex process is not easy, especially as everything happens on a length scale of femtometres (10^{-15} meter). To tease out the details, the collaboration performed precision measurements to correlate the momenta of the pions and deuterons. When they analysed the momentum difference between these particle pairs, they observed a peak in the data corresponding to the mass of the Δ baryon. This peak shows that the pion and the deuteron are kinematically linked because they share a common ancestor: the pion came from the same Δ decay that provided one of the deuteron's nucleons.

Panos Christakoglou, a member of the ALICE collaboration based at the Netherlands' Maastricht University, says the experiment is special because in contrast to most previous attempts, where results were interpreted in light of models or phenomenological assumptions, this technique is model-independent. He adds that the results of this study could be used to improve models of high energy proton-proton collisions in which light nuclei (and maybe hadrons more generally) are formed. Other possibilities include improving our interpretations of cosmic-ray studies that measure the fluxes of (anti)nuclei in the galaxy – a useful probe for astrophysical processes.

The hunt is on

Intriguingly, Christakoglou suggests that the team's technique could also be used to search for indirect signs of dark matter. Many models predict that dark-matter candidates such as Weakly Interacting Massive Particles (WIMPs) will decay or annihilate in processes that also produce Standard Model particles, including (anti)deuterons. "If for example one measures the flux of (anti)nuclei in cosmic rays being above the 'Standard Model based' astrophysical background, then this excess could be attributed to new physics which might be connected to dark matter," Christakoglou tells *Physics World*.

Michael Kachelriess, a physicist at the Norwegian University of Science and Technology in Trondheim, Norway, who was not involved in this research, says the debate over the correct formation mechanism for light nuclei (and antinuclei) has divided particle physicists for a long time. In his view, the data collected by the ALICE collaboration decisively resolves this debate by showing that light nuclei form in the late stages of a collision via the coalescence of nucleons. Kachelriess calls this a "great achievement" in itself, and adds that similar approaches could make it possible to address other questions, such as whether thermal plasmas form in proton-proton collisions as well as in collisions between heavy ions.

Martijn Boerkamp is a science writer based in the Netherlands

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