doi:10.1038/nature17884

NUCLEAR PHYSICS

Four neutrons together momentarily

A system of four neutrons known as the tetraneutron is a hypothetical state in nuclear physics. The report of evidence for the fleeting existence of this state has implications for research into neutron stars.

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Atomic nuclei are composed of protons and neutrons, generically known as nucleons. These are not genuine elementary particles because they contain quarks and gluons, which interact with each other through the strong force (one of the four fundamental forces of nature). The strong interaction has subtle properties, with the most unsettling one being that quarks and gluons are never free, only confined within nucleons. Theorists continue to struggle to find exact solutions for various states of the highly complex quark–gluon systems, and to explain the nucleon–nucleon force that extends beyond the confinement region. One long-sought state is the four-neutron system known as the tetraneutron, which has no electric charge. Writing in *Physical Review Letters*, Kisamori *et al.*[1] present evidence for the existence of such a state.

In the authors' experiment, strongly bound α-particles (composed of two protons and two neutrons, and therefore identical to helium-4 nuclei) in liquid helium-4 (^{4}He) are used as a target for an incident beam of helium-8 (^{8}He, the 'projectile nucleus'). ^{8}He has two protons and six neutrons, and is produced in nuclear-fragmentation reactions in which oxygen-18 hits a beryllium target. The reaction between ^{8}He and ^{4}He is an appropriate choice for generating tetraneutrons, because the four 'extra' neutrons in ^{8}He are weakly bound and can be easily transformed in the interaction with ^{4}He.

The authors observed that the ^{8}He projectile exchanges two units of charge with the ^{4}He target and becomes a beryllium-8 nucleus (^{8}Be, four protons and four neutrons), the energy of which was measured with high precision. Because of charge conservation, the two protons in the target ^{4}He nucleus are substituted by neutrons, momentarily generating a four-neutron system in a quasi-bound state. This lasts only a few multiples of 10^{-22} seconds, after which it disassembles into free neutrons. This short-lived state appears as a bump in the energy spectrum of the ^{8}Be nucleus that emerges from the reaction.

Nuclear forces are essentially identical between all nucleons, whether they are protons or neutrons. So it might seem strange that the tetraneutron is not bound but that the α-particle of two protons and two neutrons is strongly bound, despite the additional electrical repulsion between protons. The explanation is based on the Pauli exclusion principle, which forbids two identical nucleons from occupying the same quantum state. In the α-particle, all four particles can be in the same state because the two protons have opposite spins, as does the pair of neutrons, so that all four nucleons are different. But for four neutrons, only one pair can be in the lowest-energy state, forcing the second pair into a state of higher energy, thus making the tetraneutron unstable.

By applying the principle of energy conservation to the studied nuclear reaction, Kisamori and colleagues infer that the tetraneutron system has an internal excitation energy of about 0.8 million electronvolts (MeV); the excitation energy is the difference between the tetraneutron mass and the mass of four free neutrons. If this quantity were less than zero, the system would be bound. For the observed tetraneutron it is positive, making it an unbound system that exists for a short time before it decays into free neutrons. The statistical error (± 0.65 MeV) and systematic error (± 1.25 MeV) in the experiment are large, but the case for the existence of the tetraneutron is compelling. The width of the bump in the ^{8}Be energy spectrum is about 2.6 MeV, and this energy uncertainty suggests that the state will eventually decay to another quantum state.

The hunt for the tetraneutron has been going on for more than half a century, and experimentalists have announced the state's discovery before. In 2002, one collaboration claimed to have found a bound tetraneutron[2] in an experiment based on the detection of neutron clusters formed by fragmentation of beryllium-14 projectiles. But the result remains unconfirmed, and theorists quickly showed that, based on the best knowledge of the nucleon–nucleon interactions and other arguments[3,4], the existence of a bound tetraneutron was nearly impossible.

However, theorists could not rule out the existence of a tetraneutron as a short-lived 'resonant' state on the basis of a dineutron–dineutron structure[3,4]. The dineutron state is formed by two neutrons, and is not stable. It is known as a virtual state: if its energy were reduced by 66 keV, then the dineutron system would become bound. Decades earlier, it had been proposed[5] that dineutrons can become bound in the presence of additional nucleons; this

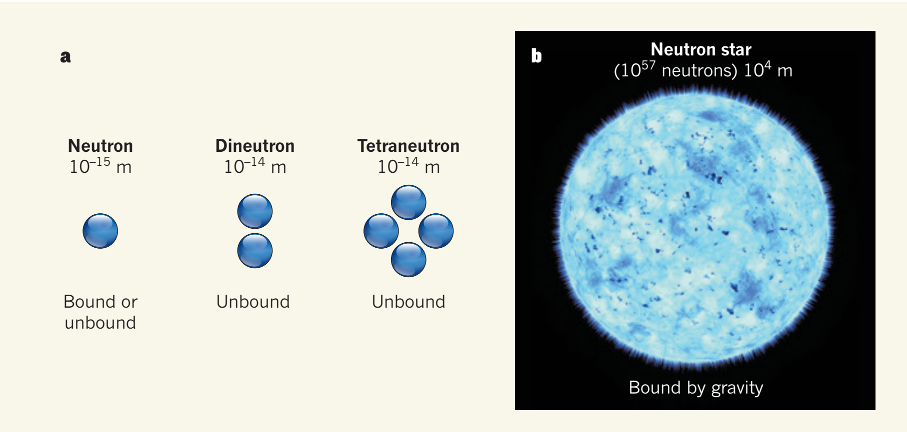

Figure 1 | Neutron systems. a, Neutrons have a radius of about one femtometre (10^{-15} m), and can be either bound in a nucleus or free (although unbound neutrons decay within about 15 minutes). Dineutrons, composed of two unbound neutrons, are ten times larger and unstable. Kisamori and co-workers[1] report evidence for a tetraneutron (a system of four neutrons) that exists in a resonant state for about 10^{-22} seconds before dissociating into free neutrons. **b**, If the existence of the tetraneutron state is confirmed, it will help to clarify nuclear interactions in few-nucleon systems, and possibly even in neutron stars.

mechanism is responsible for the properties of some bound nuclei that have a neutron excess, such as lithium-11, in which a pair of external neutrons forms a remote halo around the core of lithium-9.

The tetraneutron cannot form an atomic nucleus because it is charge neutral and therefore cannot hold electrons. But there is an intimate relationship between the tetraneutron structure and theoretical studies of neutron stars (Fig. 1), in which neutrons are compressed to densities more than 10^{14} times that of water[6]. They are prevented from imploding by an outward pressure that is generated by the nucleon–nucleon interaction and other quantum-mechanical effects.

Nuclear physicists hope to develop a full understanding of how quarks and gluons inside nucleons generate nucleon–nucleon forces, and how many-body objects evolve to form complex structures such as the uranium nucleus and neutron stars. This is a formidable task, with well-understood parts but also many missing links. If Kisamori and co-workers' report of the tetraneutron state is confirmed, even as a short-lived resonance, it will add another structure to the nuclear chart that will help to improve our understanding of the nuclear interaction. ■

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