Nuclear physics

Heaviest oxygen isotope is found to be unbound

Rituparna Kanungo

The isotope oxygen-28 is expected to be 'doubly magic', with strongly bound neutrons and protons in its nucleus. Experiments now reveal that it exists in an unbound state – casting doubt on its magic status. **See p.965**

Atomic nuclei form the core of all visible matter in the Universe, and comprise protons and neutrons that reside in shells – each of which has a different energy[1,2]. When neutrons or protons fill a shell completely, and that shell is separated from the next by a large energy gap, the nuclei are said to have a magic number of neutrons or protons. These nuclei are extremely strongly bound. With 8 protons and 20 neutrons, the most neutron-rich oxygen isotope ever seen, oxygen-28, should be 'doubly magic'. However, on page 965, Kondo *et al.*[3] report that ^{28}O is formed only momentarily and decays quickly into four neutrons and the bound nucleus oxygen-24. The observed unbound state, known as a resonance, calls into question whether 20 really is a magic number for neutrons in very neutron-rich nuclei.

The sustainability of life on Earth relies on nuclear shells: the vast majority of the oxygen nuclei in the air that we breathe (oxygen-16) is doubly magic because it has eight protons and eight neutrons. This makes it highly abundant. Adding neutrons to ^{16}O creates heavier oxygen isotopes; the larger ones become short-lived because they have many more neutrons than protons. This imbalance leads to isotopic decay through a process known as β-ray emission. The presumed strong binding of ^{28}O, expected to be the next doubly magic oxygen isotope after ^{16}O, should have made it easy to find, but methods designed to observe these bound nuclei have so far come up short[4]. In fact, no oxygen isotopes heavier than ^{24}O have been observed in bound form. The discovery of bound ^{24}O revealed 16 to be a previously unknown magic number[5,6], but the ^{28}O nucleus remained elusive, obscuring the fundamental principles behind nuclear shell structure.

Experiments on isotopes of elements spanning from fluorine to magnesium in the periodic table have revealed a smaller-than-expected energy gap beyond the last closed shell in nuclei with 20 neutrons[7–10]. This small gap allows shells at higher energy levels to become occupied unexpectedly – giving rise to arrangements termed intruder configurations. It is not clear whether this situation can arise in oxygen isotopes, however, because theory predicts that these nuclei would simply revert to their normal configurations[11].

Kondo *et al.* achieved the challenging feat of finding ^{28}O using the world's most powerful cyclotron particle accelerator. They energized an intense beam of stable calcium-48 isotopes to a total energy of around 16 billion electronvolts, and smashed it against a rotating wheel of beryllium foils. The collision fragmented the ^{48}Ca into lighter nuclei, most of which were short-lived, rare isotopes. With a speed close to that of the original beam, these fragments flew through a spectrometer that sifted out nuclei of the isotope fluorine-29.

^{29}F has one proton more than ^{28}O, and is the heaviest of the known bound nuclei with 20 neutrons[9]. The ^{29}F isotopes were separated from the other fragments, then collided with a liquid-hydrogen target[12], to knock off a proton and form ^{28}O (Fig. 1). In the hope of finding evidence that the ^{28}O isotopes might exist in an unbound state, the authors tagged and tracked the resulting decay products (four neutrons and a bound ^{24}O nucleus). This is extremely challenging, because the four neutrons must be tagged unambiguously, and must have sufficient power to make them detectable. An international team of scientists brought together detectors[13] and expertise from several countries to accomplish this task.

A large-acceptance spectrometer[14] (a device designed to measure the trajectories of almost all the particles produced in collisions) bent the path of the ^{24}O nuclei and simultaneously tagged them. Kondo *et al.* measured the momentum vectors of all five decay products and used the results to derive the energy spectrum of ^{28}O. This spectrum peaks at a rather low energy of around 0.5 megaelectronvolts; no lower-energy peak was observed, implying that this is the lowest energy (ground) state of ^{28}O. The finding challenges all theoretical predictions, most of which suggest that the resonance occurs at an energy higher than that

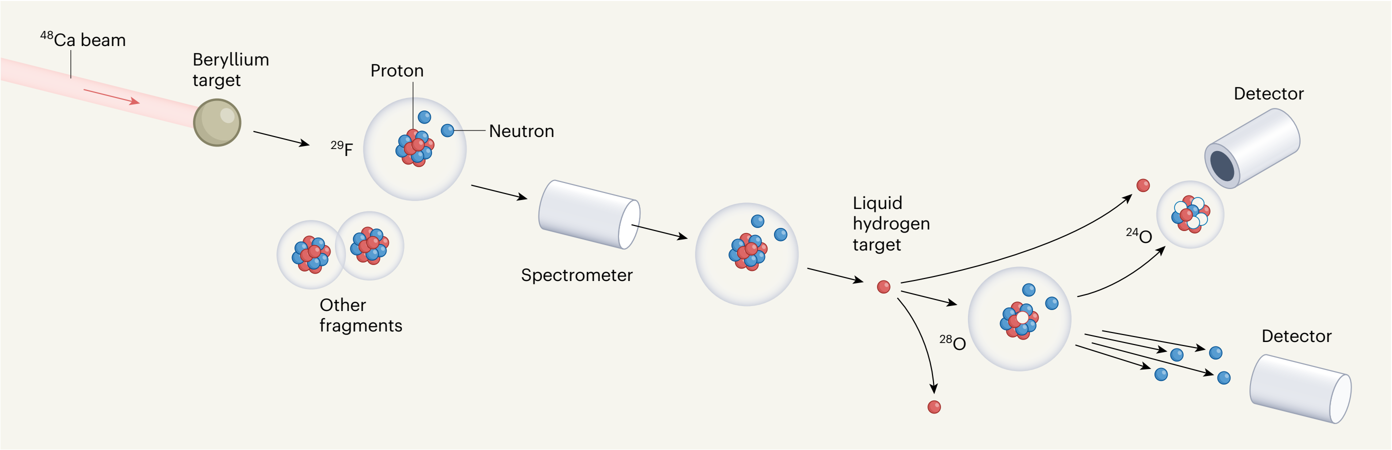

Figure 1 | An experiment to discover oxygen-28. Nuclei of the heaviest oxygen isotope, ^{28}O, are expected to be strongly bound, but Kondo *et al.*[3] found evidence that they are not. The authors fired a beam of calcium-48 isotopes at a beryllium target, fragmenting them into lighter nuclei, including fluorine-29. They used a spectrometer to sift out the ^{29}F nuclei, which have the same number of neutrons as ^{28}O, but one proton more. These nuclei then collided with a liquid hydrogen target, knocking off the extra proton to form ^{28}O. Four neutrons and an oxygen-24 nucleus were detected as the decay products of each ^{28}O nucleus, revealing that the ^{28}O isotopes exist in an unbound state.

observed, and one of which predicts a lower energy[3]. The result therefore sets a new benchmark in constraining these models.

In the same measurement, a resonance state for oxygen-27 was observed. Its energy was about 1.09 MeV – higher than that of ^{28}O, so ^{27}O cannot have been a decay product of ^{28}O. The resonance state of oxygen-25 was previously observed[15] at a lower energy than that of ^{27}O, but higher than that of ^{28}O, preventing ^{25}O from providing a decay route for ^{28}O. The lowest-energy resonance state known for nuclei heavier than ^{24}O is that of the oxygen-26 nucleus, at around 0.018 MeV (ref. 16). The authors therefore concluded that ^{28}O decay proceeded sequentially – by first emitting two neutrons to form a ^{26}O nucleus, and then emitting two more neutrons to form the bound ^{24}O nucleus.

Kondo *et al*. discuss the evidence that the 20-neutron shell is unclosed on the basis of the scenario that the neutrons remain undisturbed during the knockout of the proton from ^{29}F. It was expected that the energy gap beyond oxygen's outermost proton shell would be so high that there would be just one proton in the outermost shell of ^{29}F. The authors' value for the ground-state energy of ^{28}O is reasonably close to the predicted value of 0.68, when known corrective factors are taken into account, making it consistent with this scenario. The same model also predicts that a large proportion of neutrons occupy intruder orbitals in both ^{29}F and ^{28}O, which would explain why the shell remains unclosed. Direct evidence of these intruder orbitals is challenging to obtain, but worth pursuing.

The measured momentum distribution of the knockout proton can reveal which orbital it lies in, and the authors concluded that proton emission from a single orbital describes this distribution best, although not perfectly. Under the assumption that ^{28}O was seen in its ground state, Kondo *et al*. ruled out the possibility that the proton occasionally came from other orbitals. Measurements with lower uncertainties might help to clarify the situation in future, as will a deeper understanding of the angular momentum of the ^{29}F ground state.

"The authors achieved the challenging feat of finding ^{28}O using the world's most powerful cyclotron."

The first excited state of ^{28}O is yet to be found, but its energy will be crucial in understanding the unclosed neutron shell. The energy gap between the ground state and the first excited state can be used to determine the energy gap between shells for nuclei that have even numbers of both neutrons and protons. Exploring other reactions that produce ^{28}O might also shed light on its brief, unbound existence, although this is a daunting task. In the absence of such experiments, Kondo and colleagues' impressive finding provides much-needed insight into the physics of doubly magic nuclei at the limits of nuclear binding.

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