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RESEARCH HIGHLIGHT

Unbound ^{28}O, the heaviest oxygen isotope observed: a cutting-edge probe for testing nuclear models

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The beyond-dripline oxygen isotopes ^{27,28}O were recently observed at RIKEN, and were found to be unbound decaying into ^{24}O by emitting neutrons. The unbound feature of the heaviest oxygen isotope, ^{28}O, provides an excellent test for state-of-the-art nuclear models.

The atomic nucleus is a self-organized quantum many-body system comprising specific numbers of protons Z and neutrons N. The nuclear force, which binds protons and neutrons together, favors equal numbers for each particle. In contrast, the long-range Coulomb repulsion discourages the accumulation of protons in the nucleus. The competition between these two forces determines the *valley of stability*. However, the strong internucleon interaction binds nuclei even when many more neutrons than protons are added. Extreme N/Z asymmetry has been observed in light-neutron-rich nuclei. The particle-stable nuclei are classified as bound nuclei, which indicates that the protons and neutrons of the isotopes can be bound by nuclear forces unless radioactive decay (β decay) transforms them into other nuclei. The existence limit of the bound isotopes for a given proton number is known as the neutron or proton dripline at the neutron-rich or proton-rich edge, respectively. Beyond the driplines, nuclei may momentarily exist as resonances before emitting neutrons or protons, with very short lifetimes.

As extreme examples of particle-unstable exotic nuclei, unbound ^{27,28}O were recently produced by Kondo et al. using a proton-induced nucleon knockout with a high-energy ^{29}F beam at RIKEN [1]. The heaviest oxygen isotopes, ^{27,28}O, occur beyond the neutron dripline, ^{24}O, and appear in resonances. They quickly decay into ^{24}O through ^{26}O via sequential neutron emissions. As illustrated in Fig. 1, the ^{27}O and the ^{28}O undergo a $1n$-$2n$ and a $2n$-$2n$ emission process, respectively. Measurements of the emitted neutrons yielded ^{28}O at a ground-state energy of approximately $0.46^{+0.05}_{-0.04}$(stat) $\pm$ 0.02(syst) MeV above that of ^{24}O with an upper limit on the resonance width of 0.7 MeV [1]. Likewise, ^{27}O was obtained at an energy of approximately 1.09 $\pm$ 0.04(stat) $\pm$ 0.02(syst) MeV above that of ^{24}O with an upper limit on the width of 0.18 MeV, see Fig. 2.

The heaviest ^{28}O, which contains eight protons and 20 neutrons, is of special interest as it touches the 'expected' $N = 20$ magic shell. However, the experiment [1] supports an unclosed $N = 20$ shell in the oxygen chain, which is consistent with previous predictions [2–7]. Further experiments on a possible 2^+ excited state may be required to conclude the unclosed shell at $N = 20$. In the experimental study [1], the data of the ^{27,28}O ground-state energies were compared with different calculations or predictions, showing that none of the calculations reproduced the data well. In addition to the theoretical calculations mentioned in the Nature publication [1], Gamow shell model (GSM) calculations performed by a theoretical group at Peking University (PKU) [8, 9] show excellent predictions [8, 9] compared with the data reported in Ref. [1], as shown in Fig. 2. Unfortunately, the PKU predictions [8, 9] are missing in Ref. [1].

In the published calculations [8, 9], we used the advanced GSM, which takes into account coupling to the continuum. Continuum coupling is important for weakly bound and unbound nuclei as open quantum systems, whereas the continuum effect is absent in the models mentioned in Ref. [1]

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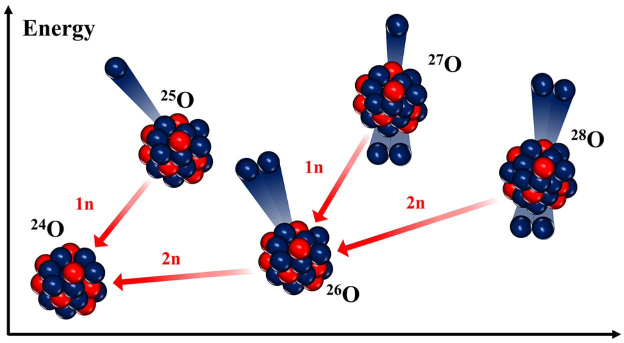

Fig. 1 (Color online) Schematic of the decay processes of the particle-unstable isotopes $^{25-28}$O

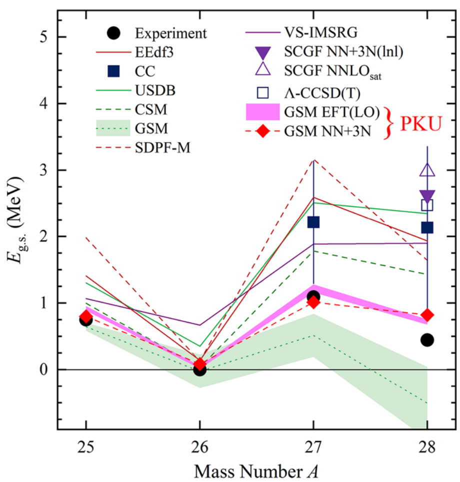

Fig. 2 (Color online) Experimental [1] and calculated $^{25-28}$O ground-state (g.s.) energies with respect to ^{24}O. Our calculations are labeled by GSM EFT(LO) [8] and GSM NN+3N [9]. Other calculations marked by EEdf3, CC, USDB, CSM, GSM, SDPF-M, VS-IMSRG, SCGF NN+3N(lnl), SCFG NNLO$_{sat}$, and Λ-CCSD(T) are explained in the original paper [1]

except for the continuum shell model [10] and GSM with phenomenological interactions [11]. In our calculations [8], a leading-order pionless effective field theory force denoted as EFT(LO) was used with only one parameter that was fitted by the binding energies of $^{24-26}$O. Various regulators for the interaction were used, showing that regulator cutoffs larger than a certain value resulted in stable calculations, as shown in Fig. 2, where the pink band indicates the range of calculated energies with cutoffs of $\Lambda = 356$, 390, and 436 MeV [8]. In another study [9], we performed ab initio GSM calculations based on chiral two- and three-nucleon interactions, which showed that both continuum coupling and three-nucleon forces were important for weakly bound and unbound nuclei. These two studies [8, 9] yielded similar results, as shown in Fig. 2, grouped by PKU labels. The predicted energies [8, 9] of ^{27,28}O were consistent with the experimental data [1] and clearly better than the other calculations reported in Ref. [1]. On the other hand, both of our studies [8, 9] showed that the inclusion of *pf* shell is necessary in the calculations for *sd*-shell weakly bound and unbound nuclei. Unbound ^{27,28}O have significant *pf* components that may be associated with the disappearance or weakening of the $N = 20$ shell closure, as claimed in Ref. [1]. Based on our calculated energies and one-body densities, we predicted [8] that ^{28}O should undergo four-neutron decay, more specifically a $2n$-$2n$ emission process through ^{26}O, which is consistent with experiments [1]. The observation of ^{28}O has opened up a new window to probe into the elaborate internucleon interplay under extreme conditions.

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