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RESEARCH HIGHLIGHT

Multi-proton emission at the limits of nuclear stability: challenges for extreme open quantum systems

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Introduction—Nuclei near and beyond the proton drip line represent a fascinating frontier in the nuclear landscape. Proton-rich nuclei exhibit intriguing phenomena, such as the Thomas-Ehrman shift and proton-halo structure. Beyond the proton dripline, nuclei become unbound, allowing protons to be emitted and giving rise to novel radioactive decay modes. Single-proton radioactivity, a process in which some nuclei with an odd number of protons (Z) decay by ejecting a proton, was discovered several decades ago and has been extensively studied [1, 2]. In comparison, two-proton ($2p$) radioactivity, which involves the simultaneous emission of two protons from some even-Z nuclei, was discovered in 2002 [3, 4]. This most recently identified decay mode, along with related phenomena, remains an active topic of research in nuclear physics [5–18]. More recently, multiproton emission processes—such as three-, four-, and five-proton emission—have been observed in the decays of some extremely neutron-deficient nuclei. These exotic decay modes provide powerful spectroscopic tools for probing the structure and decay properties of proton-rich nuclei far from the valley of stability, serving as ideal laboratories to explore exotic nuclear phenomena and test open quantum system theories under extreme conditions.

One of these exotic features that often emerges near and beyond the dripline is mirror and isospin symmetry breaking [19], driven by the large proton–neutron imbalance of dripline nuclei. Isospin symmetry is a fundamental concept in nuclear physics, positing that mirror nuclei—those with exchanged numbers of protons and neutrons—should exhibit nearly identical structures, that is, states with the same spins and parities and closely similar excitation energies. Under this symmetry, the ground states (g.s.) of the mirror nuclei are expected to have the same spins and parities. While isospin symmetry holds to a good approximation in most nuclei, striking deviations from this rule are of great interest, as they reveal subtle aspects of the nuclear structure and the underlying interactions.

Discovery of the three-proton emitter ^{20}Al—In a recent article published in *Physical Review Letters* [20], Xu, Mukha, Li *et al*. reported the first observation and spectroscopy of the previously unknown isotope ^{20}Al. This study revealed that ^{20}Al is unbound with respect to the emission of three protons, as shown in Fig. 1. The determined decay energy of ^{20}Al g.s., combined with a thorough analysis of its g.s. spin-parity, provided evidence for isospin symmetry breaking in the mirror pair of ^{20}Al and ^{20}N.

The experiment was performed at the Fragment Separator of the GSI Helmholtz Centre for Heavy Ion Research in Darmstadt, Germany. The very neutron-deficient nucleus ^{20}Al was produced in a charge–exchange reaction and decayed promptly by emission of protons. By tracking the trajectories of all its decay products with silicon microstrip detectors, ^{20}Al was observed for the first time. ^{20}Al has seven fewer neutrons than the stable aluminium isotope and lies beyond the proton drip line. It is the lightest aluminium isotope that has been discovered so far.

The authors performed a detailed analysis of angular correlations of ^{20}Al's decay products and found that the ^{20}Al g.s. decays by sequential $1p$–$2p$ emission via intermediate g.s. of ^{19}Mg. Specifically, the ^{20}Al g.s. first decays by ejecting one proton to the g.s. of ^{19}Mg, followed by the subsequent decay of ^{19}Mg g.s. via simultaneous $2p$ emission. ^{19}Mg is a known case of g.s. $2p$ radioactivity [21]. Consequently, ^{20}Al is the first observed $3p$ emitter, where its $1p$ decay daughter nucleus is a $2p$ radioactive nucleus.

The decay energy of the ^{20}Al g.s. was determined to be $1.93^{+0.12}_{-0.10}$ MeV. It is significantly smaller than the predictions

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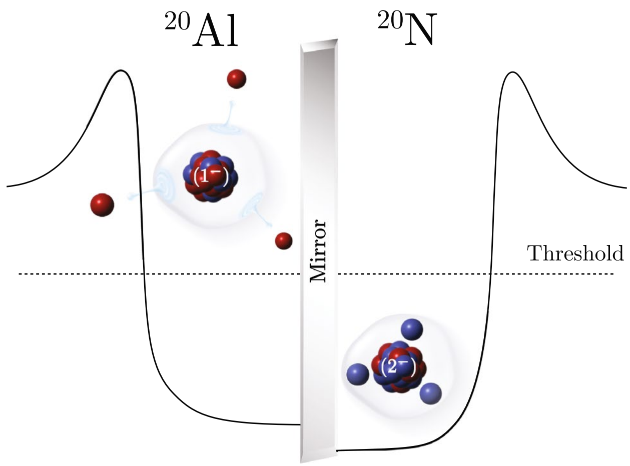

Fig. 1 (Color online) Schematics illustrating isospin symmetry breaking between the three-proton emitter ^{20}Al and its mirror partner ^{20}N

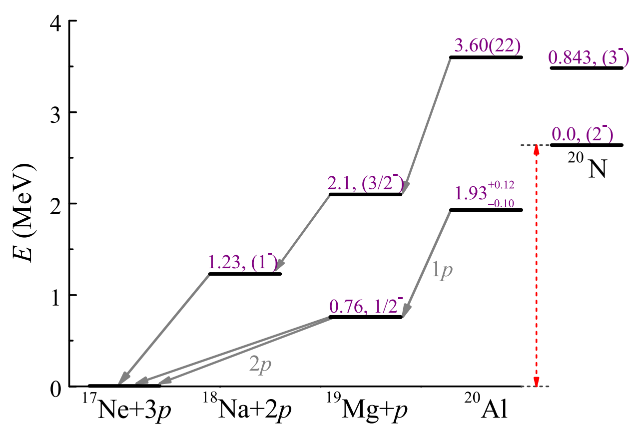

Fig. 2 Proposed decay scheme of the states observed in ^{20}Al with decay channels via ^{19}Mg and ^{18}Na states, whose decay energies are given relative to the 3*p*, 2*p* and 1*p* thresholds, respectively. On the right, the two lowest levels of ^{20}N are depicted, with their energies shifted by the mirror energy difference expected for the ^{20}N–^{20}Al pair. Adapted from Ref. [20]

inferred from the isospin symmetry by employing the neutron separation energy of ^{20}Al's mirror partner ^{20}N, which leads to an enhanced energy shift of the ^{20}Al g.s. relative to the ^{20}N g.s., as shown in Fig. 2. The unexpectedly low decay energy of ^{20}Al indicates a possible isospin symmetry breaking in ^{20}Al and ^{20}N.

Theoretical developments and challenges—Observation of the three-proton emitter ^{20}Al provides an ideal testing ground for modern theoretical frameworks of open quantum systems. To properly describe these exotic multi-particle emitters, the structural and decaying aspects need to be considered simultaneously. Although there is currently no comprehensive theory on the market, many frameworks are developing towards this direction [5, 7, 8, 22]. Particularly, in recent years, the Gamow shell model (GSM) [23, 24] and Gamow coupled-channel (GCC) approaches [25–27] have been developed to describe weakly bound and unbound nuclei by employing the Berggren basis, which consistently incorporates bound, resonant, and scattering states. In details, the former emphasizes the role of the continuum in shaping many-body correlations, whereas the latter focuses on the decay dynamics of nuclear states, highlighting the interplay between intrinsic structure and low-lying continuum couplings.

Both state-of-the-art frameworks have been applied to study ^{20}Al. In particular, the GSM calculations predict a dominant $s_{1/2}$ configuration for the valence protons in ^{20}Al, leading to a $J^{\pi} = 1^{-}$ ground state, whereas its mirror partner ^{20}N exhibits a $J^{\pi} = 2^{-}$ ground state. This spin-parity difference highlights the breaking of the isospin symmetry beyond the proton drip line (Fig. 1). GCC calculations, treating ^{20}Al as a deformed ^{18}Mg core plus valence nucleons, further support this interpretation and underline the importance of core deformation and continuum coupling in shaping the low-lying spectrum of multiproton emitters [25, 28–31].

Despite these advances, theoretical descriptions of multiproton emissions remain highly challenging. First, accurate predictions require a delicate balance between effective nucleon–nucleon interactions, continuum treatment, and few-body asymptotic behaviour. In addition, a fully microscopic framework is anticipated to describe the exotic structures and decaying dynamics on the same footing. However, this requires complicated frameworks and large computational resources. Finally, the scarcity of high-statistic experimental data on higher-order proton emitters limits the benchmarks available to validate theoretical predictions.

Outlook for multi-particle emissions—The discovery of ^{20}Al as a sequential 1*p*–2*p* emitter opens the door for systematic studies of even more exotic multiproton emission phenomena. Known cases of 3*p* emission, such as ^{31}K [32] and ^{17}Na [33], suggest that sequential emission modes dominate, whereas democratic decay mechanisms may emerge at higher excitation energies. Looking further ahead, ^{18}Mg has been claimed to be a candidate for four-proton emission, most likely proceeding via a sequential 2*p*–2*p* mechanism [34]. Similar processes are also expected in ^{8}C and in the neutron-rich system ^{28}O. Even more exotic modes, such as the reported five-proton emission from ^{9}N [35], push the limits of nuclear stability. Further theoretical and experimental work will be required to determine whether the ground state of ^{9}N is a genuine resonance or merely a scattering feature [7].

In addition to g.s. decays, multi-particle emissions from the nuclear excited states have also been observed [36]. For example, the excited states of ^{22}Mg [10, 11] provide a new dimension for exploring these exotic processes and gaining deeper insights into the dynamics of extreme open quantum systems. However, the very short lifetimes and non-localized nature of such excited states make their structures and decay mechanisms particularly challenging to unravel.

Future developments in both theory and experiment are crucial. On the theoretical side, the integration of chiral effective field theory interactions [37] with continuum-embedded models and the inclusion of three-nucleon forces will be essential for quantitative predictions. On the experimental side, next-generation radioactive beam facilities (e.g. FRIB, RIKEN, FAIR, and HIAF) with advanced detection systems will enable measurements of angular correlations, energy spectra, and lifetimes with unprecedented precision. Such coordinated efforts will not only test the robustness of isospin symmetry at the limits of stability, but also extend our knowledge of nuclear structure into the regime of chaotic multi-particle decays, potentially reshaping our understanding of the nuclear landscape far beyond the drip lines.

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