NUCLEAR PHYSICS

Odd couple decays

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The decay of proton-rich nuclei by the emission of a single proton has been known about for some time, and is well understood. The latest observation of two-proton emission, however, will provoke some head-scratching.

On page 298 of this issue[1], Mukha and colleagues report the simultaneous emission of two protons from a complex, long-lived state of the silver isotope ^{94}Ag, which has an odd number of protons. This type of radioactive decay is expected only for proton-rich nuclei with an even number of protons — so the observation leaves nuclear physicists with some explaining to do.

Whether an atomic nucleus is stable or decays depends on the interplay between two fundamental forces: the short-range, attractive strong nuclear force and the longer-range, repulsive electromagnetic Coulomb force. Whereas the strong force acts between all the nucleons (protons and neutrons) that make up the nucleus, the Coulomb force acts only between protons. This means that in nuclei that are extremely rich in protons — said to lie beyond the 'proton drip-line' (Fig. 1) — the strong force can no longer bind all protons, and such nuclei can decay through the emission of one or two protons.

In these rare radioactive decays, protons tunnel quantum mechanically out of the nucleus, through the energy barrier formed by the combined effect of the strong and Coulomb forces. In the lowest allowed energy state of a nucleus, it is energetically favourable for protons or neutrons to pair up. Single-proton emission is therefore expected to occur among proton-rich nuclei that have an odd number of protons, whereas two-proton emission should be characteristic of nuclei with an even number of protons.

Single-proton radioactivity was discovered[2] several decades ago in the decay of an excited state of cobalt-53 to the ground state of iron-52. Today, about 30 different single-proton radioactivities are known[3] for nuclei with proton numbers between 50 and 84, and the phenomenon is fairly well understood theoretically. In contrast, two-proton radioactivity was observed only recently[4,5] — from the ground states of isotopes of iron, nickel and zinc, ^{45}Fe, ^{48}Ni and ^{54}Zn, all of which have an even number of protons — and information on the energy and angular correlations of the emitted protons is incomplete. The emission of the protons was in all cases simultaneous; because of the extra energy required to break proton pairs, sequential emission is not energetically possible. A quantum-mechanical tunnelling model involving three bodies — two protons and a remnant core nucleus — describes the observations satisfactorily[6], but for the process to be further elaborated theoretically, more precise information is required about the lifetime and decay energy of the system, and about the energy and angular correlations between the emitted protons.

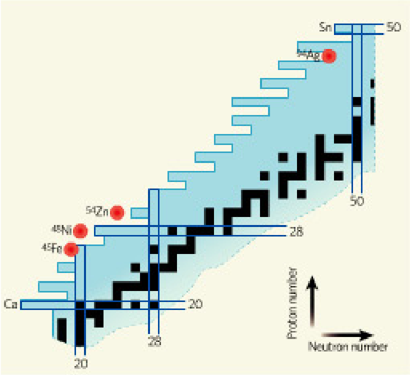

Figure 1 | Rich in proton. A part of the nuclide chart displaying proton-rich nuclei between calcium (Ca) and tin (Sn). The isotopes framed by the jagged solid line at the top (the 'proton drip-line') are predicted to be bound (that is, stable against proton emission). The black squares denote stable isotopes; proton and neutron numbers 20, 28 and 50 are 'magic' nucleon numbers for which nuclei are especially stable[7]. The isotopes with recently discovered two-proton radioactivities are shown by red circles. Three of them, ^{45}Fe, ^{48}Ni and ^{54}Zn (refs 4, 5), are outside the proton drip-line and decay through two-proton radioactivity from the unbound ground state. In the case of ^{94}Ag, the ground state is bound against one-proton and two-proton emission — but the high-spin state investigated by Mukha *et al.*[1] is unbound for these decay modes.

The two-proton radioactivity observed by Mukha and colleagues[1] was from ^{94}Ag nuclei, not in their ground state, but in a metastable, long-lived, high-spin state that the authors produced by bombarding a nickel-58 target with a beam of calcium-40 ions. They also contrived to measure the energy and angular correlations of a two-proton decay for the first time; the proton–proton and proton–nucleus correlations derived are characteristic of simultaneous rather than sequential emission. As ^{94}Ag was already known to undergo single-proton decay, Mukha and colleagues' state is the first for which both one- and two-proton decay modes have been shown to exist.

All previous studies of the two-proton decay of short-lived nuclear resonances from which sequential decay is energetically possible have proved that these decays are indeed exclusively sequential. Sequential emission is probably suppressed in ^{94}Ag because the daughter state that is populated by the first of two sequential decays would be an excited state of the palladium isotope ^{93}Pd. Rather than emitting a second proton, this state would tend to decay electromagnetically — by emitting a photon — to its ground state. But why does the energetically unfavourable simultaneous two-proton decay itself occur with such high probability?

Mukha *et al.* tackle this question using a simple model[1] that neglects any interaction between protons, but that is consistent with the observed energy and angular correlations as well as the half-life of the ^{94}Ag nucleus. Their model describes the decay as two independent emissions at either end of a strongly prolate (cigar-like) super-deformed nucleus. The authors supply a similar calculation that assumes the emission of a correlated proton pair with a relative spin of zero (a so-called ^{2}He model). However, the small number of events, and consequent limited accuracy of the results, does not allow the two modes to be distinguished. Further work is also needed to independently characterize the structure and shape of the complex high-spin ^{94}Ag state and thus allow a more detailed interpretation of the process.

Two-proton radioactivity can provide far-reaching insights into problems of low-energy quantum-mechanical tunnelling in strongly interacting systems. A full elucidation of the nature of such decays — whether from the ground state or from fast-spinning excited states — will be a major goal for further experiments at current and future radioactive ion-beam facilities. ■

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