Nuclear Structure Information Derived from Proton Radioactivity Measurements

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Recent results on proton radioactivity are described. Nuclear structure information such as spins, single particle orbital orderings, spectroscopic factors, and mass excesses have been obtained for a number of spherical proton emitters. New results on deformed proton emitters are discussed.

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1. Introduction

Proton decay presents an opportunity to obtain nuclear structure information for a nucleus situated beyond the proton drip line. This relatively rare decay mode is a quantum tunneling phenomenon where the decay rate is determined by a delicate interplay between the Coulomb and centrifugal terms of the nuclear potential. Ground-state proton emitters have been discovered for the odd-Z elements having $Z=51-55$, 63 , and $67-83$. These are shown in Figure 1.

Fig. 1 N-Z plot for $Z > 50$ showing the known proton emitters.

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Figure 2 shows a plot of the nuclear potential against radius for a spherical proton emitter, for 2 values of the angular momentum l carried off by the emitted proton. The potential consists of the real part of the optical model potential of Becchetti and Greenlees [1], plus the Coulomb and centrifugal terms. The large difference in the shape and height of the potential barrier in the two cases translates into decay rates differing by more than 4 orders of magnitude for a given proton energy, as is shown in the table inset. Measurements of the proton energy and partial half-life thus allow a unique spin assignment to be made for the proton-emitting state of a spherical or near-spherical nucleus.

Fig. 2 Radial behavior of the spherical nuclear potential seen by a proton emitted from ^{167}Ir . The inset shows half-lives calculated using the WKB approximation.

Reported here are experiments on proton radioactivity performed at the Fragment Mass Analyzer (FMA) at Argonne National Laboratory. To observe the protons, an implantation system based on a double-sided silicon strip detector (DSSD) has been constructed behind the FMA focal plane. In this system, radioactive reaction products enter the FMA, are mass-separated on a microsecond time scale, pass through the focal plane detector, and are implanted into the DSSD. The DSSD has 48 strips on each face, with the strips on one side being orthogonal to those on the other. This arrangement provides position

information in two dimensions in quasi-pixel fashion. The proton and alpha decays of the implanted nuclei will occur in the same pixel. Two types of events in the DSSD are recorded: implants and decays, according to whether they are in coincidence (anticoincidence) with a focal plane detector signal. Each event is time stamped, and thus the arrival of a reaction product and its subsequent decay can be correlated. In this way the parent-daughter information allows branching ratios and half-lives to be obtained, as well as the decay paths. Additional background suppression and recoil mass identification is provided by the parallel grid avalanche detector (PGAC) at the FMA focal plane. The excellent position and energy resolution of the DSSD combined with the fast mass separation and high efficiency of the FMA provides a system of unparalleled sensitivity for investigating the decays of short-lived low-yield exotic nuclei.

Figure 3 shows a typical M/q (mass/charge) spectrum at the focal plane, obtained during the bombardment of ^{92}Mo with 357 MeV ^{78}Kr ions. The M/q acceptance of the FMA is $\pm 4\%$, allowing up to three charge states of the same mass to be implanted into the DSSD with essentially uniform illumination.

Fig. 3 M/q spectrum for $^{78}\text{Kr} + ^{92}\text{Mo}$ measured at the FMA focal plane.

2. The Decay of ^{167}Ir

We illustrate some typical results obtained in these experiments with the study of the proton emitter ^{167}Ir [2]. Figure 4(a) shows the decay energy spectrum in the DSSD from the 357 MeV $^{78}\text{Kr} + ^{92}\text{Mo}$ experiment. Figure 4(b) shows the same data after requiring that a mass 167 implant was the decay parent and that the decay event occurred in the same pixel within 100 ms of the implantation. Figure 4(c) shows the data from Fig. 4(b) subjected to the additional requirements that a subsequent decay event occurred in the same pixel within 100 ms, with an energy of 6000 keV, the known alpha-decay energy of

^{166}Os . The two peaks at 1064(6) keV and 1238(7) keV are identified as being from the proton decay of two states in ^{167}Ir . From the time intervals between implantation and decay, the half-lives of the two ^{167}Ir proton groups were obtained.

Fig. 4. (a) Decay energy spectrum from 357 MeV $^{78}\text{Kr} + ^{92}\text{Mo}$. (b) Same as (a) after requiring that a mass 167 implant was the decay parent and that the decay event occurred in the same pixel within 100 ms of the implantation. (c) Same as (b) subjected to the additional requirements that a subsequent decay event occurred in the same pixel within 100 ms, with an energy of 6000 keV, the known alpha-decay energy of ^{166}Os .

In addition to the protons, two alpha lines associated with ^{167}Ir were observed, one strong group with an energy of 6410(5) keV and a previously unobserved weak group at 6351(5) keV. They were each identified by four generations of correlations through ^{163}Re and ^{159}Ta leading to two known alpha groups from the decay of ^{155}Lu . Combining the proton and alpha decay information shows that ^{167}Ir has a $1/2^+$ ground state ($t_{1/2} = 35.2(20)$

ms) and an $11/2^-$ isomeric state ($t_{1/2} = 30.0(6)$ ms), both of which have proton and alpha branches. Figure 5 shows the resulting decay scheme for ^{167}Ir . Figure 6 shows the decay scheme of correlated alphas from the decay of ^{167}Ir . The excitation energies and spins of the states involved have been deduced using measured half-lives, half-life calculations, and energy differences (see ref. [2] for more details).

Fig. 5 Decay scheme for ^{167}Ir .

Fig. 6 Decay scheme of correlated alphas from ^{167}Ir .

3. Spectroscopic Factors and Proton Half-Lives

Proton decay rates for the emitters with $69 \leq Z \leq 81$ have been reasonably well reproduced by WKB calculations assuming simple spherical shell model states. However, this method does not account for nuclear structure effects that may come into play when the overlap between parent and daughter nucleus is not complete. To address this problem, a low-seniority shell-model calculation of the spectroscopic factors for the proton emitters with $64 < Z < 82$ has been performed [2]. The assumptions used for this calculation were that the 18 protons occupy the $s_{1/2}$, $d_{3/2}$ and $h_{11/2}$ orbitals with degenerate single-particle energies, the residual interaction is a pairing force, and the neutrons are spectator particles. The spectroscopic factor is defined as the ratio between calculated and experimental proton half-life:

$$S^{\text{exp}} = \frac{t_{1/2,p}^{\text{calc}}}{t_{1/2,p}^{\text{exp}}}.$$

The results of the calculation show that the spectroscopic factor depends only on p , the number of pairs of proton holes below $Z = 82$ possessed by the daughter nucleus:

$$S(p) = p/9, \quad \text{with } 1 \leq p \leq 9.$$

Figure 7 shows the comparison between experimental and calculated spectroscopic factors for the known proton emitters for $69 \leq Z \leq 81$. As predicted, the spectroscopic

Fig. 7 Spectroscopic factors for new and previously observed proton emitters.

factors do indeed increase towards 1 as Z approaches 64. The large error bars on the experimental spectroscopic factors for the lighter proton emitters reflects large uncertainties in the beta branches for these nuclei. It is interesting to note that the points showing the largest disagreement with the model are all due to protons decaying from the $d_{3/2}$ orbital.

4. Mass Excesses and Proton Separation Energies

Information on mass excesses near and beyond the proton drip-line can be obtained by combining the Q -values from proton decay and α -decay. In this way comparisons can be made between the predictions of various mass models. As an example, the mass excesses of 11 nuclei involved in the alpha decay chains of ^{167}Ir and its proton daughter ^{166}Os have been obtained [2]. This was made possible because one nucleus at the end of the chain has a known mass excess. In addition, proton separation energies can be derived from Q and proton Q -values, enabling the proton drip-line to be precisely delineated. The trends in the proton separation energies also serve as guides in the search for new proton emission candidates.

5. Deformed Proton Emitters

The decay rates of a number of proton emitters cannot be explained by the use of the spherical WKB approximation. These include some of the earliest proton emitters discovered, ^{109}I and ^{113}Cs [3]. This failure has been attributed to the onset of prolate deformation. Calculations assuming Nilsson model states and treating deformation as a free parameter provide reasonable agreement with the data [4]. Proton emission from ^{141}Ho and ^{131}Eu has recently been observed at the FMA [5], and the decay rates cannot be explained by spherical WKB calculations. These nuclei are predicted to be highly deformed ($\beta \sim 0.3$) [6]. The observation of these and other proton emitters expected to be found in the $57 \leq Z \leq 65$ region should greatly increase our understanding of the role of deformation in the proton decay process.

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