INVESTIGATING PROTON EMITTERS AT THE LIMITS OF STABILITY WITH RADIOACTIVE BEAMS FROM THE OAK RIDGE FACILITY

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By using beams from the Holifield Radioactive Ion Beam Facility at the Oak Ridge National Laboratory it should be possible to identify many new ground-state proton emitters in the mass region from Sn to Pb. In these investigations nuclei produced in fusion-evaporation reactions will be separated from the incident ions and dispersed in mass/charge with a recoil mass separator and then implanted into a double-sided Si strip detector for the study of proton (and α-particle) radioactivity. This paper summarizes data presently extant on proton emitters and then focuses on tests and initial experiments that will be carried out with stable beams and with radioactive ions as they are developed at the Oak Ridge facility.

Because of the repulsive Coulomb force the proton drip line is located much closer to the valley of stability than the drip line on the neutron-rich side. Not only is the proton drip line more accessible, but even if a nucleus is proton unbound, the Coulomb barrier slows down proton emission. One can therefore obtain structure information for nuclei existing *beyond* the drip line, something that cannot be done on the neutron-rich side where decay takes place essentially instantaneously if the last neutron is unbound.

In proton decay an energetically unbound proton emerges from the nucleus by tunneling through the Coulomb and centrifugal barriers. Because only a single nucleon is involved, this process is simpler to describe than α decay since there is no particle preformation factor to consider. In addition, the decay width is much more sensitive to the shape and size of the centrifugal barrier (and therefore ℓ) than in the case of α-particle emission. Thus, measurements of proton-decay half-lives and energies can provide spectroscopic information. For example, the use of $\ell = 2$ and $\ell = 5$ potentials for the emission of a 1-MeV proton in the rare earth region results in two barrier penetration times that differ by a factor of 100.

Ground-state proton decay as a factor in determining the limit to nuclear existence had long been discussed in theoretical papers, but it was not observed until 1981 when ^{151}Lu was reported (1) to be a proton emitter. Within a few years other isotopes, ^{109}I, ^{113}Cs, and ^{147}Tm (and possibly ^{150}Lu) were found to decay by proton emission [see the summary in Ref. (2)]. Further searches proved not to be fruitful until 1992 when the Daresbury Recoil Separator was used, in conjunction with the newly-developed double-sided strip Si detectors (3), to observe proton decay from ^{156}Ta and ^{160}Re (4), ^{146}Tm (5), ^{150}Lu (6), and ^{112}Cs (7). The development of a more sensitive technique was necessitated by the fact that while the first set of emitters (2) were produced in (^{58}Ni, p2n) reactions induced on a variety of targets with cross sections of about 50 μb, the ones found at Daresbury, were produced in (^{58}Ni, p3n) reactions with cross sections down in the few μb range.

This same technique has now been used at Argonne National Laboratory during the past few years where a

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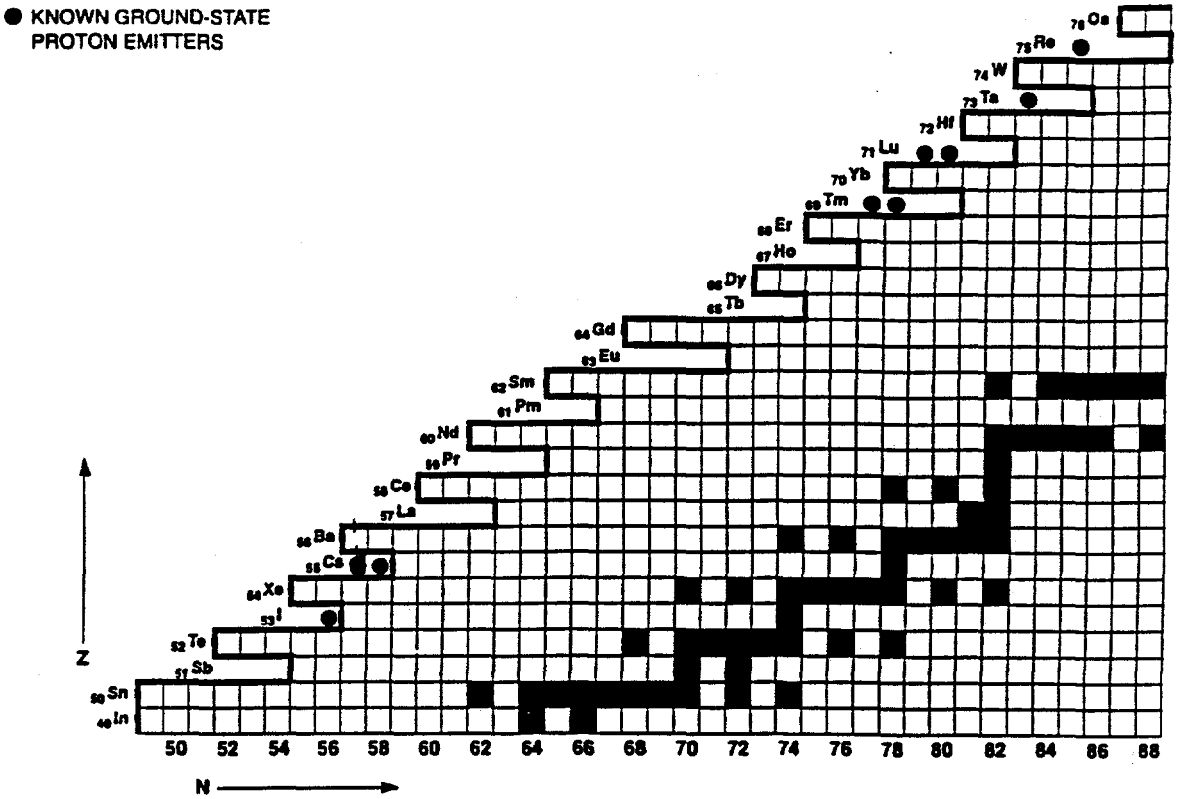

FIGURE 1. Portion of the nuclidic chart which shows one predicted (10) proton drip line (heavy border on the left side of the diagram) and the nine isotopes in this mass region that are known to emit protons from their ground states.

group of investigators (including the present authors) has studied ground-state proton decay in elements above rhenium utilizing strip detectors and a fragment mass analyzer (8). Several new cases of proton emission have been identified; that of $^{185}Bi^{m}$ has been described in a recent publication (9).

The location of known emitters (2,4-7) up to rhenium is shown in Fig. 1 where one predicted (10) drip line is indicated by the heavy border on the left side of the diagram. For the emitters near N = 82, lifetimes calculated with a one-body barrier penetration model and shell-model spin and parity assignments based on systematics of single-proton levels have been found to agree with experimental values. However, for ^{112}Cs, ^{113}Cs, and ^{109}I experimental rates are slower than calculated half-lives by factors of between 10 and 100. These hindrances are thought to be due to the fact that the three nuclei are transitional rather than spherical in shape. Bugrov and Kadmenskii (11) have recently examined these nuclei and have addressed theoretically the question of deformation effects on proton-decay half-lives. Neutron-deficient isotopes with masses between ^{113}Cs and ^{147}Tm have been predicted to be well-deformed and their proton decay rates should provide even more stringent tests for theoretical calculations. Experimental efforts to produce these emitters have not been fruitful [see e.g. Ref. (12)] partly as a result of a dearth of suitable target and beam combinations.

At the Oak Ridge National Laboratory we are mounting a research program to search for and investigate new cases of proton emission in the mass region between Cs and Tm. The attempts will be made by utilizing strip detectors, a recoil mass spectrometer (13), and beams from the Holifield Radioactive Ion Beam Facility (14).

Figure 2 shows compound systems in the In - Os mass region that could be produced with three of the radioactive beams (^{33}Cl, ^{58}Cu, and ^{69}As) considered for early delivery incident on extremely neutron-deficient even-even targets. One sees that as far as getting beyond the drip line ^{58}Cu does best overall with ^{69}As better for a

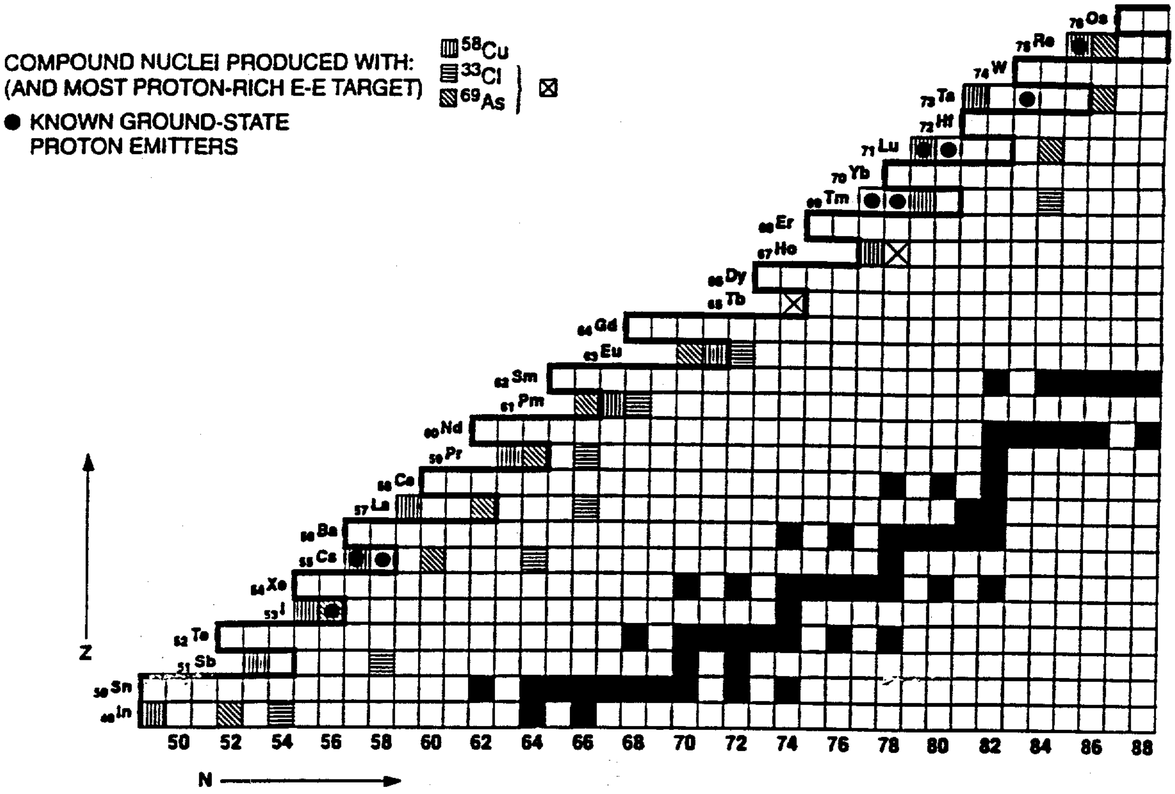

FIGURE 2. Portion of the nuclidic chart showing compound nuclei that could be formed with stable neutron-deficient even-even targets and radioactive beams of ^{33}Cl, ^{58}Cu, and ^{69}As. The two squares marked with an "X" indicate nuclei that can be formed with both ^{33}Cl and ^{69}As. Known proton emitters and one predicted (10) proton drip line (heavy border on the left side of the diagram) are also shown.

few elements and ^{33}Cl clearly not as well. Obviously (xn) evaporation products would be channels of choice but here at the drip line their cross sections are extremely low and one has to rely on reactions wherein charged particles are evaporated together with neutrons. The (pxn) channels lead to even-Z elements and, except for the heavier nuclei in Fig. 2, not beyond the drip line. However, the (αxn) channels, produce very neutron-deficient odd-Z isotopes and for many of these elements the (αn) and (α2n) channels should get us far enough to observe proton radioactivity in the region intermediate between ^{113}Cs and ^{147}Tm.

Development of intense radioactive beams at the Oak Ridge Facility has proceeded. Recently, a low intensity beam of ^{70}As was produced and accelerated through the facility's 25-MV tandem. Along with these developments, tests with stable beams from the tandem accelerator have been used to commission the recoil mass spectrometer and its ancillary experimental equipment. In a recent test, a double-sided Si strip detector of thickness 60 μm, area 4 x 4 cm, and having 40 orthogonal strips on the front and rear was placed close to the focal plane of the recoil spectrometer. A 0.5 mg/cm^2 thick foil enriched in ^{92}Mo was bombarded with ^{58}Ni and products with A = 147 were then implanted into the detector. Figure 3 shows the spectrum recorded and one sees protons that were emitted from the ^{147}Tm 0.6-s ground state and its 360-μs isomer. Further tests to fine tune the strip detector electronics have been scheduled for the near future.

During these searches for new proton emitters most of the nuclei encountered will primarily EC/β^+ decay. With this in mind, we will place a thick Si detector directly behind the strip detector and Ge detectors outside the strip detector chamber to record β-delayed proton and γ-ray spectra, respectively. For half-lives > 0.5s, we plan to use a tape collection system to extract and transport nuclides to shielded areas where their radioactivities can be studied with large Ge detectors in close geometry. The nuclides will be collected at the focal plane from either neighboring mass positions or adjacent charge states of the masses being studied with the strip detector.

In conclusion we note that the mass-tagging capabilities of the recoil separator can be used in conjunction with a Ge array at the target position. This combination permits the simultaneous study of level properties by in-beam measurements of nuclei whose decays are being investigated with detectors at the focal plane. Indeed, for in-beam studies that require additional filtering, correlation of events at the target position with decays of particular recoil products can provide isotopic identification.

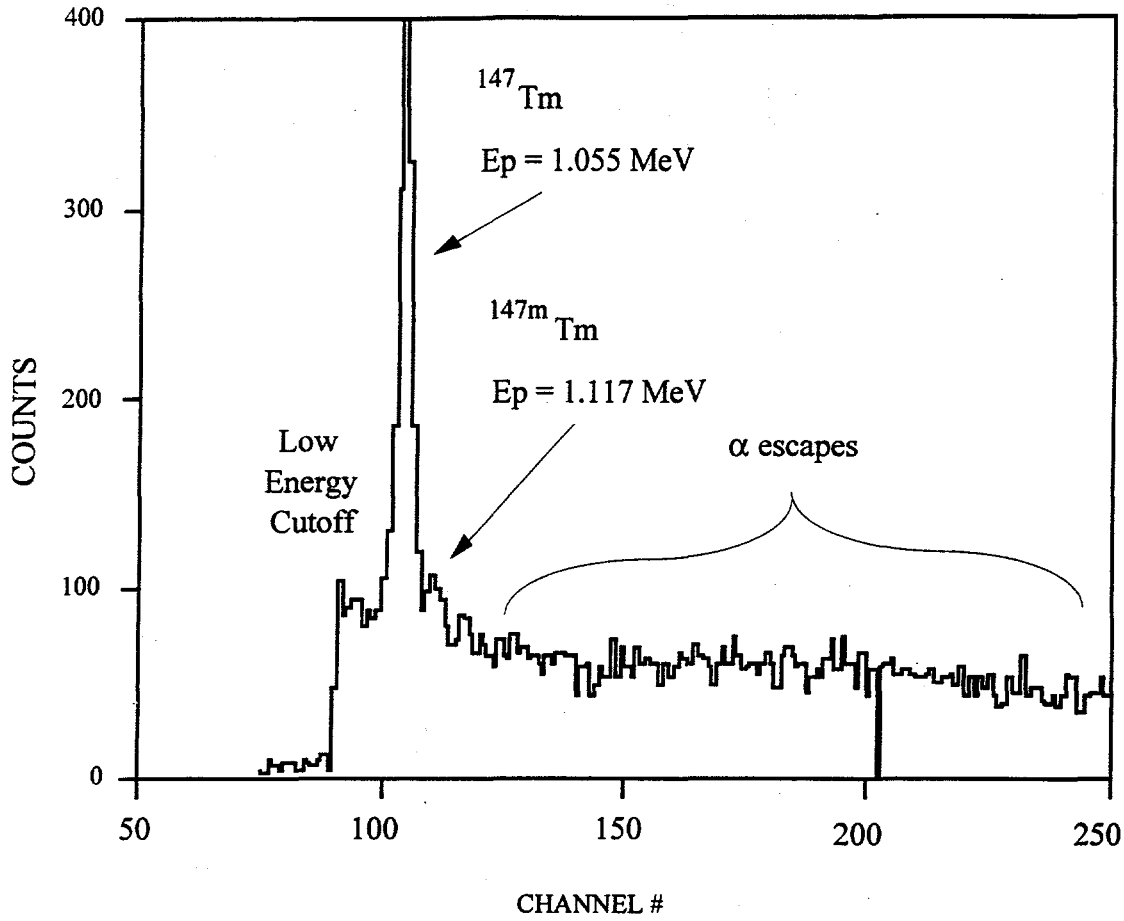

FIGURE 3. Spectrum recorded in a double-sided Si strip detector during ^{58}Ni bombardments of ^{92}Mo. The detector was positioned at the focal plane of the recoil mass spectrometer to accept A = 147 products. Protons from the ^{147}Tm 0.6-s ground state and the isotope's 360-μs isomer are seen in the spectrum together with escape α particles emitted by nuclides produced in reactions on heavier Mo isotopes present in the target.

ACKNOWLEDGMENTS

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