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Prospects for studies of ground-state proton decays with the Holifield Radioactive Ion Beam Facility

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ABSTRACT. By using radioactive ions from the Holifield Radioactive Ion Beam Facility at Oak Ridge National Laboratory it should be possible to identify many new ground-state proton emitters in the mass region from Sn to Pb. During this production and search process the limits of stability on the proton-rich side of the nuclidic chart will be delineated for a significant fraction of medium-weight elements and our understanding of the proton-emission process will be expanded and improved.

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The study of very neutron-rich nuclei looks extremely promising for the future, with a vast array of isotopes to identify and investigate. However, an examination of the nuclidic chart with respect to the limits of nuclear stability reveals that prospects for actually reaching the neutron drip line, except in the light mass region, do not appear to be good. Contrastingly, the proton drip line is much more accessible. It has been established for the low-Z region up to vanadium (Z = 23) and is delineated in limited regions of heavier nuclei as well. Also, even if a nucleus is unbound with respect to proton emission, the Coulomb barrier slows down the decay process. One can therefore obtain structure information for nuclei located *beyond* the proton drip line, something that cannot be done on the neutron-rich side where decay takes place in about 10^{-23} s if the last neutron is unbound.

In proton decay an energetically unbound proton is emitted from the nucleus by tunneling through the Coulomb and centrifugal barriers. Because only a single nucleon is

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involved, this process is simpler to describe than α decay since there is no particle preformation factor to consider. Measurements of proton-decay half-lives and energies can thus provide spectroscopic information because the decay width is much more sensitive to the shape of the centrifugal barrier (and therefore l) than in the case of α-particle emission.

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 detectors [3], to observe proton decay from ^{156}Ta and ^{160}Re [4], from ^{146}Tm [5], and from ^{150}Lu [6].

The location of these emitters is shown in Fig. 1 where the predicted [7] drip line is indicated by the heavy border on the left side of the diagram. In this mass region one needs ~ 1 MeV for the proton decay energy (E_p) to obtain a decay branch large enough to be observed. Then, as a comment on the reliability of mass formulae, note that ^{146}Tm, ^{147}Tm, ^{150}Lu, ^{151}Lu, ^{156}Ta, and ^{160}Re, whose E_p values are between 1.05 and 1.25 MeV, are three or four mass units to the left of the drip line so that we have a confirmation for the predicted limit of proton stability. Contrastingly, ^{109}I and ^{113}Cs, which have E_p values of slightly less than 1 MeV, lie just across the drip line so that here we have disagreement between experiment and prediction. 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 ^{113}Cs and ^{109}I experimental rates are slower than calculated half-lives by factors of between 10 and 100. These hindrances have been assumed to be due to the fact that the two nuclei are transitional rather than spherical in shape. Bugrov and Kadmenskii [8] have recently addressed theoretically the question of deformation effects on proton-decay half-lives.

The first set of emitters [2] were produced in (^{58}Ni, p2n) reactions induced on a variety of targets with cross sections of ~ 50 μb. The emitters found at Daresbury in 1992, and since, were produced in (^{58}Ni, p3n) reactions with cross sections down in the few μb range and their observation perforce necessitated the development of a more sensitive technique [3] based on the use of double-sided strip detectors. At Oak Ridge National Laboratory we are presently mounting a program to search for new proton emitters utilizing the same type of detectors, a recoil mass separator, and beams from the Holifield Radioactive Ion Beam Facility (HRIBF) [9] now under construction. This facility, which combines the existing Oak Ridge Isochronous Cyclotron and 25-MV Tandem Accelerator, is scheduled [10] to deliver radioactive ions in 1995.

Figure 2 shows compound systems in the In - Os mass region that could be produced with three of the beams (^{33}Cl, ^{58}Cu, and ^{69}As) slated for early delivery at the HRIBF 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 few elements and ^{33}Cl clearly not as well. Thus for clarity we further consider ^{58}Cu (and ^{69}As for elements where it does better ^{58}Cu) and show in Fig. 3 two sets of compound-nucleus products, namely, (p2n) and (α2n) evaporation residues. For comparison we also indicate the lightest known isotope for each element. Obviously (2n) or (3n) 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 (p2n) channel leads to even-Z elements and, except for the heavier nuclei in Fig. 3, not beyond the drip line. The (α2n) channel, which leads to odd-Z products, takes us far to the neutron-deficient side. In fact one sees that for many elements the much more probable (αn) channel will get us far enough to observe proton radioactivity in the region intermediate between ^{113}Cs and ^{109}I and identified emitters near N = 82. Such a connecting set of new proton emitters should expand and improve our understanding of the proton-decay process.

The trend of drip-line traversal for even-Z elements continues as we go to heavier nuclei as illustrated in Fig. 4 where the mass region between Ir and At is shown. Compound systems produced with ^{58}Cu and ^{69}As are indicated in the figure together with the most neutron-deficient known isotopes and the heaviest odd-Z candidates with high probabilities ($\gtrsim$ 10%) for proton emission. Note that here the (p2n) products are located sufficiently beyond the drip line so that one should be able to observe for the first time proton radioactivity in even-Z nuclei. The discovery of proton decay in this mass region, where α-particle decay is a dominant process, would provide for the study of the competition between proton and α-particle decay probabilities which may lead to a better understanding of the preformation of α particles on the nuclear surface. In addition, neutron-deficient nuclei near Z = 82 have both large Coulomb energies and large proton-to-neutron ratios and one may be able to address theoretical predictions of Coulomb redistribution effects, that is, is there a decreased proton density and an increased neutron density in the interiors of these nuclei? Measurements of the nuclear-charge radii *via* mass determinations and possibly laser spectroscopy may provide information concerning these neutron and proton densities.

In conclusion we note that since these searches for new proton emitters will involve previously unattainable compound-nuclear systems they will therefore allow us to extend our on-going studies of single-particle levels, α-decay rates of even-even nuclei, and mass determination from α-decay energy measurements. Investigation of these nuclei with unusual Z/N ratios will also provide a great deal of information which should serve both as stringent tests of nuclear theory and as input for further theoretical calculations. Among these data will be: 1) half-lives for comparison with calculated values,2) mass differences for improving the predictive capabilities of mass formulae, 3) β-delayed-proton spectra to compare with statistical model calculations and to obtain information on levels at high excitation energies, and, 4) spin assignments and systematics of low-energy levels populated in (EC + β^+) decay which should tell us about static shapes of the investigated nuclei.

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Figure Captions

FIGURE 1. Portion of the nuclidic chart (In - Os) which shows the predicted [7] proton drip line (heavy border on the left side of the diagram) and the eight isotopes that are known to emit protons from their ground states.

FIGURE 2. Portion of the nuclidic chart (In - Os) showing compound nuclei that could be formed with stable neutron-deficient even-even targets and beams of ^{33}Cl, ^{58}Cu, and ^{69}As. The two squares marked with an "X" indicate compound nuclei that could be formed with both ^{33}Cl and ^{69}As. Known proton emitters and the predicted [7] proton drip line (heavy border on the left side of the diagram) are also shown.

FIGURE 3. Portion of the nuclidic chart (In - Os) indicating (p2n) and (α2n) products resulting from the compound systems (see Fig. 2) formed with ^{58}Cu and ^{69}As beams. The lightest known isotope for each element is shown together with the predicted [7] proton drip line (heavy border on the left side of the diagram).

FIGURE 4. Portion of the nuclidic chart (Ir - At) showing compound nuclei that could be formed with stable neutron-deficient even-even targets and beams of ^{58}Cu and ^{69}As. The lightest known isotope for each element is shown together with the predicted [7] proton drip line (heavy border on the left side of the diagram). In addition, the heaviest isotopes that could have branches of $\gtrsim$ 10% for proton emission are indicated for Ir, Au, Tl, and Bi.

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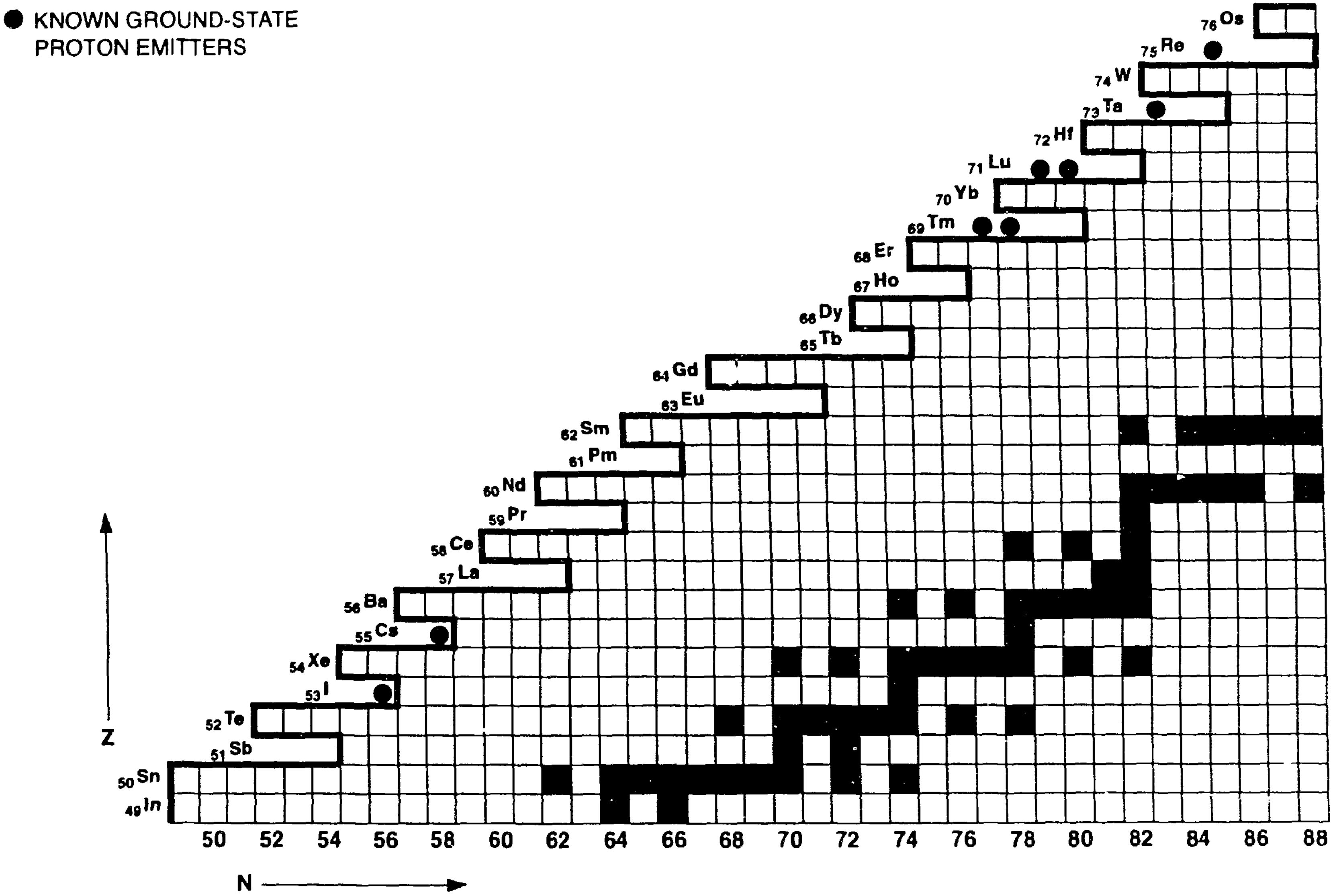

Fig. 1

ORNL-DWG 93M-7833

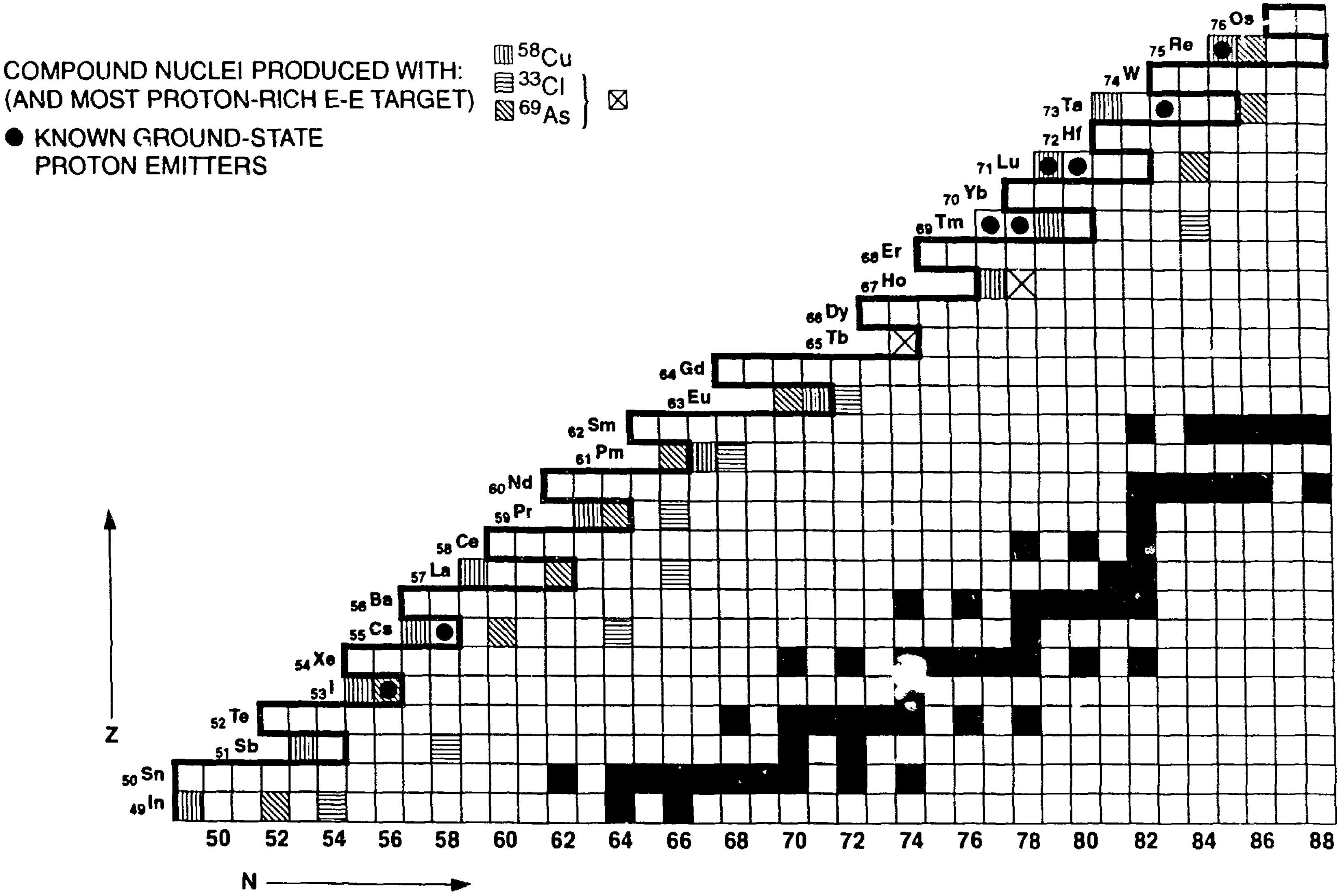

Fig. 2

ORNL-DWG 93M-7834

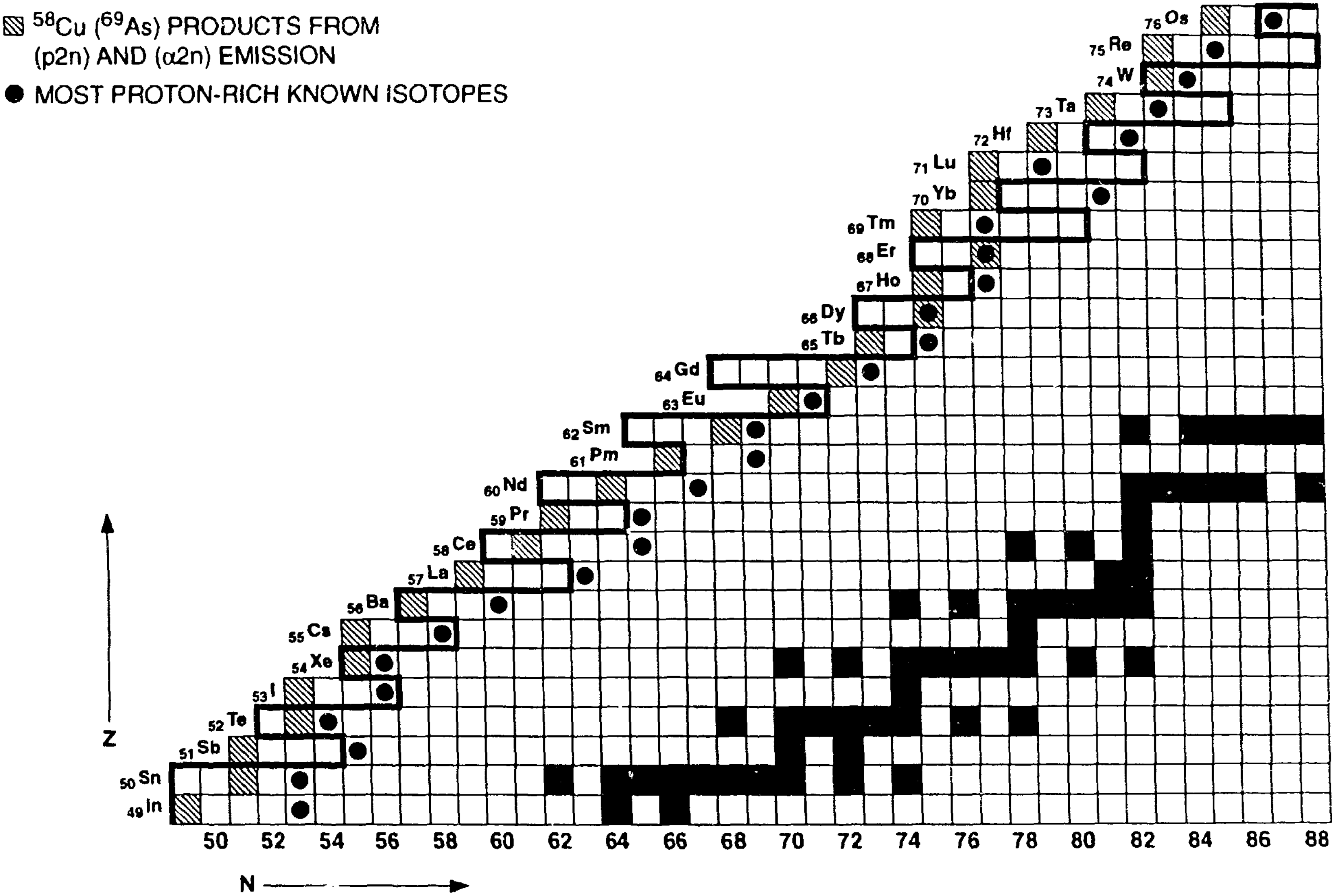

Fig. 3

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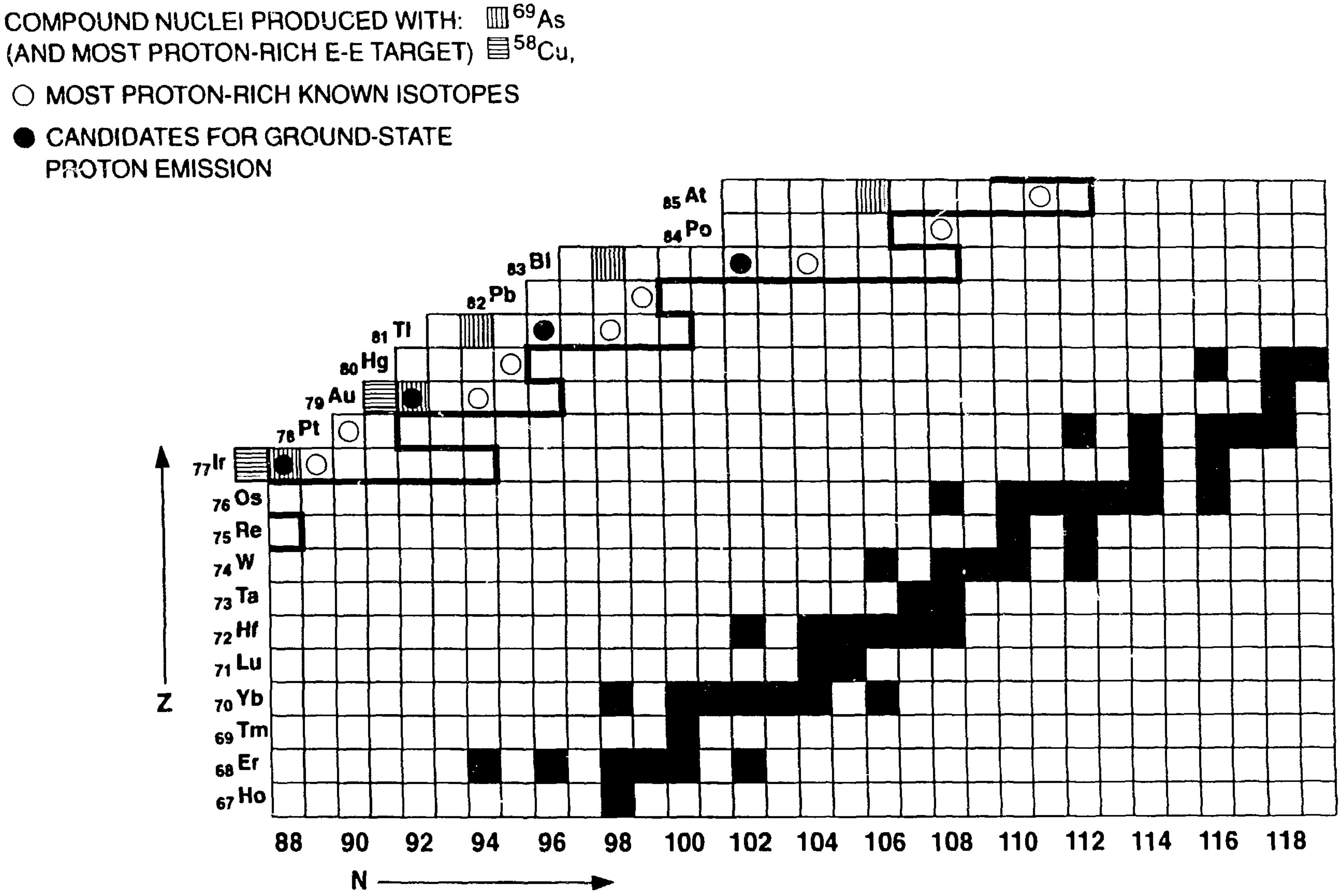

Fig. 4