Searches for proton radioactivity in odd Z drip-line nuclei from $Z=61$ to 67

K. Livingston,[1] P. J. Woods,[1] T. Davinson,[1] N. J. Davis,[1] A. N. James,[2] R. D. Page,[1] P. J. Sellin,[1] and A. C. Shotter[1]
[1]*Department of Physics, Edinburgh University, Edinburgh EH9 3JZ, United Kingdom*
[2]*Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 3BX, United Kingdom*
(Received 16 August 1993)

Beams of 185–204 MeV ^{40}Ca ions have been used to bombard ^{92}Mo, ^{96}Ru, ^{102}Pd, and ^{106}Cd targets in order to produce the proton-decay candidate nuclei ^{128}Pm, ^{132}Eu, ^{138}Tb, and ^{142}Ho via the $1p3n$ fusion evaporation channel. In each case no evidence for proton radioactivity was found. On the basis of mass model systematics it was concluded that the odd proton is not sufficiently unbound in these nuclei for proton emission to compete successfully with β decay.

PACS number(s): 25.70.De, 23.90.+w, 23.60.+e, 27.60.+j

Proton radioactivity has been identified in two regions of the proton drip line: $Z=53-55$ [1,2] and $Z=69-75$ [3-9]. In the latter region, the proton transitions are well reproduced assuming single-particle spherical shell model states. However, such a simple approach fails to reproduce the half-lives of the proton transitions in the $Z=53-55$ region. The failure has been attributed to the onset of modest prolate deformation ($\beta\simeq 0.1-0.2$) in this region [2,10]. It is therefore of great interest to establish examples of proton radioactivity in the linking region of light rare earth nuclei which are predicted [11] to be highly deformed ($\beta\simeq 0.4$). Such measurements would provide a unique insight into the role of deformation in the proton decay process.

Search experiments in the region of the light rare earth nuclei have been previously conducted using the velocity filter SHIP at GSI [9]. In these experiments 159–174 MeV beams of ^{40}Ca were used to bombard isotopically enriched targets of ^{92}Mo, ^{96}Ru, ^{102}Pd, and ^{106}Cd in order to produce the proton decay candidates ^{129}Pm ($Z=61$), ^{133}Eu ($Z=63$), ^{139}Tb ($Z=65$), and ^{143}Ho ($Z=67$) via the $1p2n$ fusion-evaporation channel. In each case the search proved negative. In the present experiment, performed at Daresbury, the same reactions were employed using a higher range of ^{40}Ca beam energies, 185–204 MeV, in order to maximize the yield in the $1p3n$ evaporation channel at a compound nucleus excitation energy of $\simeq 64$ MeV (see Table I). The Recoil Mass Separator was set up to position the isobars associated with the $1p2n$ and $1p3n$ evaporation channels on the focal plane. These ions were implanted into a 67 μm thick double-sided silicon strip detector consisting of two orthogonal sets of 48 strips, each 300 μm wide [12]. The lower energy limit for proton detection, determined by the electronics threshold, was $\simeq 500$ keV which is well below the energies required for proton emission to compete with β decay. No evidence was found for proton radioactivity from the nuclei ^{128}Pm, ^{132}Eu, ^{138}Tb, and ^{142}Ho, with corresponding cross-section limits of 100, 120, 40, and 100 nb, respectively. These limits are an order of magnitude below the $\simeq\mu$b cross sections associated with previously identified proton emitters produced via the $1p3n$ evaporation channel [3,4,6,8]. On this basis proton radioactivity with lifetimes $>10^{-6}$s can be ruled out as a dominant decay mode for the above nuclei. Furthermore, previous experiments on the proton emitting pairs of nuclei ^{146,147}Tm and ^{150,151}Lu have shown that the $1p2n$ and $1p3n$ channels are produced with approximately equal abundance at an exciton energy of $\simeq 64$ MeV. Hence the nonobservation of proton emission from the odd-even partners ^{129}Pm, ^{133}Eu, ^{139}Tb, and ^{143}Ho confirms the earlier result from [9].

Figure 1 shows proton separation energy predictions from the shell model based mass formula of Liran and Zeldes [13] for chains of odd Z proton-rich isotopes in the range $Z=61-75$. It is evident that the separation en-

TABLE I. Reaction parameters for proton radioactivity searches.

Beam				Target		Reaction products		
Isotope	Energy (MeV)	Current (particle nA)	Time (h)	Isotope	Thickness (μg cm^{-2})	Compound nucleus	E_x[a] (MeV)	$1p3n$ channel
^{40}Ca	185	8	14	^{92}Mo	500	^{132}Sm*	64	^{128}Pm
^{40}Ca	204	7	14	^{96}Ru	400[c]	^{136}Gd*	64	^{132}Eu
^{40}Ca	194	10	14	^{102}Pd	1000	^{142}Dy*	64	^{138}Tb
^{40}Ca	198	5	30	^{106}Cd	750[b]	^{146}Er*	64	^{142}Ho

[a]E_x = center of target excitation energy.
[b]Target backed with 25 μg cm^{-2} of C facing upstream.
[c]Target backed with 700 μg cm^{-2} of Al facing upstream.

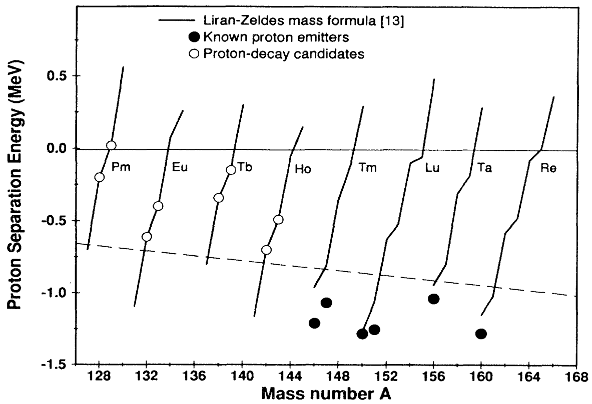

FIG. 1. Ground state proton separation energies from the Liran-Zeldes mass formula [13] for odd Z isotopes between $Z=61$ and 75. For the known proton emitters, the measured proton separation energies are shown (black circles), and for the proton emitting candidates ^{128,129}Pm, ^{132,133}Eu, ^{138,139}Tb, and ^{142,143}Ho, the Liran-Zeldes predictions are shown (white circles). The dashed line shows the separation energy required for proton decays to have a partial half-life of 1 s assuming unhindered $l_p=0$ emission.

ergies of the known proton emitters (black circles) are well reproduced although there is a slight tendency to overestimate the degree of proton binding. The dashed line across Fig. 1 shows the separation energy required for proton decays to have a partial half-life of 1 s assuming the limiting case of unhindered $l_p=0$ emission. It is clear that although the present proton decay candidates (white circles), with the exception of ^{129}Pm, are predicted to be unbound, they are not unbound enough for proton emission to complete with beta decays which have typical half-lives ~ 1 s in this region. On the basis of Fig. 1 ^{131}Eu and ^{141}Ho seem very promising candidates for future proton radioactivity searches. These nuclei would be produced via the $1p4n$ evaporation channel and cross sections $\sim 10-100$ nb might be anticipated. This is close to the sensitivity limit of existing techniques using recoil separators, bearing in mind that alpha-decay chain correlations are not available in this region. An alternative method would be to use radioactive beams in order to produce such nuclei via higher cross-section evaporation channels. Such an approach has the benefit of improving the signal to background ratio although its success depends crucially on the trade off between the loss in beam intensity and the increase in cross section. Whatever method is ultimately used, it is important that examples of proton radioactivity be discovered in this region in order to obtain an understanding of the influence of deformation on proton transition rates.

We would like to thank the NSF crew at Daresbury for providing the beam, and R. Hunt (Oxford University) for his valuable technical expertise. Financial support for K. L. was provided by the SERC and Micron Semiconductor Ltd.

[1] T. Faesterman, A. Gillitzer, T. Hartel, P. Kienle, and E. Nolte, Phys. Lett. **137B**, 23 (1984).
[2] A. Gillitzer, T. Fastermann, T. Hartel, P. Kienle, and E. Nolte, Z. Phys. A **326**, 107 (1987).
[3] K. Livingston, P. J. Woods, T. Davinson, N. J. Davis, S. Hofmann, A. N. James, R. D. Page, P. J. Sellin, and A. C. Shotter, Phys. Lett. B **312**, 46 (1993).
[4] P. J. Woods, T. Davinson, N. J. Davis, S. Hofmann, A. N. James, K. Livingston, R. D. Page, P. J. Sellin, and A. C. Shotter, Nucl. Phys. **A553**, 485 (1993).
[5] O. Klepper, T. Batsch, S. Hofmann, R. Kirchner, W. Kurcewicz, W. Reisdorf, E. Roeckl, D. Schardt, and G. Nyman, Z. Phys. A **305**, 125 (1982).
[6] P. J. Sellin, P. J. Woods, T. Davinson, N. J. Davis, S. Hofmann, A. N. James, K. Livingston, R. D. Page, and A. C. Shotter, Phys. Rev. C **47**, 1933 (1993).
[7] S. Hofmann, W. Reisdorf, G. Münzenberg, F. P. Hessberger, J. R. H. Schneider, and P. Armbruster, Z. Phys. A **305**, 111 (1982).
[8] R. D. Page, P. J. Woods, R. A. Cunningham, T. Davinson, N. J. Davis, S. Hofmann, A. N. James, K. Livingston, P. J. Sellin, and A. C. Shotter, Phys. Rev. Lett. **68**, 1287 (1992).
[9] S. Hofmann, in *Particle Emission from Nuclei,* edited by M. Ivascu and D. N. Poenaru (CRC Press, Boca Raton, FL, 1989), Vol. 2, Chap. 2.
[10] V. P. Bugrov and S. G. Kadmenskii, Yad. Fiz. **49**, 1562 (1989) [Sov. J. Nucl. Phys. **49**, 967 (1989)].
[11] P. Möller and J. R. Nix, At. Data Nucl. Data Tables **26**, 165 (1981).
[12] P. J. Sellin *et al.*, Nucl. Instrum. Methods **A311**, 217 (1992).
[13] S. Liran and N. Zeldes, At. Data Nucl. Data Tables **17**, 431 (1976).