Decays of Odd-Odd $N-Z=2$ Nuclei Above ^{100}Sn: The Observation of Proton Radioactivity from ^{112}Cs

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(Received 8 November 1993)

The discovery of the new proton emitter ^{112}Cs with an energy of 807 ± 7 keV and a half-life of 500 ± 100 μs is reported. WKB half-life calculations indicate $d_{5/2}$ proton emission with a low spectroscopic factor comparable to values for ^{109}I and ^{113}Cs. This behavior is consistent with the onset of deformation in this region. The odd-odd nuclides ^{112}Cs and ^{108}I have significantly lower Q_p values than the corresponding isotopes lying closer to stability, which is attributed to strong pairing forces between the odd nucleons. The half-life of ^{113}Cs has been measured with improved precision as 17 ± 2 μs.

PACS numbers: 23.90.+w, 21.10.Tg, 27.60.+j

Despite the dramatic advances recently achieved in searches for cases of direct proton emission around the $N=82$ shell closure [1–4], progress has proved more elusive in the second island of proton emission containing the transitional proton emitter ^{109}I and ^{113}Cs [5,6]. Unlike the heavier proton emitters, proton emission from these deformed nuclei is significantly hindered and therefore represents a stringent test for calculations of proton decay half-lives. However, it is not clear whether these are two isolated cases or represent part of a more general region of proton radioactivity exhibiting quite different characteristics to those of the heavier region. Considerable effort has been expended in trying to identify other proton emitters in this region but searches have yielded negative results [6,7], although evidence for the alpha decay of ^{108}I has been reported [8]. The apparent predominance of alpha particle emission by ^{108}I is particularly surprising since this odd-odd isotope is further beyond the proton drip line than the known dominant proton emitter ^{109}I. This observation was attributed [8] to a reduction in the Q_p value caused by a strong pairing interaction between the odd neutron and proton, which probably occupy the same $(d_{5/2})$ orbitals. A corresponding effect in ^{112}Cs has been postulated to account for the nonobservation of a proton decay line for this nuclide [7]. In this Letter we report on experiments to identify the decays of the odd-odd $N-Z=2$ nuclides ^{112}Cs, ^{108}I, and ^{104}Sb.

In the present experiments, the nuclides of interest were produced in heavy ion fusion-evaporation reactions and separated in flight according to their mass to charge state ratio A/q using the Daresbury Recoil Mass Separator (RMS) [9]. The selected ions were implanted at the focal plane of the RMS into a 63 μm thick double-sided silicon strip detector (DSSSD) comprising 48 strips, of 300 μm width, on each face which provided position information in two dimensions. The DSSSD was used to measure decay particle energies (resolution $\lesssim 20$ keV FWHM, threshold ~ 350 keV) and to correlate causally related events using the (x,y) position information and a time measurement recorded with each event [10].

In the first experiment, a 3.6 particle nA beam of 259 MeV ^{58}Ni ions was used to bombard a 520 μg cm^{-2} thick isotopically enriched ^{58}Ni target over a period of 27 h in order to produce ^{112}Cs nuclei via the $p3n$ evaporation channel. The RMS was adjsuted to position $A=112,113$ ions in atomic charge state $q=28^+$ on the DSSSD. Figure 1 shows a two-dimensional spectrum of A against energy for proton decay events occurring between 60 μs and 2 ms after an ion was implanted into the same (x,y) pixel of the DSSSD. The higher energy group in this spectrum represents the proton decays of ^{113}Cs while the group below it in energy and centered in the same region repre-

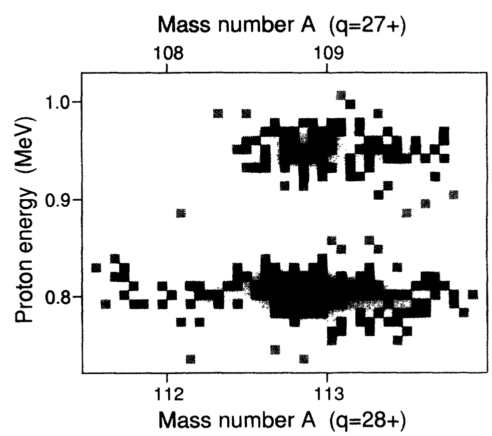

FIG. 1. Two-dimensional spectrum of mass number A for $q=28^+$ or $q=27^+$ ions against energy for proton decay events occurring between 60 μs and 2 ms after the implantation of an ion into the same DSSSD pixel. The RMS spatially separates ions according to A/q; hence $q=27^+$ ions with $A=108,109$ appear in the same A/q region as $q=28^+$ ions with $A=112,113$, respectively. The different shades represent, in order of increasing intensity, contour levels of 1, 2, and 4 counts.

0031-9007/94/72(12)/1798(4)$06.00

sents proton decays of ^{109}I nuclei produced via the $\alpha p2n$ evaporation channel, which have essentially the same A/q value for ions in charge state $q=27^+$. A closer examination of this group reveals an extension into the $A=112$ region which is not observed for the ^{113}Cs decays, suggesting that this is a distinct activity which is not energy resolved from the ^{109}I proton decay line (see Fig. 2). The half-life of the $A=112$ decay group is 500 ± 100 μs, which is significantly longer than the value of 100 ± 5 μs for ^{109}I [2] and indicates that it represents a new direct proton activity. In accordance with expected alpha decay branching ratios, a correlation analysis identified three events in this group consistent with the decay chain: $^{112}\mathrm{Cs} \xrightarrow{p} {}^{111}\mathrm{Xe} \xrightarrow{\alpha} {}^{107}\mathrm{Te} \xrightarrow{\alpha}$, establishing beyond doubt that this $A=112$ activity represents the first observation of the proton decay of the new isotope ^{112}Cs.

The energy of the ^{112}Cs proton line was measured to be 807 ± 7 keV, based on the energies of the ^{109}I proton line [11] and the ^{108,109}Te and ^{110}I alpha decay lines [7]. Corrections were applied to take into account the pulse height defect for alpha particles in silicon [12], the contribution of the recoiling daughter nucleus to the energy signal [13], and the nonlinear response of silicon detectors for low-Z ions [14]. Using this procedure, a consistent energy calibration for both protons and alpha particles is obtained [15]. The yield of this activity of ~ 50 counts corresponds to a cross section of ~ 500 nb, assuming an RMS transmission efficiency of 3% and a combined implantation and detection efficiency of 30%, which is consistent with values determined for other $p3n$ evaporation residues. In the previous negative search of Heine *et al.* the ions were not mass separated and an upper limit of 1 μb was reported for a proton energy of 800 keV [7].

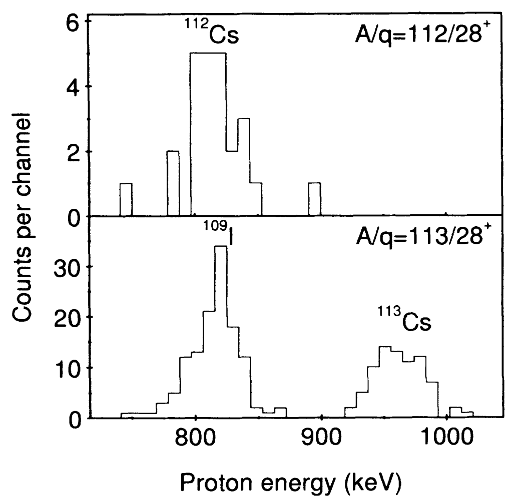

FIG. 2. Energy projections of the data from Fig. 1, gated on the $A/q = 112/28^+$ region (upper spectrum) and the $A/q = 113/28^+$ region (lower spectrum), which also includes ions with $A/q = 109/27^+$. Assignments for each of the decay lines are indicated. Although the ^{109}I proton decay line and the new $A=112$ decay line assigned to ^{112}Cs proton decays are not energy resolved, they are physically separated by mass using the RMS. Analysis of the mass profile indicates that fewer than 2 events in the $A=112$ gated spectrum can be attributed to ^{109}I proton decays.

The half-life of the ^{113}Cs proton decay line was measured with improved precision, yielding a value of 17 ± 2 μs which compares with the previously reported values of 33 ± 7 μs [6] and 22 ± 8 μs [7]. An energy of 959 ± 6 keV was determined for the ^{113}Cs line, in excellent agreement with the value of 959.3 ± 3.7 keV measured using SHIP [11] but not with the value of 974 ± 4 keV of Ref. [7]. A correlation analysis was also performed for the ^{113}Cs proton decays, yielding two correlated decay chains: $^{113}\mathrm{Cs} \xrightarrow{p} {}^{112}\mathrm{Xe} \xrightarrow{\alpha} {}^{108}\mathrm{Te} \xrightarrow{\alpha}$. This confirms the ^{113}Cs assignment and gives a first measurement of the alpha decay branching ratio of $(0.8^{+1.1}_{-0.5})\%$ for ^{112}Xe. A more precise energy value of 3216 ± 7 keV was also obtained for the ^{112}Xe decay line from the present data which, combined with the Q_p values for ^{109}I and ^{113}Cs [11], leads to a Q_α value of 3483 ± 15 keV for ^{113}Cs. With such a low Q value, alpha particle emission cannot compete significantly with proton emission in the decay of ^{113}Cs.

A separate experiment was performed to search for the decays of ^{108}I and ^{104}Sb. In a previous experiment using a less sophisticated detection system, two peaks were tentatively assigned as the alpha decay branch of ^{108}I [8]. If correct, this would represent the only known instance of a nuclide beyond the threshold for dominant proton radioactivity not decaying mainly by proton emission. However, no half-life measurement could be obtained so the possibility that the observed structure arose from a beta-delayed proton activity could not be eliminated. The present data confirmed that ^{108}I is a dominant alpha emitter and a first half-life measurement of 36 ± 6 ms was obtained. The energy of the ^{108}I alpha decay line was measured as 3947 ± 5 keV, corresponding to a Q value of 4099 ± 5 keV, based on the energies of the ^{109}I proton decay line [11] and the ^{107,108,109}Te alpha decay lines [7]. This energy is greater than the previously reported value of 3885 ± 25 keV for the higher energy line, which was based on earlier measurements of the ^{107,109}Te alpha decay lines by Schardt *et al.* [16]. However, the energy of these and other alpha decay lines has recently been remeasured with improved precision by Heine *et al.* [7] and a number of discrepancies in the previous values have been removed. Thus the two values are mutually consistent, if the changes in the calibration line energies are taken into account. A second, weaker structure tentatively reported from the previous experiment at an energy of 3730 ± 25 keV was not identified in the present data, suggesting that this peak arose from fluctuations in the beta-delayed proton background. These measurements will be discussed in more detail in Ref. [15]. No proton decay branch of ^{108}I was identified in the present work in correlations with ^{107}Te alpha decays, which indicates that the proton decay branching ratio of ^{108}I $\lesssim 1\%$ relative to alpha decay. The gross theory prediction [17] for the partial beta decay half-life of ^{108}I is $\sim$400 ms, which would suggest that this decay mode competes more effectively than proton emission with a branching ratio of $\sim$10%.

The possibility of correlated decays occurring after ^{108}I alpha decays was also investigated in a search for proton decays of the unknown daughter nuclide ^{104}Sb. From the Q_α values of ^{108}I and ^{107}Te and the Q_p value limit for ^{108}I deduced below, the Q_p value of ^{104}Sb must be $\lesssim 550$ keV. This corresponds to a lower partial half-life limit of $\sim$0.3 s for unhindered $d_{5/2}$ proton emission, so the ^{104}Sb nuclei produced by ^{108}I alpha emission cannot decay too quickly for detection. However, no correlated events were observed at energies compatible with direct proton decays and a limit for the proton decay branching ratio of ^{104}Sb $\lesssim 1\%$ was obtained. Since alpha decay across the $Z=50$ shell closure is effectively forbidden, beta decay will represent the main decay mode of ^{104}Sb with a predicted half-life of 1.5 s [17]. This half-life estimate and the proton decay branching ratio limit imply an upper limit of 460 keV for the Q_p value of ^{104}Sb, assuming unhindered $d_{5/2}$ proton emission. This limit is consistent with the predictions of Wapstra, Audi, and Hoekstra [18].

The present measurements on the new proton emitter ^{112}Cs provide the first opportunity to test whether the exceptional decay properties of ^{109}I and ^{113}Cs are specific only to these nuclei or represent general characteristics typical of this region of deformed nuclei as a whole. The lowest proton levels for nuclides just above ^{100}Sn correspond to the $d_{5/2}$ and $g_{7/2}$ orbitals. WKB calculations with a global optical model potential [19] using the measured ^{112}Cs Q_p value of 815 ± 7 keV yield partial half-lives of 64 μs and 18 ms, respectively. Since all measured partial half-lives are comparable to or longer than calculated values, one concludes that the odd proton in ^{112}Cs is emitted from a $d_{5/2}$ orbital, which is also the case for ^{109}I and ^{113}Cs [6]. The spectroscopic factor for ^{112}Cs can be obtained from the ratio of the calculated and measured half-lives as 0.13 ± 0.04, where the error bar reflects only the uncertainties in the measured quantities. This value is considerably larger than the value of 0.028 ± 0.005 determined for ^{113}Cs using the half-life measured in the present work but is more in line with the value of 0.091 ± 0.008 for ^{109}I calculated using the half-life value from Ref. [2]. These values are all considerably smaller than those determined for proton emitters around the $N=82$ shell closure where spectroscopic factors close to unity are obtained [2–4]. However, more sophisticated multiparticle calculations [20] which take nuclear deformation into account do reproduce the measured half-lives for ^{109}I and ^{113}Cs, so it is clearly of considerable importance for such a calculation to be performed for the case of ^{112}Cs.

Figure 3 shows a comparison of measured proton decay Q values for neutron deficient antimony, iodine, and cesium isotopes with the predictions of the mass estimates of Wapstra, Audi, and Hoekstra [18] and the Möller and Nix mass formula [21]. This formula gives reasonable agreement with measured Q_p values for the heavier region of proton radioactivity [1–4]. The proton energy measurements for ^{112,113}Cs establish directly that for these isotopes there is a reversal in the trend of increasing Q_p values moving away from stability, assuming that both decay lines represent transitions between nuclear ground states. WKB calculations using the upper limit determined for the proton decay branching ratio and the half-life measured from the alpha decay line imply an upper limit of 600 keV for the Q_p value of ^{108}I. This limit, obtained assuming the same spectroscopic factor for ^{108}I as for ^{109}I and $d_{5/2}$ proton emission, is 100 keV lower than the previously determined upper bound [8]. This indicates that ^{108}I is more bound against proton emission than ^{109}I by at least 220 keV, compared with the 153 ± 11 keV reduction in Q_p value for ^{112}Cs relative to ^{113}Cs. These Q_p value reductions for ^{112}Cs and ^{108}I are in accordance with calculations which indicate particularly strong neutron-proton pairing interactions for $N-Z=2$ nuclei [22]. The Q_p value staggering trends are in agreement with the atomic masses predicted by Wapstra, Audi, and Hoekstra [18] but contrary to the predictions of Möller and Nix [21]. The latter model reproduces the absolute Q_p value magnitudes for iodine and cesium isotopes fairly well but, like the majority of other recent mass models [23], predicts steadily increasing Q_p values moving away from stability. This success of the Wapstra

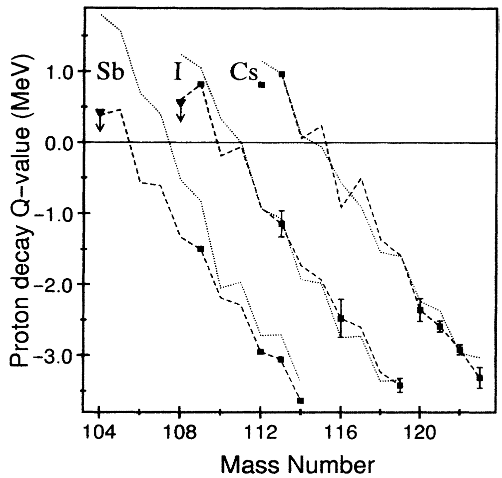

FIG. 3. A comparison of measured proton decay Q values for neutron deficient antimony, iodine, and cesium isotopes with values predicted by Wapstra, Audi, and Hoekstra [18] (dashed line) and Möller and Nix [21] (dotted line). Error bars are shown for measured Q_p values where they are larger than the symbol size and the model dependent upper limits determined in the present work for ^{104}Sb and ^{108}I are indicated by a triangular symbol and arrow.

estimates is attributed to the nucleon-nucleon pairing energy formulas of Jensen, Hansen, and Jonson [24] which are incorporated into their predictions.

In summary, the direct proton decay of the new isotope ^{112}Cs has been observed. Energy and half-life measurements for this decay line compared with WKB half-life calculations reveal that protons are emitted from a $d_{5/2}$ orbital with a low spectroscopic factor, as is also the case for ^{109}I and ^{113}Cs. The measured Q_p value for ^{112}Cs and alpha decay measurements and correlation analyses for ^{108}I establish unequivocally that these odd-odd $N-Z=2$ nuclides have lower Q_p values than their proton emitting counterparts lying closer to stability. This fact is attributed to a strong pairing interaction between the odd neutron and proton and is in striking contrast to the proton emitting thulium and lutetium isotopes for which Q_p values increase steadily moving away from stability. These results indicate that proton emitters in this region of deformed nuclei exhibit general characteristics quite distinct from those of the other, heavier island of proton radioactivity.

The authors are indebted to the crews at Daresbury for providing the ^{58}Ni beams and to the Laboratory staff for technical assistance. This work has been funded by the United Kingdom Science and Engineering Research Council and K.L. would like to acknowledge additional financial support from Micron Semiconductor Limited.

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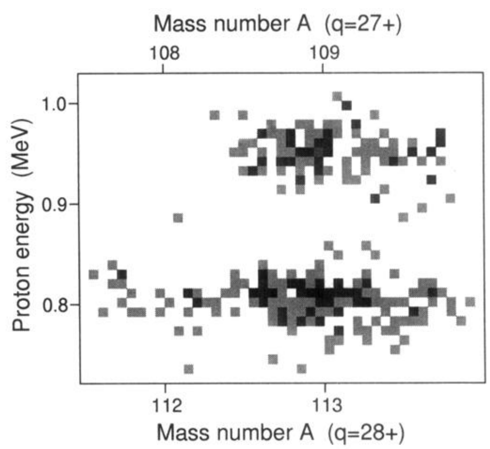

FIG. 1. Two-dimensional spectrum of mass number A for $q=28^+$ or $q=27^+$ ions against energy for proton decay events occurring between 60 μs and 2 ms after the implantation of an ion into the same DSSSD pixel. The RMS spatially separates ions according to A/q; hence $q=27^+$ ions with $A=108,109$ appear in the same A/q region as $q=28^+$ ions with $A=112,113$, respectively. The different shades represent, in order of increasing intensity, contour levels of 1, 2, and 4 counts.