Alpha radioactivity above ^{100}Sn including the decay of ^{108}I

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^{108}I is confirmed as a predominant alpha particle emitter with an energy of 3947±5 keV and half-life of 36±6 ms. The first observation of alpha decays of ^{106}Te nuclei produced directly as evaporation residues is reported with a measured energy of 4128±9 keV and a half-life of 60^{+40}_{-20} μs. Alpha decay branching ratios for ^{112}Xe and ^{108}Te have been measured from correlations with preceding proton decays as $0.8^{+1.1}_{-0.5}$% and 49±4%, respectively. Improved measurements for the ^{112}Xe alpha decay energy of 3216±7 keV and the half-life of ^{107}Te of 3.1±0.1 ms are also reported.

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Once proton radioactivity is established for a given element it is expected to become increasingly important moving further away from stability, quickly achieving predominance over other decay modes. However, the tentative observation of the alpha decay of the odd-odd nuclide ^{108}I [1] contradicts this expectation since the neighboring isotope ^{109}I is a known dominant proton emitter, $t_{1/2} = 100 \pm 5$ μs [2,3]. The apparent predominance of alpha decay by ^{108}I was attributed to a marked reduction in its Q_p value relative to that of ^{109}I caused by strong pairing forces between the odd proton and neutron which probably occupy the same orbitals. In this paper we report on experiments to identify the decays of the odd-odd nuclide ^{108}I and present improved measurements for a number of alpha emitters in the region above the presumed doubly magic nuclide ^{100}Sn.

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 using the Daresbury Recoil Mass Separator (RMS) [4]. The selected ions were implanted at the RMS focal plane into a 63 μm thick double-sided silicon strip detector (DSSSD) comprising 48, 300 μm wide strips on each face which provided position information in two dimensions. The DSSSD was used to measure decay particle energies (resolution $\lesssim$20 keV FWHM) and to correlate causally related events using the (x, y) position information and a time measurement recorded with each event [5].

The nuclide ^{108}I was searched for in two separate runs, the first of which lasted 15.5 h using a 5 particle nA beam of 255 MeV ^{58}Ni ions while in the second run a 3 particle nA ^{58}Ni beam at 240 MeV was used for a period of 21.5 h. The target used in both cases was a 500 μg cm^{-2} thick self-supporting foil of isotopically enriched ^{54}Fe, so ^{108}I nuclei would be produced via the $p3n$ evaporation channel. Figure 1 shows an energy spectrum, from the two runs combined, of decay events occurring in the A = 107–108 region of the RMS focal plane within 150 ms of an ion being implanted into the same DSSSD (x, y) pixel. The peak above the ^{107}Te alpha decay line corresponds to the higher energy line tentatively assigned to the alpha decay of ^{108}I in Ref. [1]. The total yield of this decay line is ~110 counts, corresponding to a cross section of ~500 nb in both reactions, assuming a total RMS efficiency of 3% and a combined implantation and detection efficiency of 50% in this experiment. This cross section is consistent with both the expectations for $p3n$ evaporation channels and the previous value. From the present data it was possible to determine for the first

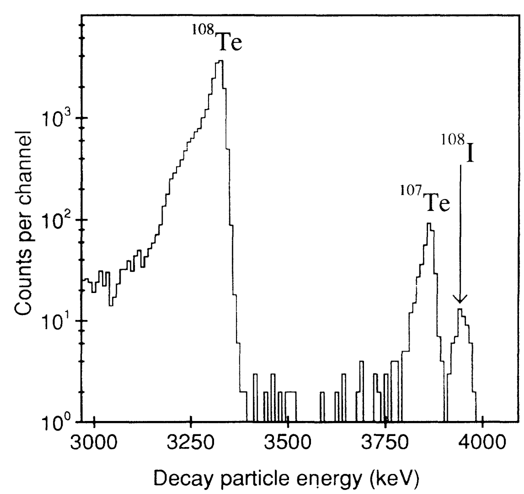

FIG. 1. Energy spectrum of alpha decay events observed in the A=107–108 region of the RMS focal plane which occurred within 150 ms of the implantation of an ion into the same DSSSD pixel. The low energy tails on the peaks is due to radiation damage of the DSSSD caused by evaporation residue implantation during the experiments.

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time the half-life of this activity, 36±6 ms, which is consistent with the previously reported lower limit of 10 ms [1]. This value is too short for a beta decay process, confirming that it does indeed represent a direct alpha activity and corroborates the earlier interpretation that this peak represents the alpha decay of ^{108}I.

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 [6,7] and the ^{107,108,109}Te alpha decay lines [7]. Corrections to account for the pulse height defect for alpha particles in silicon [8], the contribution of the recoiling daughter nucleus to the energy signal [9], and the nonlinear response of silicon detectors for low-Z ions [10] have been applied, providing a consistent energy calibration for both protons and alpha particles. The energy determined in the present work is somewhat higher than the value of 3885±25 keV determined previously, which was based on earlier measurements of the energies of the ^{107,109}Te alpha lines by Schardt *et al.* [11]. However, the energy of these and other alpha decay lines in this region have recently been remeasured with better precision by Heine *et al.* [7] and a number of discrepancies removed. The remeasurement of the tellurium isotopes' alpha energies accounts for 28 keV of the difference between the two ^{108}I energy measurements, which are therefore mutually consistent.

A second, weaker peak tentatively identified in the previous experiment at an energy of 3730±25 keV [1] was not observed in either of the present runs. Analysis of the appropriate energy region indicates that the intensity of any lower energy line would be $\lesssim$13% of that of the higher lying line, approximately a factor of 6 less than previously reported. In the earlier measurement, $\sim$ 500 μm thick conventional two dimensionally position sensitive detectors were used [12] which were sensitive to background from beta delayed proton activities. These backgrounds are suppressed by the much thinner, highly segmented DSSSDs. Furthermore, energy spectra gated on $\sim$100 ms implantation-decay time intervals, such as Fig. 1, could not be generated owing to the inferior position resolution of the detector used in the previous experiment. Hence direct alpha and long-lived beta delayed proton activities could not easily be distinguished and it is likely that the lower lying peak structure arose from a longer-lived beta delayed proton activity, a possibility which was acknowledged in Ref. [1].

In an analysis seeking correlations with ^{107}Te daughter alpha decays no proton decay branch of ^{108}I was identified, yielding an upper limit of $\sim$1% for the proton decay branching ratio of ^{108}I relative to alpha decay. This limit, combined with proton decay half-life calculations, indicates that the proton decay Q value for ^{108}I is $\lesssim$600 keV, compared with 820 keV for ^{109}I. A similar Q_p-value reversal of 153±11 keV has been measured directly for ^{112}Cs relative to ^{113}Cs [13].

The alpha decay of ^{106}Te was identified in the data obtained at the beam energy of 240 MeV. An energy of 4128±9 keV and a half-life of $60^{+40}_{-20}\mu$s were measured for this activity, both values being consistent with the only other measurement [14]. This represents the first observation of the decay of this nuclide produced directly as an evaporation residue. From the combined data of both runs an improved half-life of 3.1±0.1 ms was measured for ^{107}Te alpha decays which is in good agreement with previously reported values [1,11]. Also, correlations of ^{109}I proton decays with subsequent alpha decays yielded an alpha decay branching ratio of 49±4% for ^{108}Te, which compares with the previous value of 68±12% [11].

In a separate 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. Correlations of ^{113}Cs proton decays from these data with subsequent alpha decays of ^{112}Xe and ^{108}Te yielded an alpha decay branching ratio of $0.8^{+1.1}_{-0.5}$% for ^{112}Xe. A corresponding correlation analysis for ^{112}Cs proton decays and subsequent alpha decays yielded a combined branching ratio for the two ^{111}Xe alpha decay lines of 8^{+8}_{-5}%. A more precise energy value of 3216±7 keV was obtained for the ^{112}Xe decay line. Combining this measurement with the known Q_p-values of ^{113}Cs and ^{109}I [6] yields a Q_α value of 3483±15 keV for ^{113}Cs, assuming all decays proceed between nuclear ground states. A limit of $Q_\alpha \lesssim 3.94$ MeV is obtained for ^{112}Cs from its Q_p value [13], the upper Q_p value limit determined for ^{108}I and the Q_α value for the ^{111}Xe higher energy line [7], again assuming ground state decays.

An alpha decay branch of ^{109}I was searched for in all three data sets but no clear evidence for a new peak above 3.32 MeV with a 100 μs half-life was obtained, leading to an upper limit on the branching ratio of 0.5% which is consistent with the measurements of Berthes [15]. In-

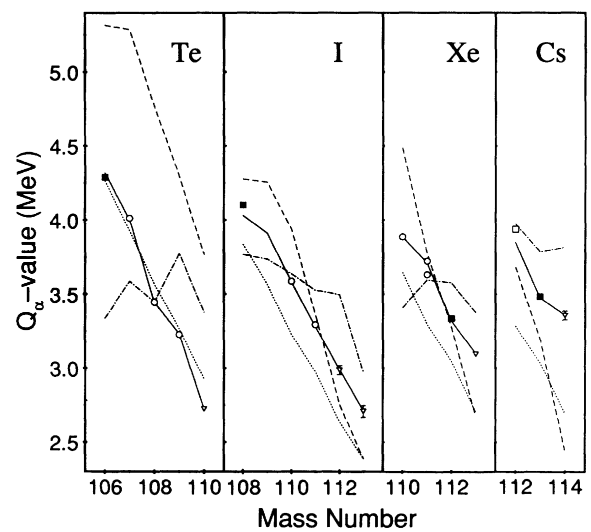

FIG. 2. A comparison of measured alpha decay Q values for neutron deficient tellurium, iodine, xenon, and caesium isotopes with values predicted by Möller and Nix [16] (dashed line), Liran and Zeldes [17] (dotted line), Comay, Kelson, and Zidon [18] (dot-dashed line), and Audi and Wapstra [19] (solid line). Measured Q_α values are taken from the present work (filled squares), from Heine *et al.* [7] (open circles), and from Schardt and co-workers [11,14] (open inverted triangles). The open square represents the upper limit on the Q_α value of ^{112}Cs discussed in the text. Error bars are shown for measured Q_α values where they are larger than the symbol size.

TABLE I. Summary of alpha decay measurements from this work with additional measurements from references [14,7,11]. Reduced alpha decay widths have been calculated assuming s-wave alpha particle emission using the method of Rasmussen [21] and normalized relative to the alpha decay of ^{212}Po.

Nuclide	Q_α value (keV)	Half-life (ms)	Branching ratio (%)	Reduced width
^{106}Te	4290±9	$0.06^{+0.03}_{-0.01}$ [a]	~100	$6.1^{+3.1}_{-1.1}$
^{107}Te	4011±5 [b]	3.1±0.1	70±30 [c]	1.7±0.7
^{108}Te	3445±4 [b]	2100±100 [a]	49±4	2.7±0.3
^{109}Te	3225±4 [b]	4100±200 [a]	3.9±1.3 [c]	3.1±1.1
^{108}I	4099±5	36±6	91±15 [d]	0.25±0.05
^{110}I	3586±5 [b]	650±20 [a]	17±4 [a]	1.6±0.4
^{112}Xe	3335±7	2700±800 [a]	$0.8^{+1.1}_{-0.5}$	$3.4^{+4.7}_{-2.5}$

[a]Reference [14].
[b]Reference [7].
[c]Reference [11].
[d]The branching ratio estimated for ^{108}I assumes a partial beta decay half-life of 400 ms [20].

terpolating between the measured Q_α values of ^{108,110}I suggests $Q_\alpha(^{109}\text{I})\approx 3.84$ MeV, which would correspond to a partial half-life of ~200 ms. This would imply a branching ratio ~0.05%, which is consistent with the limit deduced above.

The alpha decay Q-value measurements from the present work fit in well with established trends for alpha emitting tellurium, iodine, xenon, and caesium isotopes, which are compared in Fig. 2 with atomic mass predictions. Although the macroscopic-microscopic model of Möller and Nix [16] provides reasonable agreement with measurements for the heavier region of alpha emitters, it overestimates the Q_α-values of tellurium isotopes by more than 1 MeV and predicts a faster increase in Q_α for iodine, xenon and caesium isotopes moving away from stability than is observed experimentally. The semiempirical shell model mass formula of Liran and Zeldes [17], which also reproduces well the Q_α values of heavier alpha emitters, obtains good overall agreement for tellurium isotopes but consistently underpredicts the Q_α values of iodine and xenon isotopes by ~320 keV. The Garvey-Kelson mass relation based predictions of Comay, Kelson, and Zidon [18] fail to reproduce the measured Q-value systematics, reflecting the poor extrapolation performance of this type of model. The Q_α-value estimates of Audi and Wapstra [19] are based on previous measurements from this region.

Reduced alpha decay widths determined using the new and improved energy, half-life, and branching ratio measurements of this work and the energies of Heine *et al.* [7] are shown in Table I. It is particularly noticeable that the reduced width of ^{108}I is significantly lower than the other values, perhaps indicating that the alpha particles are not emitted with zero angular momentum. The remaining values are broadly consistent with reduced widths determined for alpha emitters above the $N = 82$ shell closure.

In conclusion, ^{108}I has been confirmed as a dominant alpha particle emitter and its half-life has been measured for the first time. This represents the only known instance of a nuclide beyond the threshold for dominant proton radioactivity decaying mainly by alpha particle emission. The energies of ^{108}I and other activities have been measured with greater precision using a procedure which provides a consistent calibration for both protons and alpha particles. The alpha decay of ^{106}Te has been confirmed by the first observation of the decays of this nuclide produced directly as an evaporation residue. Alpha branching ratios have been determined for the proton decay daughters ^{108}Te and, for the first time, ^{112}Xe and the half-life of ^{107}Te has been measured with improved precision.

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