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Spectroscopy of the proton emitter ^{109}I

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Excited states in the proton-unbound nucleus ^{109}I were populated using the ^{54}Fe(^{58}Ni,$p2n$) reaction at a beam energy of 220 MeV. Gamma rays in ^{109}I were identified using the recoil-decay tagging technique. The analysis of proton-correlated $\gamma\gamma$ coincidence data produced the yrast decay sequence in ^{109}I, which can be tentatively assigned as built on the $h_{11/2}$ proton state based on systematic trends in the neighboring isotopes. This sequence is completely different from that reported previously. A comparison of the $h_{11/2}$ band in ^{109}I with those in heavier iodines shows that ^{109}I continues the trend of decreasing quadrupole deformation with decreasing neutron number. [S0556-2813(99)50804-2]

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Until recently, experimental studies of very proton-rich, medium- to heavy-mass nuclei have been difficult. When using fusion-evaporation reactions with stable beams and targets to populate these nuclei, the production cross sections are often very small (less than 100 μb) and other reaction channels account for more than 99% of the reaction products. The physics importance of such studies, however, has been made clear by theoretical predictions. For example, calculations [1] show that established nuclear structure properties found in nuclei near the line of stability may be significantly modified in those near or beyond particle-drip lines. Knowledge about the structure of nuclei beyond the proton-drip line, therefore, can provide an important basis for the understanding of fundamental nuclear interactions.

The development of modern electromagnetic devices, such as the Argonne Fragment Mass Analyzer (FMA) [2], as well as the use of a new generation of highly efficient γ-ray detector arrays, such as Gammasphere [3], make it possible to study some nuclei at or beyond the proton-drip line. Recent studies [4–9] have taken advantage of such instruments and successfully obtained information on excited states in a number of proton-unbound nuclei. These studies utilized the so-called ''recoil-decay tagging'' (RDT) technique [4], which correlates the prompt γ rays detected at the target position with the charged-particle radioactivity detected at the focal plane. The combination of such correlations with the mass identification from a recoil mass separator makes it possible to select very weak signals associated with γ decays of extremely proton-rich nuclei. In this Rapid Communication, we report a new study of the proton emitter ^{109}I using the RDT technique.

In a previous RDT experiment using the EUROGAM-I array and the Daresbury recoil separator, five γ-ray transitions (505, 596, 729, 845, and 908 keV) were reported [4] to form the yrast decay sequence in ^{109}I. This result was based on a very weak proton-correlated γ-ray spectrum [see Fig. 7(b) of Ref. [4]], as well as on $\gamma\gamma$ coincidence spectra which were not correlated with protons. The lack of statistics in this previous study was partly caused by a beam energy that was not optimized to produce ^{109}I.

To verify, and possibly extend the information on excited states in ^{109}I, we carried out an RDT experiment using the same ^{54}Fe(^{58}Ni,$p2n$) reaction used in the previous study, but at the optimized beam energy of 220 MeV. The ^{58}Ni beam was provided by the ATLAS superconducting linear accelerator at Argonne National Laboratory and the target was an isotopically enriched, 500-μg/cm^2, self-supporting ^{54}Fe foil. Prompt γ rays were detected with Gammasphere, which consisted of 101 large-volume Compton-suppressed Ge detectors. Recoiling ions passed through the FMA (tuned to $A=109$), and their masses were determined at the focal plane by a position-sensitive parallel-grid avalanche counter (PGAC). To reduce the high count rate, blocking slits were placed at the focal plane so that only the $A=109$ ions were allowed to reach the PGAC. These ions were then implanted into a 40 mm$\times$40 mm, 60-μm-thick double-sided silicon strip detector (DSSD) for the identification of charged-particle decays. The 1600 pixels of the DSSD provided effective spatial and time correlations between an implant and its subsequent charged-particle decay. The master trigger for the data acquisition system was set such that only the following two types of events were collected: (1) events with at least two γ rays in coincidence with the PGAC; (2) any recoil or decay events determined by the combination of PGAC and DSSD. For each event, the energy, absolute time (from a continuously running clock), pixel ID, and event

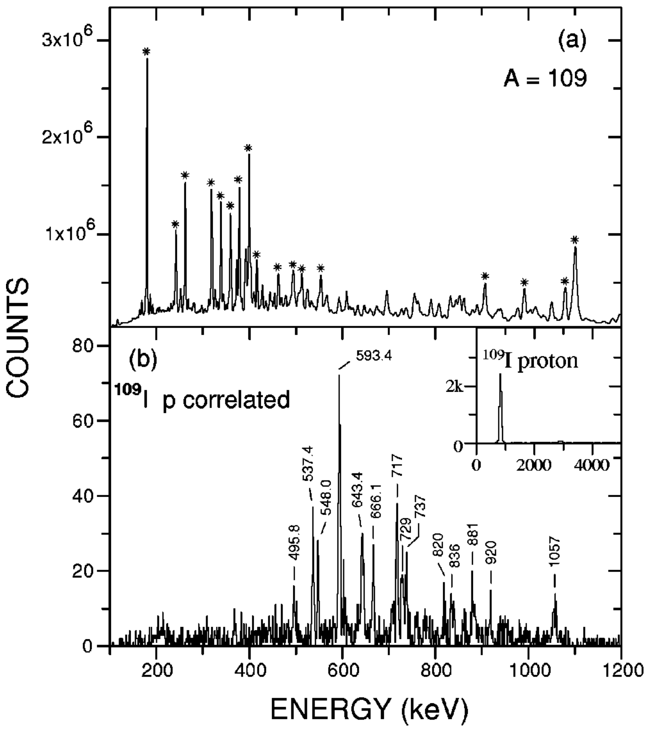

FIG. 1. (a) Gamma-ray spectrum corresponding to $A=109$ nuclei produced in the ^{58}Ni+^{54}Fe reaction at a beam energy of 220 MeV. Peaks marked with asterisks are known [13] transitions in ^{109}Sb. (b) Gamma-ray spectrum correlated with the 829-keV ground-state proton decay of ^{109}I. The inset shown in the upper-right corner is the charged-particle spectrum corresponding to the 829-keV proton decay in ^{109}I, obtained by restricting the decay time $T_d<500$ μs.

TABLE I. Energies and relative intensities of γ rays assigned to ^{109}I measured from the ^{54}Fe(^{58}Ni,$p2n$) reaction at a beam energy of 220 MeV. The γ rays were assigned to ^{109}I based on their correlation with the ground-state proton decay in this nucleus.

E_γ[a] (keV)	I_γ(relative)
495.8	17±3
537.3	36±4
548.0	30±4
593.4	100±7
643.4	48±5
666.1	30±4
717	63±6
729	35±4
737	40±5
820	15±3
836	28±6
881	44±8
920	20±5
1057	39±7

[a] Errors on these energies are approximately 0.5–1.0 keV.

type (recoil or decay) of the particle were recorded. With a beam-on-target time of about 70 hours and an average beam current of about 5 particle nA, the total number of events recorded to tape was about 190 million.

The ^{109}I ground-state proton decay has been previously established [10–12] to have a proton energy and half-life of $E_p=829\pm4$ keV and $T_{1/2}=100\pm5$ μs, respectively. This proton decay was easily identified in the present experiment. When the decay time was restricted to $T_d\leqslant500$ μs, the DSSD charged-particle decay spectrum shows this 829-keV ^{109}I proton peak with very little background [see inset of Fig. 1(b)]. The total number of ^{109}I protons observed from the experiment was about 6000. An accurate measurement of the production cross section would require the FMA efficiency, which could not be obtained from the experiment. However, assuming an FMA efficiency of 3%, the production cross section for ^{109}I would be about 16 ± 4 μb. Of the 6000 protons, about 3500 were correlated with prompt γ rays, and these events were used in the final analysis.

A spectrum of γ rays corresponding to mass $A=109$ is shown in Fig. 1(a). This spectrum is dominated by the known [13] γ rays in ^{109}Sb (peaks marked with asterisks). When correlating these γ rays with the ground-state proton decay of ^{109}I, a new spectrum emerges, see Fig. 1(b). The peaks shown in this new spectrum do not resemble any of the strong lines in Fig. 1(a). Based on their correlation with the ground-state proton decay of ^{109}I, these γ rays are assigned as transitions depopulating excited states of ^{109}I. The energies and relative intensities of these transitions are summarized in Table I.

From the proton-correlated, two- or higher-fold γ events, a $\gamma\gamma$ coincidence matrix was constructed. An analysis of this matrix showed that the 593-, 717-, 881-, and 1057-keV transitions form the yrast decay sequence in ^{109}I. Other weaker transitions either feed into or decay out of this sequence. Examples of gated coincidence spectra are presented in Fig. 2. Based on coincidence relationships as well as intensity arguments, a decay scheme for ^{109}I was established and this is shown in Fig. 3. Since the statistics achieved in the present experiment were too low for any angular correlation analysis, the spin and parity assignment for the shown levels has to be based on systematic trends in nuclei neighboring ^{109}I. In ^{113,115,117}I [14–16], the level schemes are dominated by a yrast decay sequence which is built on the $\pi h_{11/2}$ single particle state. This state then decays through several $9/2^+$ and $7/2^+$ states to the $5/2^+$ ground state. In ^{111}I, the decays between the $\pi h_{11/2}$ state and the $\pi d_{5/2}$ ground state were observed [17] to be similar to those in ^{113,115,117}I, except that the $\pi h_{11/2}$ level is isomeric with $T_{1/2}=21$ ns. The band built on the $\pi h_{11/2}$ level, however, was not observed. In ^{107}Sb, the neighboring isotone of ^{109}I, the low spin excitations (under 4 MeV excitation energy) were identified [18] as the $d_{5/2}$ and $g_{7/2}$ protons coupled to excited states of the even-even core, and no $\pi h_{11/2}$ state was observed. The absence of the $\pi h_{11/2}$ band in ^{107}Sb is understandable, since Sb has only one proton (as opposed to three protons in the case of I isotopes) outside the $Z=50$ closed shell, and thus the deformation is much smaller. As a result, the $\pi h_{11/2}$ state must have a higher excitation energy. For transitions observed in ^{109}I, their energy and intensity characteristics strongly suggest that the 593-, 717-, 881-, and 1057-keV sequence is the band built on the $\pi h_{11/2}$ state. The intensity of this sequence dominates that of the total decay, very similar to the dominant intensities of the $\pi h_{11/2}$ bands in ^{113,115,117}I. The spin and parity assignment of transitions shown in Fig. 3, as well as the ensuing discussions, therefore, are based on the assump-

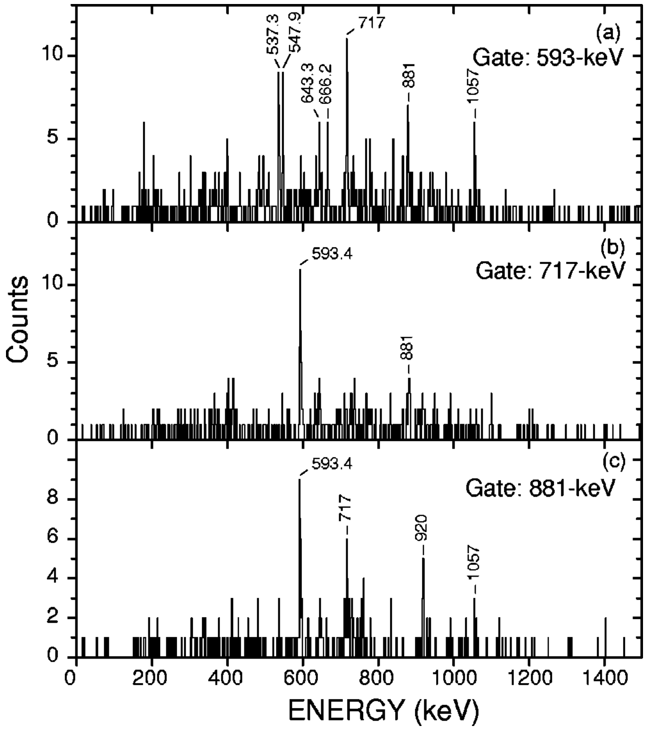

FIG. 2. Gamma-ray spectra obtained by gating on the (a) 593-keV, (b) 717-keV, and (c) 881-keV transitions in the $\gamma\gamma$ coincidence matrix that is correlated with the 829-keV ground-state proton decay in ^{109}I.

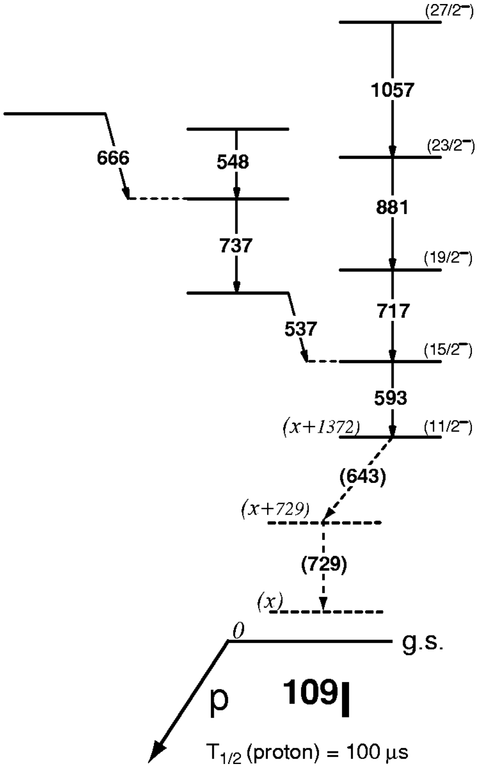

FIG. 3. Proposed level scheme of ^{109}I based on the present work. See text for detailed arguments for the placement of transitions and their spin and parity assignment.

tion that this sequence is the $\pi h_{11/2}$ band. The 537-, 737-, 548-, and 666-keV transitions are only in coincidence with the 593-keV γ ray. As a result, they are assigned as feeding the $h_{11/2}$ band at spin $I=15/2^-$. The ordering of the 737-, 548-, and 666-keV transitions is, however, less certain due to the weaker intensities. No spin and parity assignment could be obtained for these side-feeding transitions. Two other γ rays, i.e., the 643- and 729-keV transitions shown in Fig. 1(b), were found to be in coincidence with the lower-spin members of the $h_{11/2}$ band. These two transitions could be decaying out at the bandhead. Their very weak intensities, however, make it difficult to place them firmly in the level scheme. The 920-keV transition is also in coincidence with the $h_{11/2}$ band, but its intensity is too weak and thus is not placed in the level scheme. For the remaining three peaks shown in Fig. 1(b), i.e., the 495-, 820-, and 836-keV transitions, the proton-correlated $\gamma\gamma$ coincidence data did not provide any indication about their positions in the level scheme.

It is worth noting that the $h_{11/2}$ band shown in Fig. 3 is completely different from that proposed in the previous study [4], and no evidence could be found in the present data to support the 5-transition sequence proposed in [4]. The spin and parity of the ground state in ^{109}I have not been firmly established by experiments. In ^{113,115,117}I, the ground states were measured to be the $5/2^+$ spherical state. This suggests that^{109}I should have the same ground state, since there is evidence suggesting that ^{109}I is less deformed than ^{113,115,117}I (see ensuing discussions). However, a recent theoretical analysis [19] of proton-decay half-lives suggests that the ground state in ^{109}I could also be the $1/2^+$ state. Due to limited statistics, the decay from the $h_{11/2}$ band to the ground state could not be firmly established from the present data set. In ^{113}I, the $11/2^-$ bandhead decays to three $9/2^+$ states, among which the main branch (a 389-keV $E1$ transition) carries more than 80% of the intensity. This branch then decays to the $5/2^+$ ground state via a 629-keV $E2$ transition. Heavier iodine isotopes exhibit similar decay-out patterns. For ^{109}I, the decay out from the $h_{11/2}$ bandhead must have a lower relative intensity (less than 50%) compared to that in ^{113}I. This suggests that the bandhead may be isomeric, or that it decays out via more fragmented multiple paths. As mentioned above, coincidence relationships show that the 643- and 729-keV transitions (which are in coincidence with each other) could be those decaying out of the bandhead. Additionally, there may be weaker, unobserved transitions connecting to the ground state. The excitation energy of the $h_{11/2}$ bandhead, therefore, can be tentatively estimated as $E_x \geqslant 1372$ keV. A summary of the $h_{11/2}$ band excitation energies for light iodine isotopes is presented in Fig. 4(a).

Previous systematic analyses [20,21] of proton emitters have shown that, while most known proton emitters have experimental spectroscopic factors close to unity, ^{109}I stands out as one of the few which have very small spectroscopic factors. The spectroscopic factor, S, is defined as the ratio of the calculated and experimental proton partial half-lives. The calculated half-life can be obtained using the WKB approximation, with no nuclear structure information included other than the angular momentum removed by the proton decay. For^{109}I, $S=0.055$ [20]. Such a small spectroscopic factor has been interpreted [12,20,21] as evidence for substantial prolate deformation. In fact, using a multiparticle theory for proton transitions, Bugrov and Kadmensky [22] could reproduce the half-life of ^{109}I with a quadrupole deformation of $\beta \sim 0.10-0.15$.

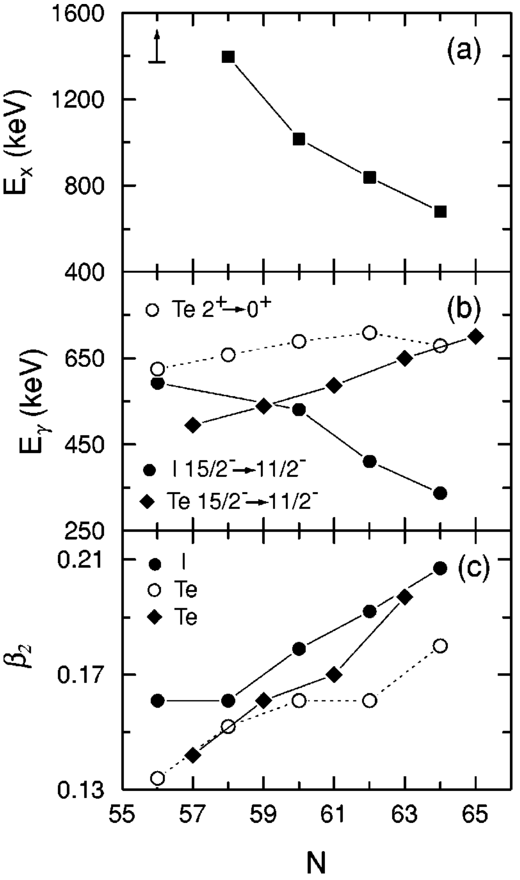

FIG. 4. (a) Experimental excitation energies of the $h_{11/2}$ bands in odd-A iodine isotopes. The lower limit for ^{109}I is tentatively deduced from the present work. Data for $^{111-119}$I are from Refs. [17,14–16,25]. (b) Experimental $15/2^- \to 11/2^-$ transition energies for the iodine isotopes (closed circles), $2^+ \to 0^+$ transition energies for the even-even tellurium isotopes (open circles), and the $15/2^- \to 11/2^-$ transition energies for the odd-A tellurium isotopes (diamonds) as a function of N. Data for ^{109}I are from the present work, for $^{113-119}$I are from Refs. [14–16,25], and those for $^{108-117}$Te are from Refs. [4,26–29]. (b) Calculated [23] quadrupole deformation β_2 for odd-A iodine isotopes at ground states.

Although no direct measurement of deformation could be obtained from the present experiment, a comparison of excited states in ^{109}I with those of its neighboring nuclei can be used to gain insight into the evolution of deformation with changing mass. In Fig. 4(b), the $15/2^- \to 11/2^-$ transition energies (closed circles) of the $\pi h_{11/2}$ bands for a series of odd-A iodine isotopes are presented as a function of neutron number. For comparison, the $2^+ \to 0^+$ transition energies (open circles) of the even-even Te core isotopes, and the $15/2^- \to 11/2^-$ transition energies (diamonds) of the $\nu h_{11/2}$ bands for the odd-A Te isotopes are also shown in the same figure. The light iodines lie in a transitional region. The low-spin part of the $h_{11/2}$ bands in these nuclei can be understood as formed by coupling the $h_{11/2}$ protons to their respective even-even Te cores, which are weakly or moderately deformed vibrators. The ground state quadrupole deformation of Te and I isotopes has been predicted [23] to decrease with decreasing neutron number, see Fig. 4(c). For iodine isotopes, the trend of the $15/2^- \to 11/2^-$ transition energies seems to agree with the predicted trend of the quadrupole deformation, i.e., the rising $E_\gamma(15/2^- \to 11/2^-)$ corresponds to a decreasing β_2 with decreasing N. Such a trend shows that although ^{109}I may be deformed, which could result in a small spectroscopic factor, the deformation is small and follows the the deformation pattern in the iodine isotopes. This contradicts the conclusion of Ref. [4], which suggested an increase of deformation from ^{113}I to ^{109}I based on its proposed level scheme.

Figures 4(b) and 4(c) also show two features which are interesting but difficult to understand: (1) The increasing $E_\gamma(2^+ \to 0^+)$ as a function of N for the telluriums is not expected according to the prediction [Fig. 4(c)] of increasing β_2 as a function of N. (2) When an $h_{11/2}$ proton is added to the tellurium core, the N dependence of the $E_\gamma(2^+ \to 0^+)$ is reversed: the $E_\gamma(15/2^- \to 11/2^-)$ for iodines decreases with N, a trend that is opposite to that shown by the telluriums [see open and closed circles in Fig. 4(b)]. An earlier study [24] of heavier iodine isotopes already pointed out this phenomenon, and suggested that a microscopic collective model with a higher order perturbation expansion of the particle-core interaction may offer an explanation. It is interesting to note that when adding an extra $h_{11/2}$ neutron to the core, the odd-A telluriums show an $E_\gamma(15/2^- \to 11/2^-)$ that closely follows the trend of the even-even telluriums [see open circles and diamonds in Fig. 4(b)]. The addition of an $h_{11/2}$ proton seems to have a much larger modification to the Te core than the addition of an $h_{11/2}$ neutron. This could be due to the fact that the proton Fermi level is much closer to the $N=50$ closed shell, and thus the nuclear properties are more sensitive to the change of valence particles.

In conclusion, a new RDT study of ^{109}I was carried out with much improved statistics compared to the previous measurement [4], and the resulting level scheme is very different. Based on a tentatively assigned configuration as well as spins and parity, our new data indicate that, the deformation of ^{109}I is small, making it the least deformed nucleus among light iodine isotopes. This fits the systematic trend of deformation in known light iodine isotopes. The new data also continues the trend of increasing $E_\gamma(15/2^- \to 11/2^-)$ with decreasing N, which is opposite to that found in tellurium cores.

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