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Evidence for the ground-state proton decay of ^{105}Sb

R. J. Tighe, D. M. Moltz, J. C. Batchelder, T. J. Ognibene, M. W. Rowe, and Joseph Cerny

Department of Chemistry and Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

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Utilizing the compound nuclear reaction ^{58}Ni+^{50}Cr and a new low-energy proton detector ball, we have observed the ground-state proton decay of ^{105}Sb. A proton energy of 478 ± 15 keV was measured along with an estimated ground-state proton branching ratio of $\sim 1\%$, compatible with emission from a $d_{5/2}$ level and a spectroscopic factor of order unity.

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Proton emission from the nuclear ground state is not only expected to determine the limit of stability for proton-rich nuclei, but also yields information on nuclear masses and structure very far from beta stability. This decay mode was first observed in 1981 from ^{151}Lu [1] and shortly thereafter from ^{147}Tm [2] (proton decay was first reported in 1970 from a spin-gap isomer of ^{53}Co [3]). Eight ground-state proton emitters have by now been reported (not including the results presented in this paper) and of these, six are in the region near the closed $N = 82$ neutron shell. A recent detailed review of proton radioactivity is given in Ref. [4].

There has been much recent experimental work, including detailed studies of ground-state alpha, ground-state proton, and beta-delayed particle radioactivity, in the vicinity of the expected doubly magic nucleus $^{100}_{50}$Sn$_{50}$. This includes the discovery of the (previously) lightest known ground-state proton emitters $^{109}_{53}$I and $^{113}_{55}$Cs [5]. Searches for ground-state proton emission from both ^{108}I [6–8] and ^{112}Cs [8,9] have yielded negative results. Recently, tentative assignment of two alpha lines has been made to the ground-state decay of ^{108}I [7]. We report here on the observation of the ground-state proton decay of $^{105}_{51}$Sb. There have been unsuccessful searches for this decay with the "fast catcher" system at Munich [6,10], and with both the on-line mass separator [11] and the velocity filter SHIP [12] at Gesellschaft für Schwerionenforschung Darmstadt m.b.H. (GSI). However, in these studies low-energy proton thresholds from 500 to 600 keV have been reported. Our observation of the proton decay of ^{105}Sb represents the lightest observed case of ground-state proton emission. The measured energy and yield of this proton peak give a stringent test of mass models and provide valuable spectroscopic information near the long sought doubly magic nucleus ^{100}Sn.

From half-life considerations, the odd proton in both ^{109}I and ^{113}Cs has been assigned to the $2d_{5/2}$ shell [6]. The spectroscopic factors deduced by comparing the calculated and measured half-lives for ^{109}I and ^{113}Cs are 0.1 and 0.02, respectively. These relatively small spectroscopic values may be the result of various factors (e.g., changes in deformation between the cores of the parent and daughter or collective degrees of freedom in the proton emitting states). The study of ^{105}Sb is particularly interesting, since it presumably has the simple configuration of a single proton occupying a $d_{5/2}$ level outside the closed $Z = 50$ shell. However, at proton energies less than ~ 500 keV, beta emission is expected to dominate the decay of ^{105}Sb simply from half-life considerations.

We have utilized a helium-jet system to collect and transport reaction products to a low-background counting area. A full description of the He-jet system is given elsewhere [13]. Briefly, our targets were located in a chamber pressurized to ~ 1.5 atm with helium. Reaction products were transported to the counting chamber via a thin 75 cm long capillary where they were deposited onto a slowly moving tape in the center of our new low-energy proton detector ball. The tape movement was used to reduce the beta background from longer-lived activities. The new low-energy detector ball is capable of detecting protons with energies down to $\sim$ 200 keV. It consists of six individual gas-ΔE, gas-ΔE, Si-E triple telescopes, although in He-jet studies only four of the telescopes are used. Relative to the collection point, the four individual detectors each subtend a solid angle of approximately 4% of 4π. It has been demonstrated that this triple detector telescope design reduces the random beta rate which enters the low-energy proton region by a factor of $> 10^6$. A full description of this detector will be presented elsewhere [14]. Because the helium pressure inside the ball is reduced via pumping only through the restricted opening in the ball by which the tape enters, the energy resolution of the detector is partially degraded for high He-flow rates.

Figure 1 shows a typical proton spectrum measured with one of these detectors for the well-known beta-delayed proton emitter ^{25}Si [15]. It is clear from this figure that the random beta rate is effectively suppressed between the known 387 keV and 905.7 keV proton lines. The proton energy resolution is approximately 45 keV full width at half maximum (FWHM) for both the 387 and 4088 keV lines, but is known to be a function of the helium pressure inside the ball. The relative intensity of the lines is not relevant here, as it was necessary to have high gas-detector thresholds to reduce the beta rate at the lower energies. The calibration used only the Si-E detector signals, with the gas detectors simply employed for particle identification.

Three separate experiments were performed in our search for the ground-state proton decay of ^{105}Sb. We utilized the compound nuclear reaction ^{50}Cr(^{58}Ni, $p2n$) to produce ^{105}Sb recoils. The 88-Inch Cyclotron at Lawrence Berkeley Laboratory was used to accelerate ^{58}Ni $^{13,14+}$ beams to energies between 370 and 405 MeV, which after correcting for energy loss through our He-jet chamber windows, corresponded to on-target beam energies of approximately 220 and 260 MeV. The ^{58}Ni beam intensities were $\sim$ 8 to 10 particle nA, while our targets were $\sim$ 1 mg/cm^2 thick ^{50}Cr$_2$O$_3$ (^{50}Cr 96.8% enriched) slurried onto $\sim$ 2 mg/cm^2 thick aluminum backings. To optimize our He-jet transport efficiency, we utilized the ^{58}Ni+^{54}Fe reaction to produce the strong ground-state alpha emitters ^{108,109}Te. Aluminum degrader foils of varying thickness were placed behind the production target to maximize the yield of these two alpha lines. For the present series of experiments, we artificially set a low-energy proton threshold of $\sim$ 300 keV. Due to our concern with potential half-life losses in He-jet transit, we, out of necessity, used a fairly large diameter transport capillary (inside diameter =1.4 mm). However, this resulted in a high partial vacuum inside the detector ball. Consequently, for two of the three experiments only one of the telescopes was capable of resolving the low-energy proton lines observed (see below).

In each of the three independent ^{58}Ni+^{50}Cr$_2$O$_3$ bombardments, a proton peak centered at $\sim$ 480 keV was observed. In the first experiment, a 7.6 mC bombardment of a 260 MeV (on target) ^{58}Ni beam, a proton group at 476 keV with 14 counts was seen. In the second run, we performed a 5.0 mC bombardment of a 260 MeV (on target) ^{58}Ni beam. In this experiment, two telescopes had the required resolution to separate the observed low-energy proton peaks. The resulting summed spectrum yielded a proton group at 484 keV with 22 counts. In the final measurement, a 7.7 mC bombardment of a 220 MeV (on target) ^{58}Ni beam, a proton group at 472 keV with 21 counts was observed. It should be noted that in all three experiments the value for the FWHM of the proton peak at $\sim$ 480 keV agrees with that of the 387 keV ^{25}Si group determined in the calibration. Taking a weighted average of the three experiments, we obtain a value of 478 keV for this proton peak.

We present in Fig. 2 the proton spectrum resulting from a sum of the three independent ^{58}Ni+^{50}Cr$_2$O$_3$ bombardments. As discussed below, we assign the group at 478 keV to the ground-state proton decay of ^{105}Sb. Neglecting any screening corrections [4], this corresponds to a Q value for the proton decay (Q_p) of 483 keV. Combining the uncertainties from our calibration and in the determination of the centroid from the three measure-

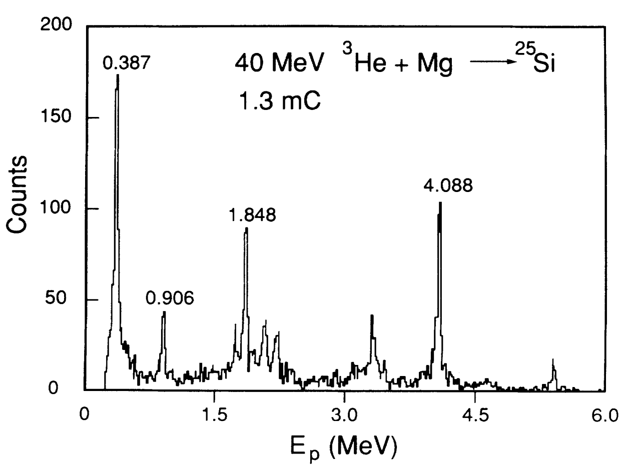

FIG. 1. A beta-delayed proton spectrum from ^{25}Si measured with one of our new gas-ΔE, gas-ΔE, Si-E triple telescopes.

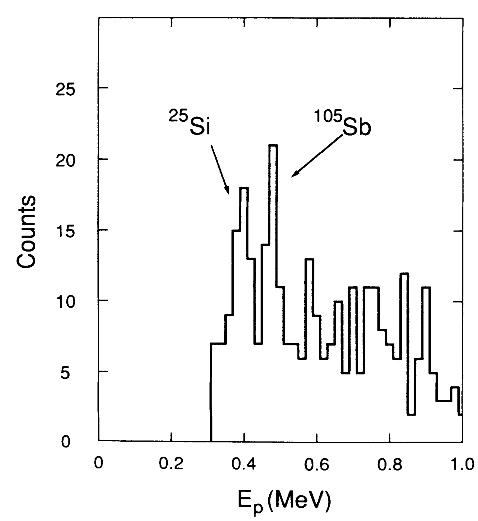

FIG. 2. The proton spectrum obtained when the results of the three independent ^{58}Ni+^{50}Cr$_2$O$_3$ bombardments are summed.

ments, we find a total uncertainty of $\sim$ 15 keV for the energy of this peak. Utilizing the FWHM determined in our calibrations, the 478 keV peak is determined to contain $\sim$ 57 counts (not subtracting any background; see below).

In order to account for reactions on the oxygen component in the target, a 25 mC bombardment was carried out with a 74 MeV (on target) $^{16}O^{4+}$ beam with an intensity of 250 pnA and a 1 mg/cm^2 ^{nat}Ni target. No proton group was observed in the region near $\sim$ 480 keV resulting from this O+Ni cross bombardment.

It can be seen in Fig. 2 that another low-energy line is present. The energy of this peak is 390 keV and we assign it to ^{25}Si beta-delayed protons made from a complex rearrangement reaction on the aluminum stopping foils. While the cross section for such a reaction is expected to be small, we note that the "100%" proton group from ^{25}Si at 4088 keV was also observed. Having seen that such complex rearrangement reactions were present, we made a survey of the $A = 4n + 1$, $T_z = -\frac{3}{2}$ strong beta-delayed proton emitters ^{21}Mg, ^{29}S, and ^{41}Ti. No evidence was observed for any strong proton lines below $\sim$ 740 keV. A proton peak at $\sim$ 480 keV from any of the remaining members of this series can be ruled out either because they are not transported efficiently by the He-jet (^{13}O, ^{17}Ne, and ^{33}Ar) or have no strongly populated intermediate states which correspond to this proton energy. To produce members of the other known series of strong beta-delayed proton emitters would require still more complex reactions [16].

The delayed-proton emitters produced in the ^{58}Ni+^{16}O reaction (e.g., ^{69}Se) are known to have tails extending only down to $\sim$ 900 keV [17], while any direct proton emission with an energy of $\sim$ 480 keV in this lighter mass region would have a lifetime much shorter than our transport time of $\sim$ 25 ms [18]. The delayed-proton emitters produced in the ^{58}Ni+^{50}Cr reactions (^{101,103,105}Sn [19,20]) and ^{58}Ni+^{27}Al reactions (^{81,83}Zr [21,22]) are known to have tails that extend only to $\sim$ 1.0 MeV. Thus, this 478 keV group must originate from a direct proton emitter produced in the ^{58}Ni+^{50}Cr compound nuclear reaction forming ^{108}Te*. The proton drip line is inaccessible at $Z = 52$ (Te) or $Z = 50$ (Sn) at the bombarding energies used here due to the increased binding energy of a proton pair and the closed shell at $Z = 50$, respectively. This leaves ^{104}Sb or ^{105}Sb from the $p3n$ and $p2n$ channels as the only possible sources of the observed proton line. The cross section predicted by the statistical evaporation code ALICE [23] for the production of ^{104}Sb is $\sim$ 50 times smaller than that expected for ^{105}Sb ($\sim$ 50 μb [6]). Furthermore, we observe no reduction in the intensity of this peak as we lower the beam energy to 220 MeV, where we expect the cross section for ^{104}Sb production to drop by a factor of $\sim$ 2 to 5. Therefore, we assign this peak to the ground-state proton decay of ^{105}Sb. (^{104}Sb is also eliminated on other grounds as noted below.)

Having successfully suppressed the random beta rate in our proton calibrations (see Fig. 1), we are confident that the events seen in Fig. 2 at energies greater than $\sim$ 500 keV are also "true" proton events (e.g., part of the events at $\sim$ 900 keV are due to the "17%" group from ^{25}Si and some are from the tails of the heavier beta-delayed proton emitters). However, it is difficult to identify the origin of all events in this region, in part due to the paucity of experiments performed with the sensitivity of our triple telescopes at these low proton energies. Still, as noted above, we expect no significant "proton background" near 480 keV. However, even if we were to fit a background under the region of the 478 keV line (see Fig. 2), our results would not be significantly altered.

The shell model predicts that an odd proton outside the $Z = 50$ closed shell will occupy either the $2d_{5/2}$ or the $1g_{7/2}$ orbital. These assignments would correspond to the emission of either an $l = 2$ or 4 proton from ^{105}Sb, respectively. Assuming this pure shell-model configuration for the emission of the odd proton from either of these levels implies a spectroscopic factor of 1 [4]. Utilizing the R-matrix formalism along with the Bohr approximation [24], we have calculated the partial lifetime for proton decay from ^{105}Sb for $l = 0$, 2, and 4 as a function of proton-decay energy. The results are displayed in Fig. 3(a). Also shown in this figure is the proton-decay branching ratio (dashed curve) assuming an $l = 2$ decay, a spectroscopic factor of unity, and an ^{105}Sb beta-decay half-life of 500 ms (as predicted by the gross theory [25]).

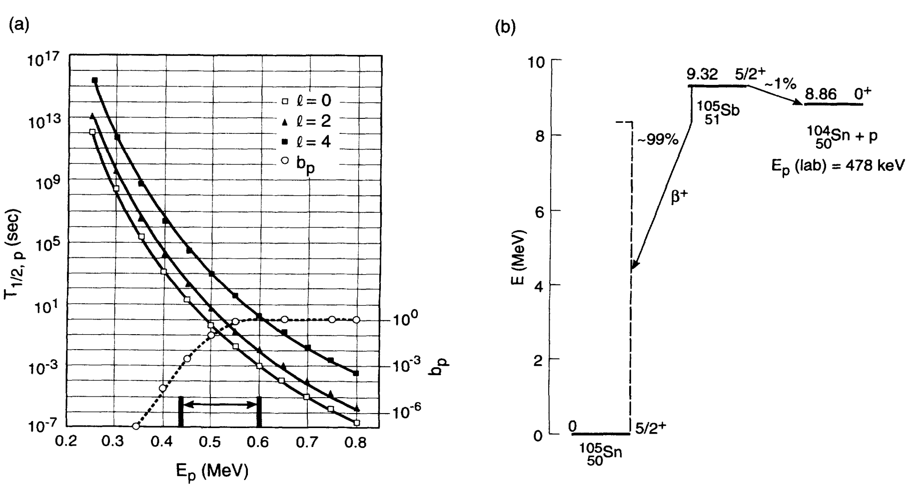

FIG. 3. (a) The calculated partial half-life for $l = 0$, 2, or 4 proton decay from ^{105}Sb, vs energy (see text). Also shown is the corresponding proton branching ratio for an $l = 2$ decay, assuming a spectroscopic factor of unity and a beta-decay half-life of 500 ms. The limits given along the energy axis represent the experimental window of observation for the present work (see text). (b) Proposed decay scheme for ^{105}Sb.

In addition, our experimental window of observation is indicated. It is determined on the low-energy side by the proton branching ratio and on the high-energy side by the predicted proton half-life and our estimated He-jet transport time.

If we use the observed yield of the 478 keV group, and assume a production cross section of ~ 50 μb for the $p2n$ channel (as was determined for the $p2n$ reactions producing ^{109}I and ^{113}Cs [6]), the resulting proton branching ratio is $\sim 1\%$ (within a factor of 2). For the emission of an $l = 2$ proton with an energy of 478$\pm$15 keV, our calculations predict a partial half-life of from 7 to 70 s, in agreement with Ref. [6]. Combining this with the beta-decay half-life of 500 ms, we find a spectroscopic factor of order unity for the ground-state proton decay of ^{105}Sb from a $d_{5/2}$ level. It is difficult to make a stronger statement than this due to the rapidly changing proton penetrability as a function of decay energy, the uncertainty of our He-jet transport efficiency ($\sim 2\%$), and the unknown beta-decay half-life. This apparently large value for the spectroscopic factor is in contrast to the values discussed above for ^{109}I and ^{113}Cs [6]. [The odd proton cannot be assigned to the $g_{7/2}$ level (i.e., $l = 4$), since an unrealistic spectroscopic factor ($\gg 1$) is obtained. Hence, the shell ordering agrees with that determined from the proton decay of ^{109}I and ^{113}Cs [6].] Making the assignment of the 478 keV group to ^{104}Sb ground-state proton decay results in an unreasonably large spectroscopic factor (i.e., $\gg$1 given the expected cross section noted above). This is further confirmation of our assignment of this group to ^{105}Sb.

Figure 3(b) gives a proposed decay scheme for ^{105}Sb. This shows an $\sim$ 99% branch to ^{105}Sn by beta decay and an $\sim$ 1% branch to ^{104}Sn by ground-state proton emission. Comparing our experimentally determined Q_p value for ^{105}Sb with those predicted by the various mass formulas in Ref. [26], that of Wapstra *et al.* gives the best agreement with our result. We also use these predictions in Fig. 3(b).

Our identification of the ground-state proton decay of ^{105}Sb represents the lightest experimentally observed case of this decay mode. The measured Q value of 483 keV and the yield of this proton peak imply emission of a $d_{5/2}$ proton with a spectroscopic factor of order unity. This continues the trend of increasing spectroscopic factors for proton decay as the $Z = 50$ closed shell is approached from above, and suggests the core wave functions of ^{105}Sb and ^{104}Sn are similar. With this decay energy, proton decay competes with beta decay at approximately the 1% level.

Note added in proof. Proton emission from ^{112}Cs has recently been reported [R.D. Page *et al.*, Phys. Rev. Lett. **72**, 1798 (1994)].

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