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EVIDENCE FOR THE GROUND-STATE PROTON DECAY OF ^{105}Sb

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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 a ground-state proton branching ratio of ~1%, compatible with emission from a $d_{5/2}$ level and a spectroscopic factor consistent with unity.

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 $^{100}_{50}\mathrm{Sn}_{50}$. 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 GSI. However, in these studies low-energy proton thresholds from 500 keV to 600 keV have been reported.

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, large changes of Q_2 and Q_4 moments are predicted in going from ^{105}Sb to ^{104}Sn [13], which potentially could result in a small spectroscopic factor for proton emission from ^{105}Sb. Further, at proton energies less than ~500 keV, beta emission is expected to dominate the decay of ^{105}Sb simply from half-life considerations. These factors could individually or in combination result in a weak proton branch for ^{105}Sb.

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 [14]. Briefly, our targets were located in a chamber pressurized to ~1.5 atm with helium. Reaction products recoiled out of a target, were thermalized in the helium, and were swept out of the chamber (on KCl aerosols suspended in the gas) through a thin capillary (75 cm long) and transported to the counting chamber. Here, 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 ~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. Figure 1a depicts a cross-sectional view of one such telescope. The current design uses grids rather than nickel foils as electrodes. The gas detectors are typically pressurized to ~15 Torr of tetrafluoromethane. 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 [15]. Because the helium pressure inside the ball is reduced via pumping only through the opening in the ball by which the tape enters, the energy resolution of the detector is partially degraded for high He-flow rates .

Figure 1b shows a typical proton spectrum measured with one of these detectors for the well known beta-delayed proton emitter ^{25}Si [16], produced via the ^{24}Mg(^{3}He,2n) reaction. The 40 MeV ^{3}He beam was pulsed and the counting electronics were enabled only during the beam-off periods to eliminate neutron-induced background events. 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 FWHM for both the 387 keV 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. Hence, the "100%" group at 4088 keV appears to have a smaller yield than the "73.7%" group at 387 keV. The detector ball was calibrated in each experiment using the ^{25}Si proton lines. The calibration used only the Si-E detector signals, with the gas detectors simply employed for particle identification. The energy dependence of the energy loss in the gas region was built into the calibration.

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 MeV and 260 MeV. The ^{58}Ni beam intensities were ~8 to 10 pnA, while our targets were ~1 mg/cm^2 thick ^{50}Cr$_2$O$_3$ (^{50}Cr 96.8% enriched) slurried onto ~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 ~300 keV. Due to our concern with potential half-life losses in He-jet transit, we of necessity used a fairly large diameter transport capillary (i.d.=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).

Figure 2a shows the proton spectrum (unshaded) resulting from a 7.6 mC bombardment of a 260 MeV (on target) ^{58}Ni beam incident on a $^{50}Cr_2O_3$ target. 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. The shaded spectrum in each part of Figure 2 indicates the proton spectrum obtained in this ^{16}O + Ni cross bombardment. This ^{16}O beam energy corresponds to approximately the equivalent center-of-mass energy as in the case of ^{58}Ni + ^{16}O at 260 MeV. A peak centered at 482 keV with 12 counts resulting from the ^{58}Ni + $^{50}Cr_2O_3$ bombardment can be seen in the unshaded spectrum in Figure 2a. No normalization was attempted between the ^{58}Ni + $^{50}Cr_2O_3$ and ^{16}O + Ni spectra. Rather, we simply wish to indicate that no peak arises at ~480 keV from the Ni + O reaction.

The proton spectrum from a second experiment, which consisted of a 5.0 mC bombardment of a 260 MeV (on target) ^{58}Ni beam is given in Figure 2b. A peak centered at 482 keV with 21 counts is observed. In this experiment our ΔE-gas thresholds were set higher, resulting in lower efficiency for proton energies above ~700 keV. This spectrum represents the sum of events from two detector telescopes, both of which had the required resolution to separate the observed low-energy proton peaks. In a final run, a 7.7 mC bombardment was performed with a ^{58}Ni on-target beam energy of 220 MeV. Figure 2c shows the results of this experiment where a peak at 473 keV with 19 counts is seen. It should be noted that in all three experiments the value for the FWHM of the proton peak at ~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. As discussed below, we assign this group 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 measurements, we find a total uncertainty of ~15 keV for the energy of this peak.

It can be seen in Figure 2, especially in parts b and c, 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 (*i.e.*, a proton in and three neutrons out). 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, Tz = -3/2 strong beta-delayed proton emitters ^{21}Mg, ^{29}S, and ^{41}Ti produced via (^{3}He,2n) reactions on ^{20}Ne, ^{28}Si, and ^{40}Ca targets. No evidence was observed for any strong proton lines below ~740 keV. A proton peak at ~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. Members of the other known series of strong beta-delayed proton emitters would require still more complex reactions to produce [17].

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 ~900 keV [18], while any direct proton emission with an energy of ~480 keV in this lighter mass region would have a lifetime much shorter than our transport time of ~25 ms [19]. The delayed-proton emitters produced in the ^{58}Ni + ^{50}Cr reactions (^{101,103,105}Sn [20,21]) and ^{58}Ni + ^{27}Al reactions (^{81,83}Zr [22,23]) are known to have tails that extend only to ~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 [24] for the production of ^{104}Sb is ~50 times smaller than that expected for ^{105}Sb (~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 ~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.)

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 $\ell = 2$ or $\ell = 4$ 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 one [4]. Based on the R-matrix formalism, the partial lifetime for proton decay is given by

$$\tau_p = \hbar / \left(2\gamma^2 \cdot P_\ell(E)\right), \tag{1}$$

where $P_\ell(E)$ is the penetrability for a proton with angular momentum ℓ through the Coulomb and angular momentum barriers, and γ^2 is the reduced width for the proton decay channel (note that $T_{1/2,p} = (\ln 2)\, \tau_p$). The reduced width can be written as

$$\gamma^2 = \left(\hbar^2/2\mu\right) \cdot S_{\ell j} \cdot \left| R_{n\ell j}(r_0)\right|^2 \cdot r_0 \,. \tag{2}$$

Here, $S_{\ell j}$ is the spectroscopic factor, μ is the reduced mass for the proton channel, and $R_{n\ell j}$ is the radial part of the interior wave function at the radius of the nuclear surface r_0. The Bohr approximation [25] can be used for an orbital with small binding energy and is given by

$$r_0 \cdot \left| R_{n\ell j}(r_0) \right|^2 \approx 1.4 / r_0^2 \, . \qquad (3)$$

Figure 3a shows a plot of the calculated partial proton half-life versus energy for ^{105}Sb using this formalism. The calculated half-life is given for ℓ-values of 0, 2 , and 4, with the spectroscopic factor set equal to one. For the emission of an $\ell = 2$ proton with an energy of 478 ± 15 keV, our calculations predict a partial half-life of from 7 to 70 s, in agreement with Ref. [6]. Also shown in Figure 3a is the resulting ground-state proton branching ratio assuming an ℓ-value of 2 (as seen for ^{109}I and ^{113}Cs), a spectroscopic factor of one, and a beta-decay half-life of 500 ms (as predicted by the gross theory [26]). 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 ~1%. Combining this with the 500 ms half-life for ^{105}Sb and an $\ell = 2$ proton decay ($d_{5/2}$ orbital), we find a spectroscopic factor consistent with unity (see Figure 3a) for the ground-state proton decay of ^{105}Sb. 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 (~2%), and the unknown beta-decay half-life. This 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.*, $\ell = 4$), since an unrealistic spectroscopic factor (>> 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. This is further confirmation of our assignment of this group to ^{105}Sb.

Figure 3b gives a proposed decay scheme for ^{105}Sb. This shows a ~99% branch to ^{105}Sn by beta decay and a ~1% branch to ^{104}Sn by ground-state proton emission. Table I gives the predicted proton separation energies of several mass formulae [27] for light Sb isotopes. Comparing the predictions for the Q_p-value of ^{105}Sb for all the mass formulae in Ref. 27, that of Wapstra, *et al.* gives the best agreement with our result. The results of Möller and Nix are typical of the majority of mass models insofar as the proton separation energy is predicted to continuously decrease as the mass of an isotope decreases. It is interesting to note that the predictions of

Wapstra, *et al.* and Comay, *et al.* both show an increased binding energy for ^{104}Sb relative to ^{105}Sb. This odd-even staggering of the proton separation energy caused by the n-p pairing interaction has been proposed as an explanation for the observation of the ground-state alpha decay of ^{108}I [7] and the non observation of the ground-state proton decay of both ^{108}I [6-8] and ^{112}Cs [8,9]. If indeed the prediction of Wapstra, *et al.* is correct in that ^{104}Sb is bound to proton emission by 80 keV more than ^{105}Sb, then unlike ^{108}I, ^{104}Sb will have a beta-decay branch of ~100%. (The predicted alpha-decay energy of ^{104}Sb is ~2.0 MeV, implying a partial alpha-decay half-life of ~10^{11} seconds.)

The observation of the ground-state proton decay of ^{105}Sb with a Q-value of 483 keV implies emission of a $d_{5/2}$ proton with a spectroscopic factor consistent with 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. Further, it is likely that ^{104}Sb does not undergo observable proton decay.

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Table 1

Q-value predictions of several mass formulae for the ground-state proton decay of neutron-deficient Sb isotopes.

	Q_p (MeV)		
	Wapstra, *et al.*[a]	Möller and Nix[a]	Comay, *et al.*[a]
^{106}Sb	-0.569	0.691	-0.309
^{105}Sb	0.461	1.561	0.281
^{104}Sb	0.381	1.801	0.261

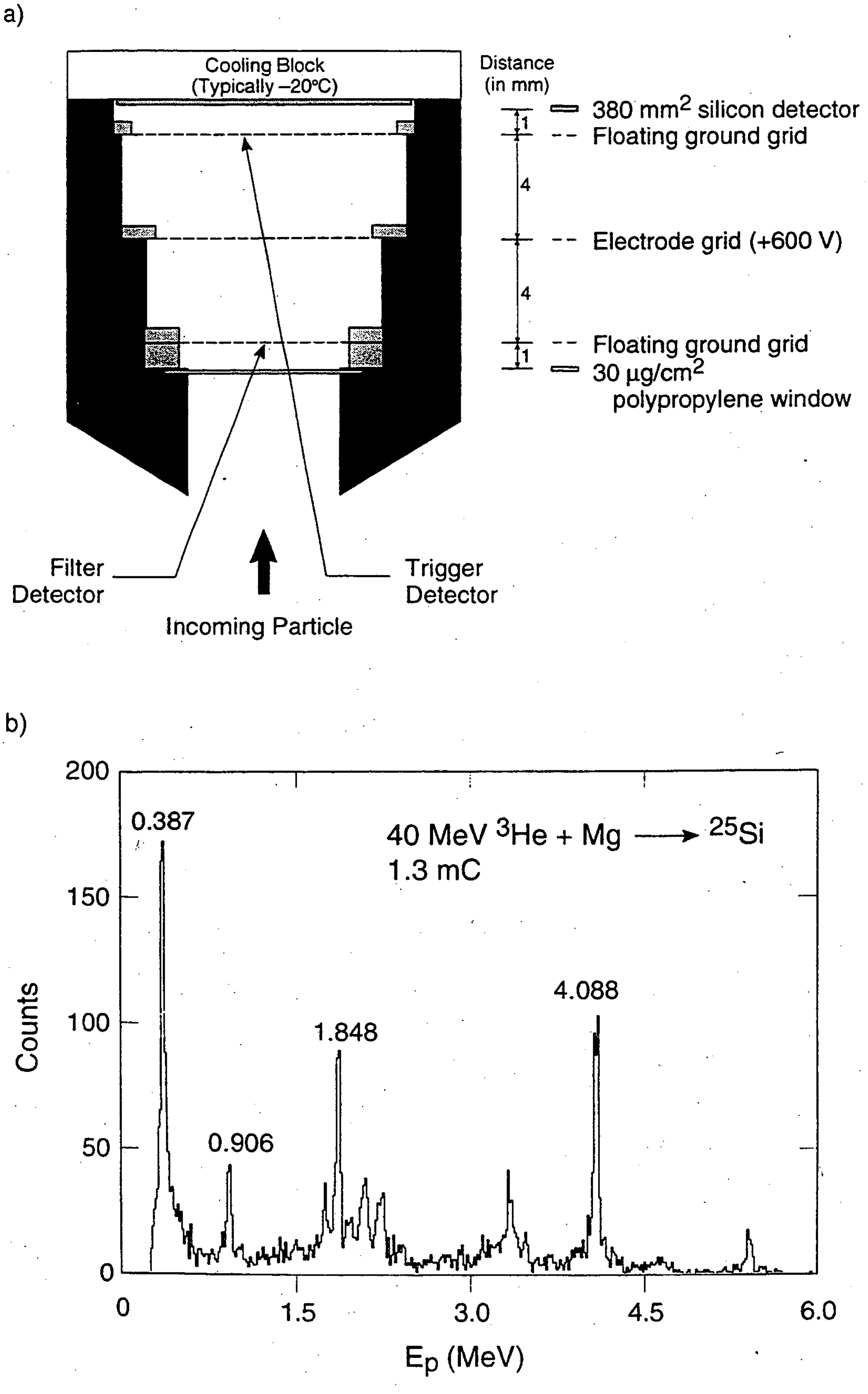
[a] Ref. [27]

Figure Captions

Figure 1. (a) A cross sectional view of one of our new low-energy gas-ΔE, gas-ΔE, Si-E triple telescopes. (b) A beta-delayed proton spectrum from ^{25}Si measured with one of these telescopes.

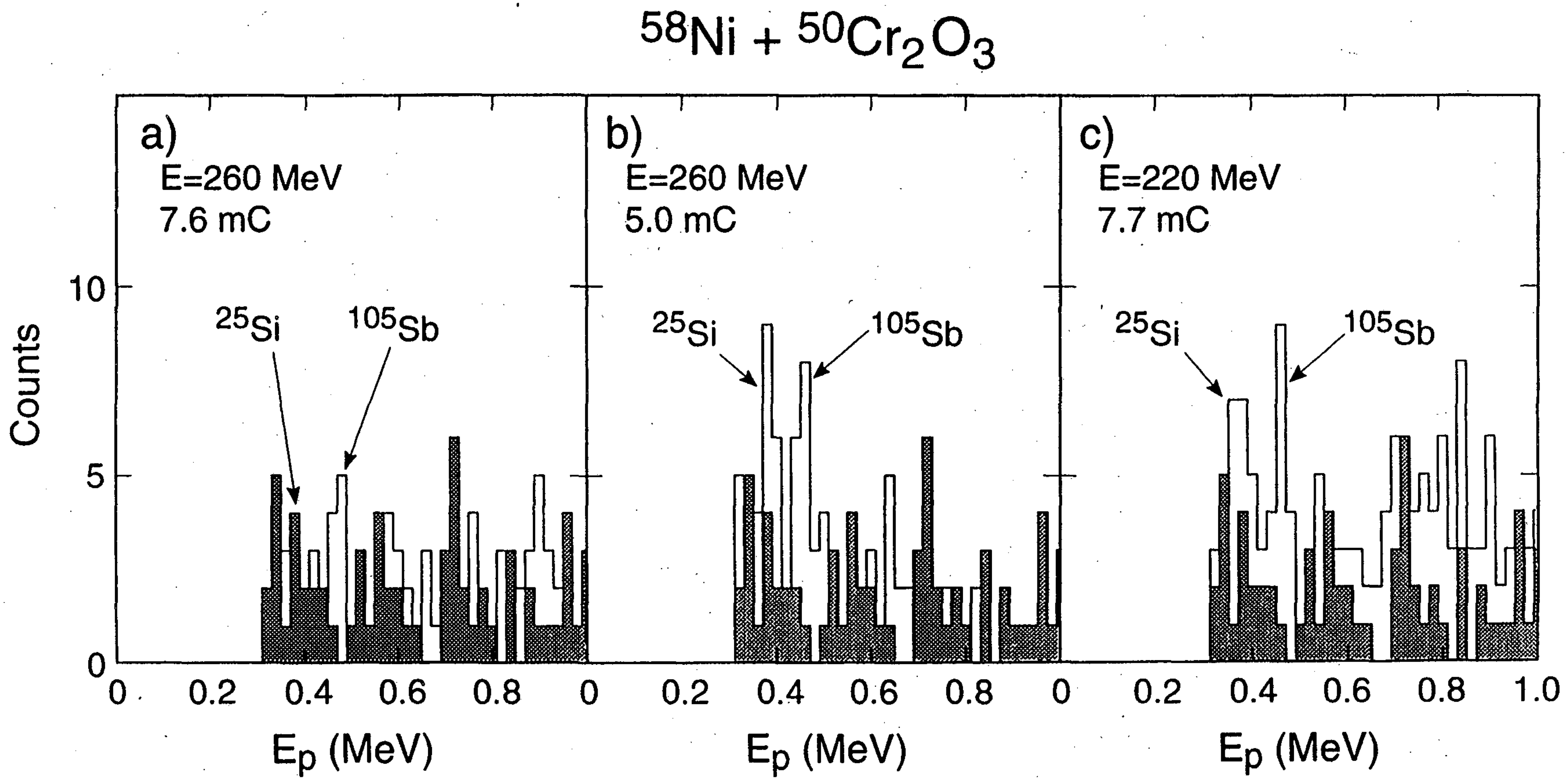
Figure 2. The proton spectra from three separate bombardments of ^{58}Ni + $^{50}Cr_2O_3$ (unshaded) with the proton spectrum from a 25 mC ^{16}O + ^{nat}Ni bombardment (shaded) superimposed. (a) A 7.6 mC bombardment with 260 MeV ^{58}Ni beam energy. (b) A 5.0 mC bombardment with 260 MeV ^{58}Ni beam energy (two detectors summed, see text). (c) A 7.7 mC bombardment with 220 MeV ^{58}Ni beam energy.

Figure 3. (a) The calculated partial half-life for an $\ell = 0$, 2 or 4 proton decay from ^{105}Sb versus energy (see text). Also shown is the corresponding proton branching ratio for an $\ell = 2$ decay, assuming $S_{\ell j} = 1$ 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. (b) Proposed decay scheme for ^{105}Sb, where the energy levels are given relative to the ground state of ^{105}Sn. Mass predictions are from Wapstra, *et al.* (see text).



XBL 937-4339

Figure 1



XBL 937-4340

Figure 2

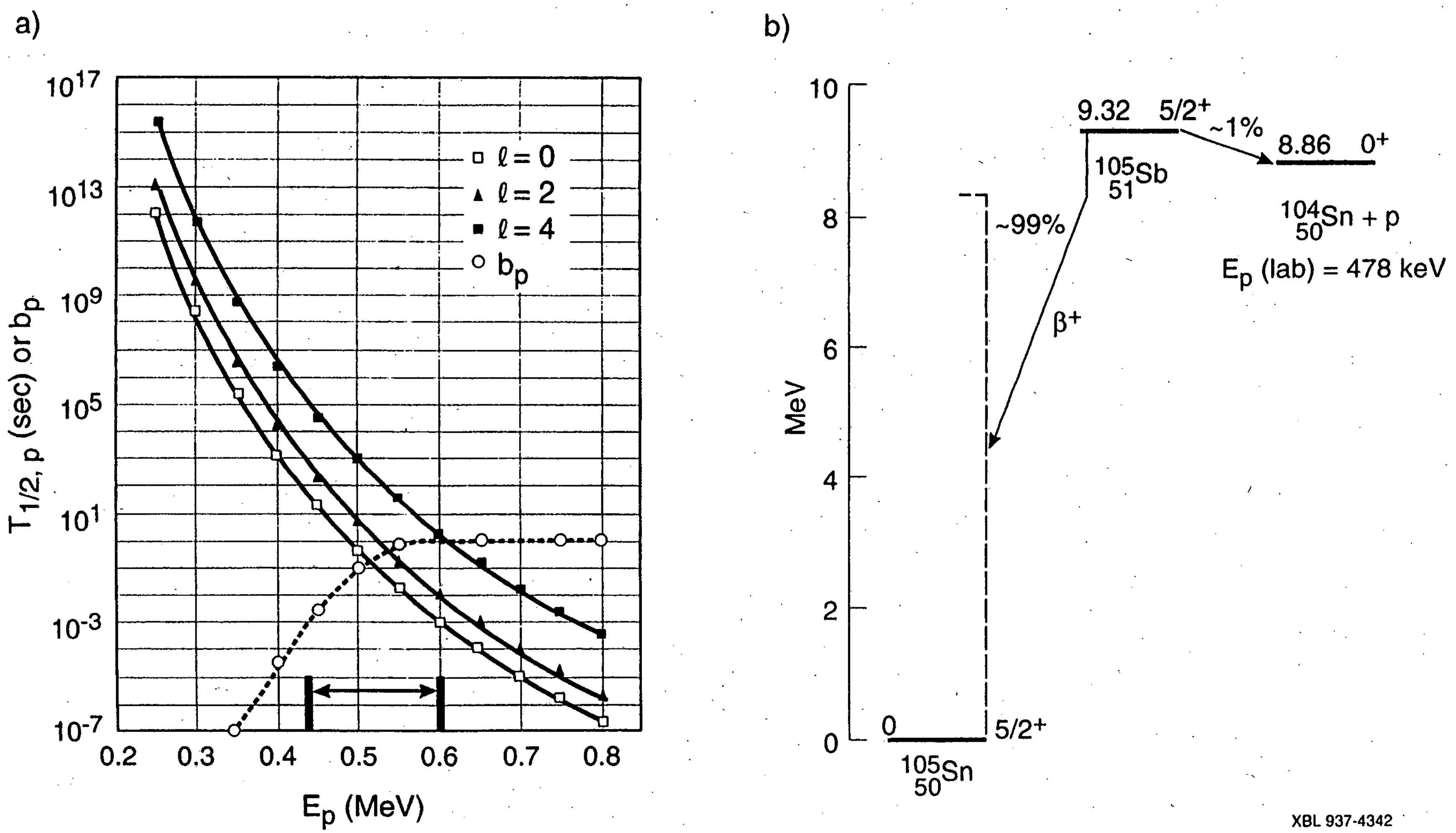


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Figure 3

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