Reinvestigation of direct proton decay of ^{105}Sb

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Proton radioactivity from ^{105}Sb has been reinvestigated at the GSI on-line mass separator. The nucleus was produced in the reaction ^{50}Cr(^{58}Ni,1$p2n$), and collected with a tape transport system. A double-sided Si strip detector was used for proton spectroscopy. The direct proton decay of ^{105}Sb reported in an earlier experiment at Berkeley was not observed. The present data imply an upper limit $\sim 10^{-3}$ for the ground-state proton decay branching ratio for proton energies higher than 430 keV.

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The proton drip line defines one of the fundamental limits to nuclear stability. Nuclei lying beyond this locus are energetically unbound to the emission of a constituent proton from their ground states [1]. Proton radioactivity is an inherently simple decay mode, which provides a sensitive probe of nuclear structure far from the valley of stability. The lightest isotope for which ground-state proton radioactivity has been reported is ^{105}Sb [2]. It forms a link at the proton drip line between spherical nuclei close to doubly magic ^{100}Sn and the onset of deformation in iodine and cesium isotopes. Recent in-beam γ-ray studies suggest the structure of ^{105}Sb to be approximately spherical [3]. The first ground-state proton radioactivities to be discovered in this region were ^{109}I and ^{113}Cs [4]. Their spectroscopic factors were found to be anomalously low (0.1 and 0.02) by using spherical WKB calculations, but the decay rates could be reproduced by using a multiparticle calculational approach assuming modest quadrupole deformations ($\beta \sim 0.05$–0.10 and 0.10–0.15, respectively) [5].

Ground-state proton radioactivity of ^{105}Sb was reported by Tighe *et al*. in helium jet experiments performed at Berkeley [2]. A 478±15 keV line was observed and assigned to ground-state proton emission from ^{105}Sb. However, no half-life measurement was obtained, and a branching ratio of approximately 1% was estimated from an assumed production cross section of 50 μb (as was determined for the $p2n$ reactions producing ^{109}I and ^{113}Cs [4]). This led to an assignment of proton decay from a spherical $\pi d_{5/2}$ configuration [2]. As the experimental technique used in this experiment did not allow for background suppression, the proton energy spectrum contained a large number of discrete low-energy lines associated with β-delayed proton decays from other light reaction products produced in the target. Despite a number of studies, no other groups have reported the observation of a 478 keV proton decay line from ^{105}Sb [4,6–9]. In particular, experiments performed by using the projectile fragment separator (FRS) at GSI identified the production of ^{105}Sb directly, and the half-life of ^{105}Sb was determined to be 1.12±0.16 s from the measurement of 98 β^+ decay events [10]. In these data one protonlike event was found (with an 85% confidence level) at an energy of 550±30 keV, in clear disagreement with the Berkeley value. An attempt to clarify the situation was made at the GSI on-line mass separator by using two very thin single-element ΔE Si detectors (15.6 μm, 20.3 μm) to search for low-energy protons [11]. Although the experiment was very sensitive, and no direct proton decay line was observed, the presence of a significant level of low-energy β-decay background in the region of interest meant that the Berkeley result could not be conclusively excluded.

The present experiment was also performed at the GSI on-line mass separator using a tape transport system. However, in this case a double-sided silicon strip detector (DSSD) was mounted at the counting station covering a solid angle $\sim$10% of 4π. The DSSD had 48×48 orthogonal 300 μm wide strips on front and back and a thickness of 67 μm [12]. It has been demonstrated that such detectors are extremely insensitive to low-energy β-decay background [13]. This is due to the relatively long range of positrons in Si compared with that of low-energy protons and the ability to reject pile-up events compared with a large-area single-element Si detector. Consequently, a high degree of β background can be eliminated by requiring single-strip multiplicities and approximately equal energy deposition on the front and back faces of the DSSD. For the detection of low-energy protons, the energy responses of all 96 channels were carefully studied with precision pulser signals. The DSSD system was calibrated with the well-known 1.05 MeV proton decay of the ^{147}Tm ground state ($T_{1/2} = 0.58$ s) [14,15] shown in Fig. 1. The peak has an energy resolution $\sim$40 keV FWHM. The continuously distributed events are β-delayed protons from $A = 147$ isobars, mainly ^{147}Er($T_{1/2} = 2.5$ s) [15]. The energies of these β-delayed protons are higher than 2 MeV; consequently most of them deposit only part of their energies

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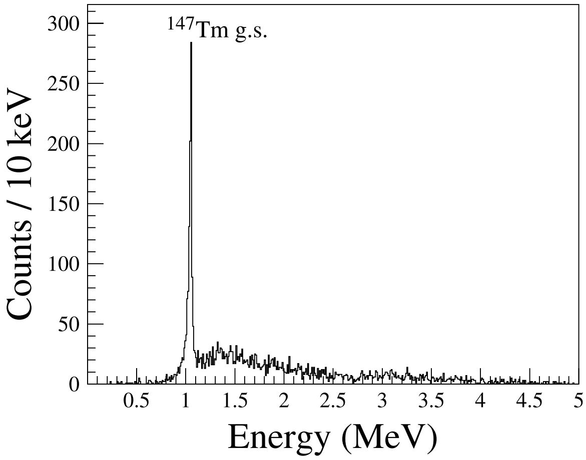

FIG. 1. Energy spectrum of decay events from the $A = 147$ run in the ^{58}Ni + ^{92}Mo reaction. The 1.051 MeV proton line is from the ground-state decay of ^{147}Tm.

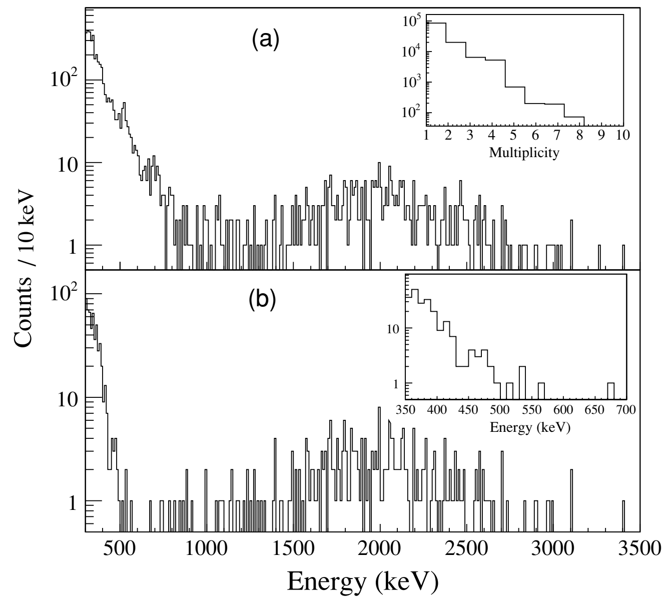

FIG. 2. (a) Energy spectrum in all strips on one side of the DSSD; the inset shows the multiplicity for β events below 400 keV. (b) Energy spectrum obtained with the condition of multiplicity $M = 1$ and energy difference of less than 3σ (05 keV) on both sides of the DSSD. The region of interest is expanded in the inset.

in the thin DSSD detector. In this first part of the experiment relatively high electronic thresholds (~500 keV for most of the strips) were set for the DSSD signals as a result of electronic pickup; consequently there is very little β background present below the ^{147}Tm ground-state proton peak in Fig. 1. For the main part of the experiment described below, the source of the pickup was identified and the electronic thresholds were reduced, to around 200–300 keV for all strips.

A 290 MeV ^{58}Ni beam provided by the UNILAC impinged on a 3.0 mg/cm^2 ^{50}Cr target (97% isotopically enriched) with molybdenum backing in order to produce ^{105}Sb ions. The molybdenum backing was 2 mg/cm^2 thick and facing the beam. The beam energies on the surface and in the middle of the ^{50}Cr target corresponded to 255 and 222 MeV, respectively, covering the energy range at which the proton line was reported at Berkeley [2]. The average beam intensity was 36 particle nA. A FEBIAD-E-type ion source was used with improvements in efficiency made for antimony isotopes [11]. The total separation efficiency between production and collection depends sensitively on the half-life value. A lower limit around 2% was expected for ^{105}Sb, with the error on the experimental half-life giving an uncertainty factor of ~2. The mass separated $A = 105$ activity was collected on a transport tape, and then moved to the counting position every 2.8 s. The run for ^{105}Sb lasted for 60 h. The resulting energy spectra are displayed in Fig. 2. Figure 2(a) shows the energy spectrum recorded in all individual strips on one side of the DSSD detector. There is a broad bell-shaped distribution of events between 1.5–3.0 MeV associated with protons produced in β-delayed proton decays, with ^{105}Sn expected to be the dominant source of this activity. Below 1 MeV the spectrum is dominated by background from β decays, which increases steeply with decreasing energy. The inset shows the multiplicity distribution (defined as the total number of fired strips on the same side of the DSSD) within the β-decay energy region. In order to optimally suppress these low-energy β events, a front and back DSSD signal multiplicity condition $M = 1$ was applied, and events were restricted to those with equal energies within 3σ (50 keV) on both sides of the DSSD. The resulting energy spectrum is shown in the lower panel of Fig. 2. As expected, the events associated with β-delayed protons are largely unaffected by the gate conditions. However, there is a drastic reduction in the β-decay background. The region of interest is expanded in the inset. Around 20 counts appear in the entire energy region between 430 and 530 keV—the relatively flat time distribution of these events is inconsistent with the known half-life of ^{105}Sb [10]. Assuming a production cross section of 30 μb (estimated experimentally by Lipoglavsek *et al.* [3]), an effective target thickness of 1.5 mg/cm^2 and a 2% efficiency for the separation of ^{105}Sb, a production rate of around 2.0 atoms/s was expected for ^{105}Sb at the tape collection position. Based on the yield rate of the 478 keV proton line measured in the Berkeley experiment [2], a peak with ~150 counts should appear. The present data are therefore in disagreement with the Berkeley result.

From the present data an upper limit $\sim 10^{-3}$ is implied for a ground-state proton decay branch from ^{105}Sb for energies higher than 430 keV. For comparison, a simple WKB calculation assuming a spherical $d_{5/2}$ proton orbital and a spectroscopic factor ~1 would give a branching ratio $\sim 10^{-3}$ for a 430 keV proton energy by using the known β-decay half-life of 1.12 s [10].

The current experimental data cast further doubt on the existence of a 478 keV ground state proton decay line from ^{105}Sb. However, a more decisive approach to this issue could be achieved in the future by two feasible routes. First, with improved primary Xe beam intensities it should be possible to greatly increase the yield of ^{105}Sb produced on the FRS at GSI, thereby setting unambigous and stringent limits on the possible existence of a weak proton decay branch. Second, precise measurements of the ground-state masses of ^{105}Sb and ^{104}Sn using ion traps would determine the proton decay Q value and could be compared with the Berkeley result.

The reported observation of ^{103}Sb [16] in fragmentation studies at GANIL is also hard to reconcile with the Berkeley result. Q_p-value systematics [1] would suggest an increase in Q_p of ~800–900 keV for ^{103}Sb relative to ^{105}Sb, which would lead to a ground-state proton-decay lifetime too short for observation by using the LISE separator (flight time of 1.5 μs). A new fragmentation measurement confirming the existence of ^{103}Sb would therefore also be very valuable.

In summary, the direct proton decay of ^{105}Sb was reinvestigated with higher sensitivity on the GSI on-line mass separator with a DSSD detector. No evidence was observed for the existence of the previously reported proton line from experiments at Berkeley. The present results imply an upper limit $\sim 10^{-3}$ for proton decays from ^{105}Sb with energies higher than 430 keV.

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