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Beta-delayed proton decay of ^{65}Se

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The $T_Z=-\frac{3}{2}$, $A=4n+1$ nuclide ^{65}Se produced in the ^{40}Ca(^{28}Si,3n) reaction has been observed via beta-delayed proton emission. A single proton group at 3.55±0.03 MeV has been observed, corresponding to the decay of the $T=\frac{3}{3}$ isobaric analog state in ^{65}As to the ground state of ^{64}Ge. Combining this measurement with a Coulomb displacement energy calculation yields a mass excess for ^{65}Se of −33.41±0.26 MeV.

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INTRODUCTION

The decays of many proton-rich light nuclei near the proton drip line have been identified by beta-delayed proton emission. In the case of a strong proton emitter, the isobaric analog state (IAS) populated by the superallowed beta transition is unbound with respect to proton emission. Proton decay from this IAS to $T=0$ states in the daughter is isospin forbidden, and thus emission from the IAS can only proceed via isospin mixing. All members of the $T_Z=-\frac{3}{2}$, $A=4n+1$ series from ^{9}C to ^{57}Zn are beta-delayed proton emitters and are discussed in the review by Cerny and Hardy in 1977 [1]. More recently, the next highest member, ^{61}Ge [2], was discovered via its delayed-proton branch.

In this paper, we wish to report the successful discovery of ^{65}Se as a beta-delayed proton emitter. This next member of this series has been predicted by all the mass formulas in the 1988 mass tables [3] to be bound to ground state proton emission. Currently the lightest Se isotope known is ^{67}Se [4].

To predict the emitted proton energy, one can use the fact that the binding energies between mirror nuclei differ mostly by their respective Coulomb energies. Although the masses of most of these very proton rich $T_Z=-\frac{1}{2}$ nuclides are not known, those of the corresponding neutron-rich mirrors are known. These masses are needed for the Kelson-Garvey mass relation [5] which is used to predict the masses of proton-rich nuclides with $T_Z\leq-1$; this method has proven to be the most effective in this region. The masses of the $T_Z=-\frac{1}{2}$ nuclei used in the Kelson-Garvey mass relation have been predicted by a Coulomb displacement energy formula [6]. Using this method, the mass excess for ^{65}Se is −33.35±0.27 MeV. The large error is due to the errors in the measured masses associated with the known $T_Z=\frac{1}{2}$ nuceli, and those arising from the calculated $T_Z=-\frac{1}{2}$ nuclei. This approach was also used to predict the IAS of the beta daughter (^{65}As) to be unbound to proton emission by 3.61±0.37 MeV (in the laboratory frame).

^{65}As, the β daughter of ^{65}Se, has been predicted to be unbound to direct proton emission from the ground state by 360 keV. Searches for the ground state proton emis-

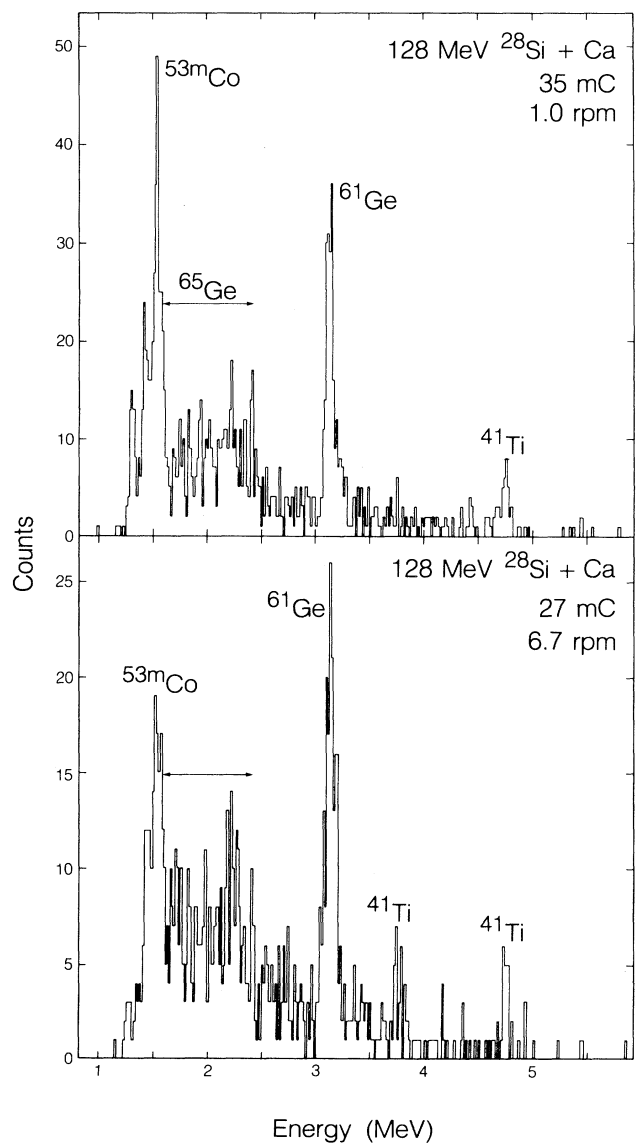

FIG. 1. Delayed proton spectra from Ref. 2. Data were taken at two wheel speeds: top (1.0 rpm); bottom (6.7 rpm).

sion of this nuclide have proved unsuccessful [7,8,9], with an upper limit for the proton decay branch to be less than 0.5% [7]. However, recent experiments [4] have, in fact, confirmed the existence of ^{65}As. A measurement of the β-delayed proton energy allows one to measure the IAS in ^{65}As and then predict more accurately the mass of the ground state of ^{65}Se by use of the aforementioned Coulomb displacement energy formula [6].

A previous search [2] for ^{65}Se using a ^{28}Si beam on a ^{nat}Ca target reported no evidence for its decay by beta-delayed protons, a result which we now attribute to the making effects of "background" protons from the well-known strong β-delayed proton emitter ^{41}Ti [10] arising from reactions on oxygen contaminants in the Ca targets. There are two ^{41}Ti delayed proton transitions which could interfere with the possible observation of ^{65}Se decay protons at $\sim$3.6 MeV, a 15.5$\pm$0.8% transition at 3.69 MeV and a 31.0$\pm$2.0% transition at 3.749 MeV [11] (compared to a defined 100% for the transition at 4.74 MeV). Figure 1 shows the data presented in the original ^{61}Ge paper [2]. In this experiment, a helium-jet system was used to deposit activity on a slowly rotating wheel which was then viewed directly by a Si-Si detector telescope. Data are shown for two different wheel speeds. Since the activity is deposited on the wheel in front of the detector, and then rotated away, shorter lived species are more likely to be observed at faster wheel speeds. At the slower wheel speed, there is a small peak at 3.7 MeV with approximately the correct ratio of counts compared to the 100% ^{41}Ti peak at 4.74 MeV. However, at the faster wheel speed, the ratio of the 3.7 MeV peak to the main ^{41}Ti peak is too large to be due entirely to ^{41}Ti. Therefore, this peak could be partially due to a different species with a half-life much shorter than that of ^{41}Ti ($t_{1/2}$=80$\pm$2 ms) [10]. It was decided that this anomaly required additional investigation to determine whether this peak could be due in part to the β-delayed proton decay of ^{65}Se.

EXPERIMENTAL METHOD

^{65}Se was produced via the ^{40}Ca(^{28}Si, 3n) reaction, utilizing a 175 MeV $^{28}Si^{6+}$ beam from the Lawrence Berkeley Laboratory 88-Inch Cyclotron degraded to differing on-target energies. Typical beam currents were 1 μA. The helium-jet setup employed in this experiment is shown schematically in Fig. 2. Recoil nuclei from a 2.1 mg/cm^2 natural Ca target were transported on KCl aerosols in the helium, through a 145 cm capillary (1.4 inner diam mm) to a shielded detector chamber. They were then deposited on a slowly moving tape positioned directly in front of various semiconductor detector telescopes. The tape was slowly rotated to reduce the beta background from longer lived species. The total transit time for this system was $\sim$30 ms.

The Ca targets used were produced as oxygen free as possible to reduce background protons from ^{41}Ti. Two different energies (at the target midpoint) of 115 and 128 MeV were obtained by use of Al degraders located upstream of the target. These energy losses were in addition to the energy losses in the window assemblies and in

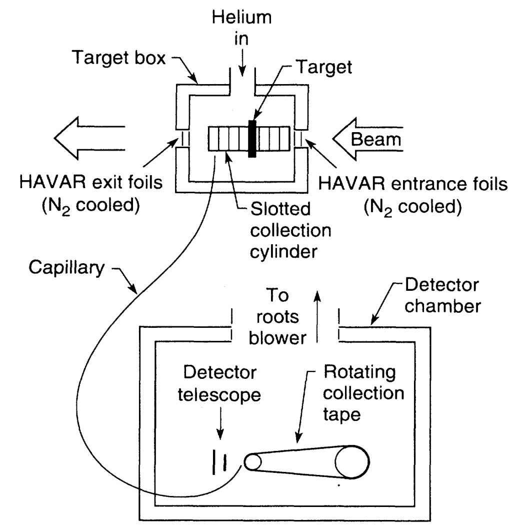

FIG. 2. Schematic diagram of the He-jet transport system and the basic telescope arrangement employed.

the helium. A single Si-Si detector telescope was used consisting of a 27 μm ΔE and a 300 μm E detector with a solid angle of $\sim$11% of 4π. Calibration of the telescope was accomplished by using delayed protons from ^{25}Si [11,12] produced in the ^{24}Mg (^{3}He, 2n) reaction at $E_{^3\mathrm{He}}$=40 MeV.

RESULTS

Figure 3(a) shows the delayed proton energy spectrum arising from the bombardment of 173 mC of 115 MeV $^{2}Si^{6+}$ on a reduced oxygen content ^{nat}Ca target. Delayed protons from ^{65}Ge [13] (which are emitted as a continuum from 1.1 to 2.3 MeV), ^{61}Ge [2], ^{25}Si [11,12], as well as those arising from ^{41}Ti [10] are clearly present. ^{25}Si is believed to be produced in direct reactions on the HAVAR He-jet chamber windows. ^{37}Ca is produced from reactions on the ^{16}O contaminants. The broad peak at $\sim$3.7 MeV contains 125 counts, compared to 119 counts in the main 100% ^{41}Ti peak at 4.74 MeV (all energies are reported in the laboratory frame unless otherwise stated). The expected contribution from ^{41}Ti in the lower energy peak would be only 56$\pm$7 counts. Fitting this peak as a double Gaussian yields one centroid at 3.54$\pm$0.06 MeV with 57 counts and a second centroid at 3.70 $\pm$0.06 MeV wit 68 counts. The area and energy of the higher energy Gaussian are generally consistent with the 3.69–3.75 MeV ^{41}Ti doublet. Therefore the lower-energy Gaussian may be preliminarily assigned to the β-delayed proton emission of ^{65}Se. To further illustrate the influence of ^{41}Ti upon this peak, Fig. 3(b) shows the β-delayed proton spectrum from ^{41}Ti produced in the bombardment of 40 MeV ^{3}He on a ^{nat}Ca target. (Some ^{37}Ca is also produced, which does not have proton groups in the region under discussion.) Figure 3(c) compares the contribution from ^{41}Ti to the total spectrum [from 3(a)] showing the "extra" counts in the 3.5 MeV region, which we assign to the decay of ^{65}Se.

Although these extra events are strongly suggestive, further evidence to support our assignment of this peak to the decay of ^{65}Se is the delayed proton spectrum arising from increasing the ^{28}Si beam bombardment energy on ^{nat}Ca. This spectrum is shown in Fig. 4 and is the result of 63 mC of integrated beam. Once again, peaks from ^{65}Ge and ^{61}Ge are observed. The yield of ^{61}Ge has increased relative to the previous spectrum, as would be expected from predicted cross sections using the statistical evaporation code ALICE [14]. In this spectrum, the primary ^{41}Ti peak is observed at 4.7 MeV with only 7 events, and a peak is observed at 3.56 MeV with 24 counts. If this peak had been due solely to the decay of ^{41}Ti, we would have observed only ~ 3 events. This peak has been assigned to the decay of ^{65}Se. The weighted average of the two peaks assigned to ^{65}Se at the two bombarding energies gives 3.55 ± 0.03 MeV for proton decay following beta decay to the IAS.

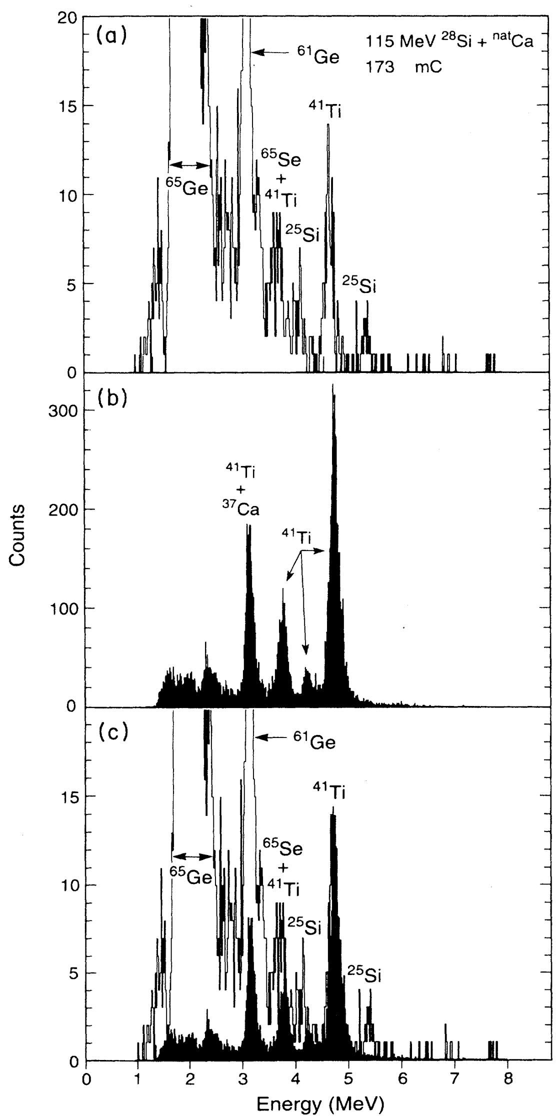

FIG. 3. (a) Delayed proton spectrum resulting from the compilation of several 115 MeV ^{28}Si+^{nat}Ca reaction data sets. (b) β-delayed proton spectrum from ^{41}Ti produced in the 40 MeV ^{3}He+^{nat}Ca reaction. (c) ^{41}Ti spectrum from (b) normalized to the 4.7 MeV peak in (a) and superimposed on spectrum (a).

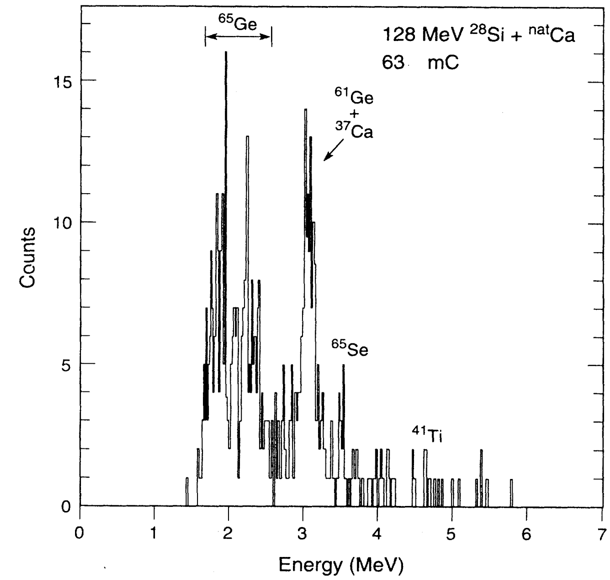

FIG. 4. Delayed proton spectrum from the ^{28}Si+^{nat}Ca reaction at 128 MeV.

The ALICE [14] cross-section prediction for ^{65}Se in this reaction is a relatively constant value of 540 nb for beam energies between 115 and 130 MeV. ALICE consistently overpredicts the cross section in this region by as much as a factor of 10, as was the case with ^{61}Ge [15]. However, ratios of ALICE cross-section predictions in similar reactions are generally good. The absolute efficiency for the He-jet system was measured for Ge ($\sim 5\%$ with a single capillary system and the large recoil energy), and was assumed to be the same for Se. Takahashi's gross theory of beta decay [16] predicts the half-life of ^{65}Se to be ~ 15

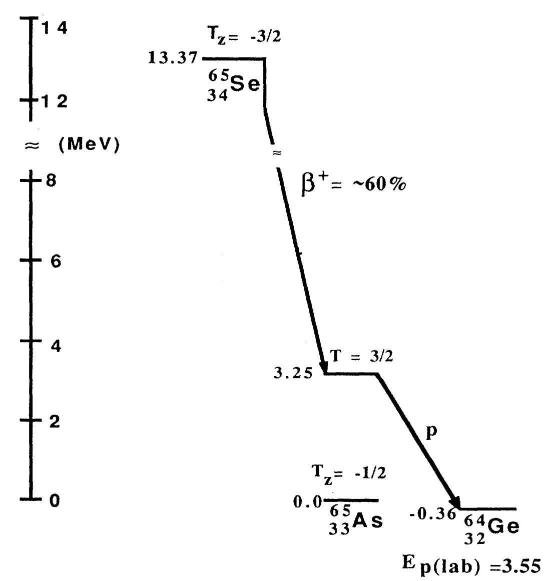

FIG. 5. Proposed decay scheme for ^{65}Se. Energy levels are given relative to the ground state of ^{64}Ge.

TABLE I. Comparison of the experimental mass vs selected mass models for ^{65}Se. The energy of the emitted proton is given in the laboratory frame. All energies are given in MeV.

	$\Delta(^{65}\text{Se})$	$\Delta(^{64}\text{Ge})$	E_p(lab)[a]
Möller-Nix	−32.51	−53.00	3.03
Möller *et al.*	−32.65	−53.09	2.98
Comay-Kelson-Zidon	−33.29	−54.25	3.50
Tachibana *et al.*	−33.50	−53.88	2.92
Jänecke-Masson	−33.73	−54.36	3.17
Masson-Jänecke	−33.53	−54.45	3.46
Experimental		−54.43±0.25	3.55±0.03

[a]A constant value for $\Delta E_{\text{Coul}} = 10.12$ MeV has been used.

ms. (However, all the known $T_Z = -\frac{3}{2}$, $4n+1$ nuclei in the fp shell have half-lives ranging from 40 to 75 msec, with the closet two members of interest, ^{57}Zn [1] and ^{61}Ge [2], having half-lives of 40±10 ms and 40±15 ms, respectively.) Using the predicted half-life of 15 msec, the experimental cross sections for the ^{40}Ca (^{28}Si, $3n$)^{65}Se reaction are 27±2 nb at 115 MeV and 32±2 nb at 128 MeV. The ratio of ALICE predictions to observed values is ~20. This discrepancy may be due to a large drop in the reaction cross section or that the half-life is longer than 15 ms. However, the possibility that the transport efficiency of the He jet is different for Ge and Se cannot be ruled out.

CONCLUSIONS

A proposed partial decay scheme for ^{65}Se is shown in Fig. 5. The beta branching ratio to the IAS has been estimated assuming a superallowed transition with a $\log ft = 3.3$. The laboratory energy of the observed delayed proton peak from ^{65}Se is 3.55±0.03 MeV. Combining this result with the Coulomb displacement formula [6] and the measured mass excess of ^{64}Ge (−54.43±0.25 MeV) [17] yields a mass excess for ^{65}Se of −33.41±0.26 MeV. This mass is 60 keV lower than that predicted by the Kelson-Garvey mass relation. Although this is actually quite good agreement, it is also consistent with the observation that as one moves farther away from the valley of stability, the Kelson-Garvey mass formula under predicts the stability of nuclei.

Table I shows a comparison of these data to selected theoretical models given in the 1988 mass predictions [3]. The value for the energy of the emitted proton is calculated utilizing a constant value of 10.12 MeV for ΔE_{Coul} which is used with the corresponding predicted values for the masses of ^{65}Se and ^{64}Ge. Agreement within 100 keV is seen with Comay-Kelson-Zidon (Garvey-Kelson mass relation using a different Coulomb energy formula) and Masson-Jänecke relations (inhomogeneous partial difference equation with higher order isospin contributions). The Jänecke-Masson prediction (Kelson-Garvey mass relation) uses Wapstra's mass evaluations [3] for the masses of the $T_Z = -\frac{1}{2}$ nuclei, and is 380 keV lower than the value reported in this work. The other three mass formulas, Tachibana *et al.* (empirical mass formula with a realistic proton-neutron interaction), Möller *et al.* (finite-range droplet model), and Möller and Nix (unified macroscopic-microscopic model), predict proton energies that are lower than experimental by >500 keV; these models are internally consistent with other predicted masses in this region. These results justify using a mass prediction method based upon recursive mass relations (such as Kelson and Garvey).

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