

^{69}Kr β -delayed proton emission: A Trojan horse for studying states in proton-unbound ^{69}Br A. M. Rogers,^{1,*} J. Giovinazzo,² C. J. Lister,¹ B. Blank,² G. Canchel,² J. A. Clark,¹ G. de France,³ S. Grévy,³ S. Gros,¹ E. A. McCutchan,¹ F. de Oliveira Santos,³ G. Savard,¹ D. Seweryniak,¹ I. Stefan,³ and J.-C. Thomas³¹Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA²Centre d'Etudes Nucléaires de Bordeaux Gradignan, Université Bordeaux I, UMR 5797 CNRS/IN2P3, Chemin du Solarium, BP 120, F-33175 Gradignan Cedex, France³Grand Accélérateur National d'Ions Lourds (GANIL), CEA/DSM-CNRS/IN2P3, Bvd Henri Becquerel, F-14076 Caen, France

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Particle decay of ^{69}Br and ^{65}As was observed through β -delayed proton emission of ^{69}Kr and ^{65}Se , respectively. Decay spectroscopy was performed through β - p correlations using a position-sensitive silicon-implantation detector surrounded by a γ -ray detector array. A β -decay half-life of 27(3) ms was measured for ^{69}Kr and 33(4) ms for ^{65}Se . The ^{69}Kr ground state decays by a superallowed transition to its unbound isobaric analog state in ^{69}Br which immediately decays by a 2.97(5)-MeV proton group to the first excited state in ^{68}Se at 854.2 keV. This chain of decays constrains both the mass and spin of the ^{69}Kr ground state. We observed no evidence of ground-state proton decay from ^{69}Br .

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Beyond determining the limits of existence of very neutron-deficient nuclei between nickel and tin, slow progress has been made in the spectroscopy of exotic nuclei with $N < Z$, that is, nuclei with negative T_z , in this region. This is unfortunate, as these nuclei and their decays are critical in understanding the rapid-proton capture (rp) process, providing key information for testing the CVC hypothesis, exploring the breakdown of mirror symmetry due to Coulomb effects and poor binding, and yielding stringent tests of contemporary nuclear-structure models.

Recently, considerable progress has been made concerning the astrophysical aspect: For both the ^{64}Ge and ^{68}Se rp -process “waiting points,” measurements of their proton-unbound precursors, ^{65}As and ^{69}Br , have been reported [1,2]. In the case of ^{64}Ge the waiting point is likely bypassed, while in ^{68}Se it likely is not. Interest, however, in the spectroscopic and structural properties of these nuclei remains. We report on the decay of ^{65}Se and ^{69}Kr into their proton-unbound daughters ^{65}As and ^{69}Br . These parents are relatively long-lived, ~ 30 ms, allowing them to be cleanly separated, transported, and implanted in a decay station where the nuclei β decay, populating states of interest in their short-lived daughter nuclei. The original goal was to observe the ^{69}Kr β -decay strength that bypassed the isobaric analog state (IAS) and fed the ^{69}Br ground state, where the observation of a low-energy proton group would quantify the mass differences. In fact, this branch was found to be very small ($< 5\%$), and we were not successful in our search. The decay to the analog states, however, has proven to be rich in information and is the subject of this Rapid Communication.

Both ^{69}Br and ^{65}As have properties that make direct and detailed studies of them a challenge. The short lifetime and location beyond the proton drip line complicates the direct study of ^{69}Br . Traditional implantation-decay studies as well as direct mass measurements are not possible as the lifetime is too short [3]. Measurements must then be carried out

through indirect techniques or through direct observations immediately following ^{69}Br production using in-flight decay [2]. Initial searches attempted to produce ^{69}Br through fusion-evaporation reactions [4] and ^{78}Kr projectile fragmentation, leading to a lifetime upper limit of 24 ns [3,5]. The first direct measurement of ^{69}Br ground-state proton decay, reconstructed from the breakup into $p + ^{68}\text{Se}$, found ^{69}Br to be unbound by 785^{+34}_{-40} keV [2].

Similar complications exist for ^{65}As . Compared to ^{69}Br , ^{65}As is considerably longer lived ($t_{1/2} = 190^{+110}_{-70}$ ms) [6]. It still, however, lies near the proton drip line and is difficult to produce in sufficient quantities required for measurement in a Penning trap. Recently, the ^{65}As ground-state mass was determined by a storage-ring lifetime measurement [1]. The inferred decay Q_p value is so low, 90(80) keV, that sequential $2p$ capture through ^{65}As significantly bypasses the ^{64}Ge waiting-point nucleus in the explosive rp -process environment. The only spectroscopic information comes from β -decay data where ^{65}Se was reported to decay to the IAS in its ^{65}As daughter followed by an observed 3.55(3) MeV proton-decay group to the ^{64}Ge ground state [7].

Because of the additional binding due to pairing for even- Z nuclei, the proton drip line extends out farther and, correspondingly, lifetimes are longer for proton-rich Kr isotopes compared to Br isotopes. By producing the relatively long-lived particle-bound ^{69}Kr ($t_{1/2} \sim 30$ ms) and performing decay spectroscopy, the ground and excited states in ^{69}Br , its β -decay daughter, can be populated and studied. Proton-rich Kr isotopes have been previously produced in Refs. [5,8]. Accessing the ^{69}Br ground state, however, is hindered since most of the β -decay flux goes to the two-quasiparticle isobaric analog state [9].

The experiment was performed at Grand Accélérateur National d'Ions Lourds (GANIL). Projectile fragmentation of a 70-MeV/nucleon ^{78}Kr primary beam on a 200-mg/cm² natNi target was used to produce proton-rich isotopes, including ^{69}Kr . Fragmentation products were selected by means of the LISE3 separator [10] configured with a 50- μm beryllium

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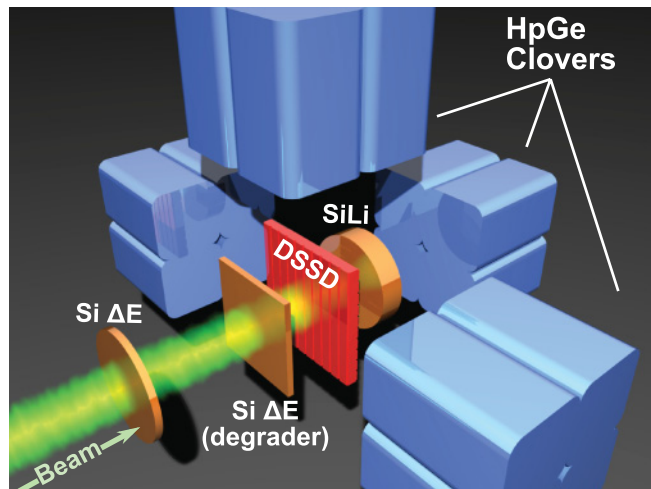


FIG. 1. (Color online) Schematic of the implant-decay station. Proton-rich nuclei implanted into the DSSD decay and are correlated with β and p decay products as well as coincident γ rays measured in the surrounding HpGe array. Energy loss and timing signals were generated from the first silicon ΔE detector with additional time-of-flight information measured using two upstream microchannel plate detectors (not shown).

degrader at the intermediate focal plane and transported to an implantation station at the end of the LISE3 beamline. Time-of-flight (TOF) and energy-loss (ΔE) measurements allowed event-by-event fragment identification. Decay spectroscopy was performed on fragments implanted into a double-sided strip detector (DSSD), correlated with β -delayed protons.

The detection setup, shown in Fig. 1, consisted of a set of four silicon detectors: a 300- μm energy-loss (ΔE) detector, a 300- μm degrader, a 300- μm 3-mm pitch DSSD with 16×16 strips used for implantation, and a 5-mm lithium-drifted silicon detector [Si(Li)] used, in addition to detecting β particles, as a veto for heavy ions not stopped by the DSSD. Given our threshold settings, the experiment is sensitive to decays above 400 keV. Redundantly measured timing signals from the ΔE detector relative to two microchannel plate (MCP) detectors at the LISE focal plane and the cyclotron-radiofrequency (rf) signal provided time-of-flight (TOF) information. Surrounding the implantation array were four high-purity germanium (HpGe) clovers, three EXOGAM [11] and one mini-clover, to detect coincident γ rays.

Correlating in space and time heavy-ion implant events with heavy-ion decay events allowed us to perform decay spectroscopy using a technique similar to that described in Ref. [12]. In this method a direct correlation between the implanted isotope and its decay is not established. An implant is, instead, correlated with all decays occurring within a given time window, chosen in this case to be 2000 ms. Falsely correlated decays occur randomly as a function of time, producing a constant background in decay-time spectra. True correlations form a signal on top of this random background. By requiring implants and decays to have occurred in the same pixel of the DSSD, false correlations can be reduced. Charged-particle energy spectra also contain false correlation

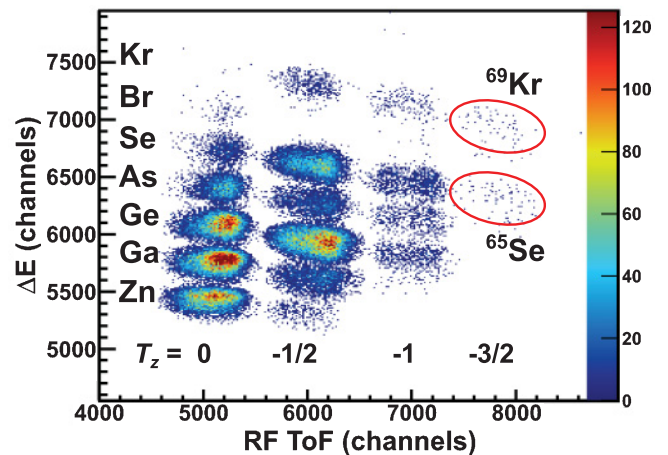


FIG. 2. (Color online) Partial particle-identification spectrum for implanted heavy ions in the DSSD. The energy-loss signal is measured by the silicon ΔE detector while the RF, gated on the additional timing signals, measures the heavy-ion TOF. Particles are separated based on their charge, Z , and isospin, T_z .

events and are removed by subtracting uncorrelated events in the latter half of the time window [12].

Heavy ions implanted into the DSSD, corresponding to triggers in the ΔE detector, were identified via ΔE -TOF where the redundant TOF information reduced the backgrounds in the particle-identification spectrum. DSSD triggered events, without a ΔE signal, correspond to decay events. A set of parallel electronics utilizing low and high gain settings digitized the DSSD high-energy implant events and lower-energy decay events. A proton energy calibration was performed using a triple- α source containing lines from ^{239}Pu , ^{241}Am , and ^{244}Cm .

Figure 2 shows a partial particle-identification spectrum where the LISE3 facility settings were optimized for ^{69}Kr implants. The various implanted particle groups are cleanly separated and identified according to their charge, Z , and their isospin, T_z . In total, we observed 245 ^{65}Se and 212 ^{69}Kr implantations. In the same ^{69}Kr optimized setting ^{65}Se , a known β -delayed proton emitter, was also implanted in the DSSD. The β -decay half-life of ^{65}Se has not previously been published in a major journal, though Wenxue *et al.* [13], using the reaction $^{40}\text{Ca}(^{28}\text{Si},3n)$, reported a value of $t_{1/2} = 9.6^{+5.3}_{-4.1}$ ms for a proton group at 3.70(8) MeV. A study of ^{65}Se decay protons from Batchelder *et al.* [7], also produced through the $^{40}\text{Ca}(^{28}\text{Si},3n)$ reaction, found evidence of a proton-decay group at an energy of 3.55(3) MeV. Our measured ^{65}Se decay-time spectrum is shown in Fig. 3. The data is fit with an exponential-decay curve combined with a constant background function yielding a measured half-life of 33(4) ms. Figure 4 shows the ^{65}Se charged-particle spectrum where uncorrelated events from the latter half of the time-correlation window have been subtracted. A peak at an energy of 3.51(2) MeV is observed and is assumed to correspond to proton emission from the ^{65}As IAS. In all cases proton groups were fitted with a Gaussian function combined with a high-energy tail to account for β summing. The proton group is not in coincidence with γ rays and therefore presumably directly populates the ^{65}As ground state. Both the half-life

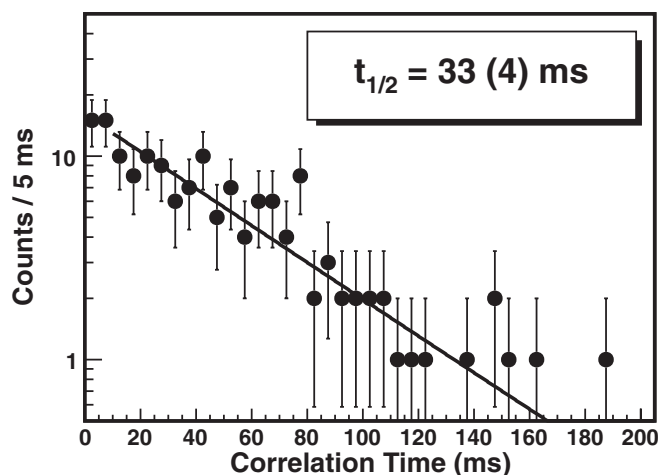


FIG. 3. β^+ -decay correlation-time spectrum for ^{65}Se .

and decay group are in disagreement with the earlier work of Ref. [13]. The proton group, however, is in agreement with the previous observation of the analog state decay in Ref. [7] and verifies the functioning of our experiment. Although weaker, two additional proton-decay peaks are seen at energies of 2.62(3) and 3.77(3) MeV. The energy of the decay peak at 2.62(3) MeV is consistent with the 901.7-keV $2^+ \rightarrow 0^+$ transition in ^{64}Ge [14]; however, we did not observe coincident γ rays. In this case, given the γ -ray detection efficiency and the number of counts in the proton peak, we would expect at a maximum to observe only one coincident γ ray.

Using the ^{65}As mass measurement of Tu *et al.* [1], we can build an absolute-energy decay scheme for these $A = 65$ nuclei, as illustrated in Fig. 5. A Coulomb displacement energy (CDE), however, is required between the $T = 3/2$ state in ^{65}As and its analog, the ^{65}Se ground state, to complete the energy scale. CDE values for many nuclei have been tabulated and parameterized by Antony *et al.* [15]. The recent measurement of the ^{65}As ground state allows us to test

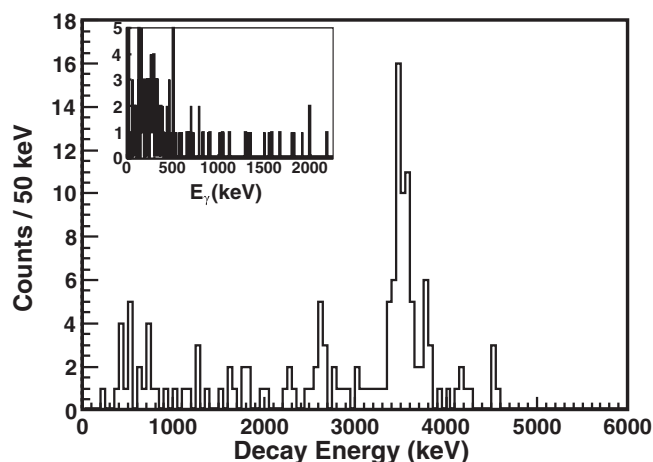


FIG. 4. Charged-particle decay-energy spectrum for time-correlated ^{65}Se implant events. The γ -ray spectrum (upper left), coincident with charged particles, does not show clear evidence for any transition in ^{64}Ge .

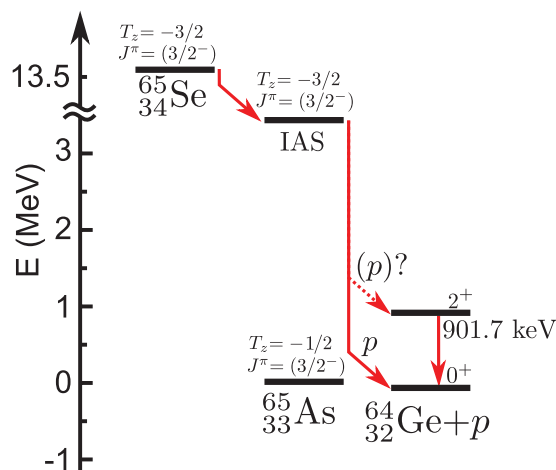


FIG. 5. (Color online) Proposed partial decay scheme for ^{65}Se . The proton decay at 2.62(3) MeV was not in coincidence with any γ rays but is consistent in energy with the 901.7-keV $2^+ \rightarrow 0^+$ transition in ^{64}Ge and is tentatively represented by a dashed line.

the Antony extrapolation. For the $T = 1/2$ members of this multiplet we have a direct measurement from the ^{65}As – ^{65}Ge mass difference. Using the masses from Refs. [1,16] the CDE is 10326(85) keV for the $T = 1/2$ members. This agrees with the Antony extrapolation of 10255(50) keV, with a difference of 71(85) keV. As we discuss below, however, this is generally not the case. New data on heavier nuclei above ^{56}Ni indicate a systematic deviation between data and the fits. Consequently, to estimate the CDE between $T = 3/2$ members, we use the experimental data for the $T = 1/2$ CDE in this mass chain shifted by the difference in CDEs between the Antony extrapolation of the $T = 1/2$ ^{65}As – ^{65}Ge and $T = 3/2$ ^{65}Se – ^{65}As members. The adjusted $T = 3/2$ CDE value between ^{65}As and ^{65}Se is 10941(111) keV compared to 10870(50) keV as given by the Antony extrapolation. With this prescription we reach a mass excess for ^{65}Se of $-33358(141)$ keV. The largest contribution to the uncertainty is from the ^{65}As mass, which is critical in our estimate of the CDE. This mass-excess value for ^{65}Se is more bound than the AME 2003 estimation by 438 keV [17] and is a more direct, as well as precise, determination compared to the AME despite the large uncertainty in the CDE.

With an estimated mass excess we can analyze the ^{65}Se β -decay properties. The ^{65}Se – ^{65}As decay Q value is 13579(165) keV and the ^{65}As analog state has an excitation energy of 3420(87) keV. The partial proton-branching ratio for the 3.51(2) and 2.62(3) MeV ^{65}Se proton groups was found to be 62(13)%. Proton-detection efficiencies were simulated, with the results shown in Fig. 6, using GEANT4 [18] and were used to correct the calculated partial proton-branching ratios. We estimate the β -decay feeding of the IAS to be 52(18)%, yielding a $\log(ft)$ value of 3.44(17), consistent with a $\Delta T = 0$ superallowed decay expected between pure analog states. As we will discuss further in contrast to the case of ^{69}Kr decay, the spin of the ^{65}As analog state and the ^{65}Se parent is low, most likely $J^{\pi} = 3/2^-$, which inhibits decay to excited states. This implies that ^{65}Se ($T = 3/2$, $T_z = -3/2$) has the same spin and parity as its mirror partner ^{65}Ga ($T = 3/2$, $T_z = +3/2$,

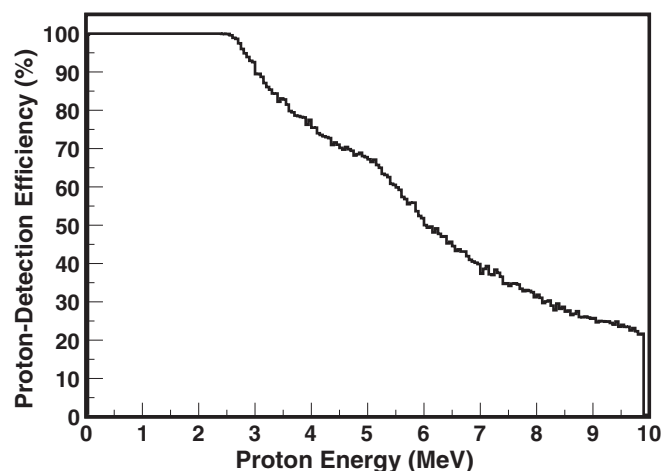


FIG. 6. Proton-detection efficiency in the DSSD as a function of proton-decay energy. The silicon detectors, beam properties, implantation depth, and energy losses were simulated using the GEANT4 toolkit.

$J^\pi = 3/2^-$), suggesting that mirror symmetry is not distorted in this system. It is interesting that the spectrum of β -delayed protons extends to low energies, as can be seen in Fig. 4. Careful inspection, however, of the events below 1 MeV before the uncorrelated events are subtracted showed that they are not correlated with decays from a 33-ms parent.

A previous study of analogous ^{69}Kr β -delayed protons from Ref. [9], produced through the $^{40}\text{Ca}(^{32}\text{S},3n)$ reaction, found evidence for a proton-decay group at an energy of 4.07(5) MeV and a half-life of 32(10) ms. Figure 7 shows the ^{69}Kr decay-time spectrum which yields a measured half-life of 27(3) ms, in agreement with the previously measured value. The ^{69}Kr background-subtracted charged-particle spectrum is shown in Fig. 8. We observe a peak at an energy of 2.97(5) MeV which is correlated with 854.2-keV γ rays as shown in the spectrum in the upper right of the figure. The 854.2-keV γ ray corresponds to the $2^+ \rightarrow 0^+$ transition in ^{68}Se [19,20], establishing that the decay protons are from ^{69}Br . Our observed proton-decay peak, however, disagrees

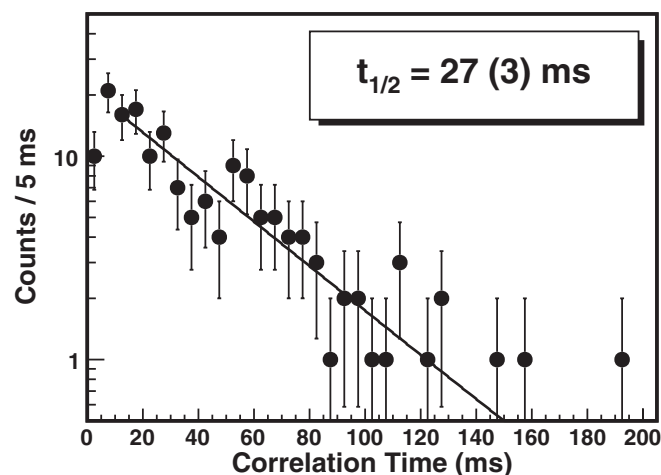


FIG. 7. β^+ -decay correlation-time spectrum for ^{69}Kr .

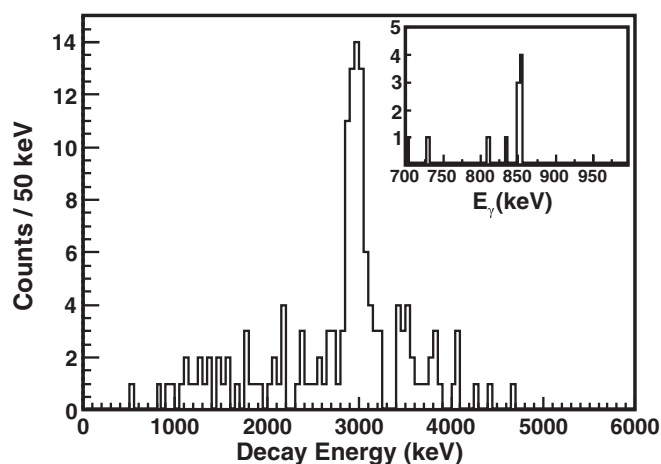


FIG. 8. Charged particle decay-energy spectrum for time correlated ^{69}Kr implant events. The γ -ray spectrum (upper right), gated on the 2.97(5)-keV proton-decay peak, shows coincident 854.2-keV γ rays corresponding to decay from the first excited state in ^{68}Se .

by ~ 1 MeV from the result claimed in Ref. [9]. Moreover, we do not observe any statistically significant proton group at an energy of 4.07(5) MeV. For energies below 1 MeV, we find no evidence for proton decay from the ^{69}Br ground state, suggesting that a significant fraction of the β -decay flux goes to the IAS while the rest is fragmented among other states. As with ^{65}Se we can again build an absolute-energy decay scheme for these $A = 69$ nuclei, as shown in Fig. 9.

The ^{69}Kr decay differs strikingly from the ^{65}Se decay discussed above, despite having similar relative energies for all the states involved. It can be explained if the analog state in ^{69}Br and the ^{69}Kr parent has a higher spin than the $A = 65$ case, most likely $J^\pi = 5/2^-$ which is the same as the ^{69}As $T_z = 3/2$ mirror partner. In this case, the decay to the ^{68}Se ground state, with $J^\pi = 0^+$, is inhibited by an angular momentum barrier as the protons must have $\ell \geq 3$. There is a suggestion of a small IAS-to-ground-state proton branch in the spectrum at 3.81(2) MeV, but this is statistically marginal and is $< 10\%$ of

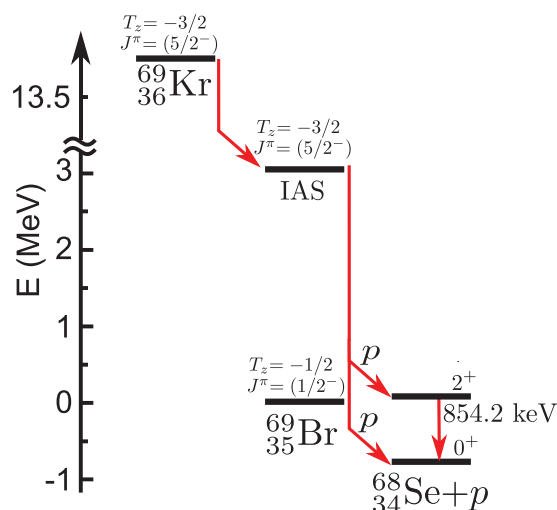


FIG. 9. (Color online) Proposed partial decay scheme for ^{69}Kr .

the decay. Altogether, these branches correspond to 57(14)% of the ^{69}Kr β decays.

Using the same method for estimating the CDE as for ^{65}Se , we can analyze the ^{69}Kr β -decay properties. Masses from Refs. [2,21] result in a CDE of 11102(40) keV for the $T = 1/2$ members. In this case, the CDE disagrees with the Anthony extrapolation of 10698(50) keV by 404(64) keV. An adjusted $T = 3/2$ CDE value between ^{69}Br and ^{69}Kr of 11731(81) keV yields a ^{69}Kr mass excess of $-32128(96)$ keV. Compared to AME 2003 [17], ^{69}Kr is less bound by 312 keV, consistent with the trend in mass excess of both $^{70,71}\text{Kr}$ isotopes. The ^{69}Kr - ^{69}Br decay Q value is 13987(104) keV where the ^{69}Br analog state has an excitation energy of 3039(64) keV which, with an estimated 50(19)% β -decay feeding to the IAS, implies a $\log(ft)$ value of 3.53(18) consistent again with a superallowed decay.

Total proton-branching ratios were also calculated for both systems by integrating the decay-time spectrum gated on events in the charged-particle spectra above 900 keV. We find

total proton-emission branching ratios of $88_{-13}^{+12}\%$ and $99_{-11}^{+1}\%$ for ^{65}Se and ^{69}Kr , respectively. Given our statistics, the ^{69}Br ground-state proton-branching ratio is found to be $<5\%$.

We have reported on proton emission from the astrophysically interesting nucleus ^{69}Br , populated through ^{69}Kr β -delayed proton decay, as well as ^{65}Se . Proton-decay groups corresponding to the population of the IASs were observed at 3.51(2) and 2.97(5) MeV for ^{65}Se and ^{69}Kr , respectively. The ^{69}Kr proton group was found to be in disagreement by ~ 1 MeV from that reported by Xu *et al.* [9]. Unfortunately, we were unable to observe ground-state proton decay from ^{69}Br due to the small β -decay branching. Ground-state decays should be observable given an increase in statistics.

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