# ^{69}Kr β-delayed proton emission: A Trojan horse for studying states in proton-unbound ^{69}Br

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# $^{69}$Kr $\beta$-delayed proton emission: A Trojan horse for studying states in proton-unbound $^{69}$Br

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Particle decay of $^{69}$Br and $^{65}$As was observed through $\beta$-delayed proton emission of $^{69}$Kr and $^{65}$Se respectively. Decay spectroscopy was performed through $\beta$-$p$ correlations using a position-sensitive silicon-implantation detector surrounded by a $\gamma$-ray detector array. A $\beta$-decay half-life of 27(3) ms was measured for $^{69}$Kr and 33(4) ms for $^{65}$Se. The $^{69}$Kr ground sate 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 did not observe any evidence of ground-state proton decay from $^{69}$Br.

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, $\sim 30$ ms, allowing them to be cleanly separated, transported, and implanted in a decay station where the nuclei $\beta$ decay, populating states of interest in their short-lived daughter nuclei. The original goal was to observe the $^{69}$Kr $\beta$-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 paper.

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 $p + {}^{68}$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 $\beta$-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 $\beta$-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 $\beta$-decay flux goes to the two-quasiparticle isobaric analog state [9].

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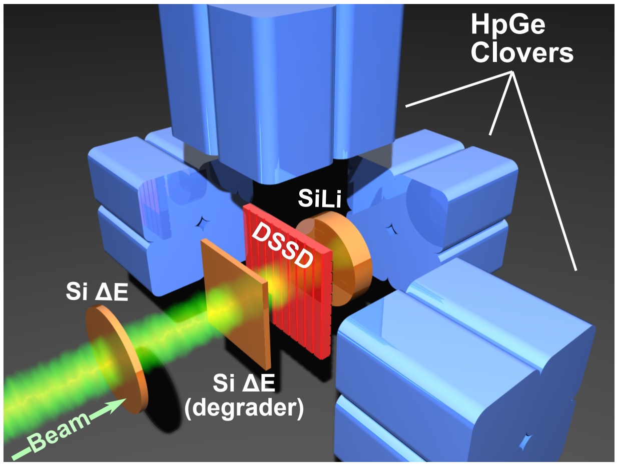


FIG. 1. (color online). Schematic of the implant-decay station. Proton-rich nuclei implanted into the DSSD decay and are correlated with $\beta$ and $p$ decay products as well as coincident $\gamma$ rays measured in the surrounding HpGe array. Energy loss and timing signals were generated from the first silicon $\Delta E$ detector with additional time-of-flight information measured using two upstream micro-channel plate detectors (not shown).

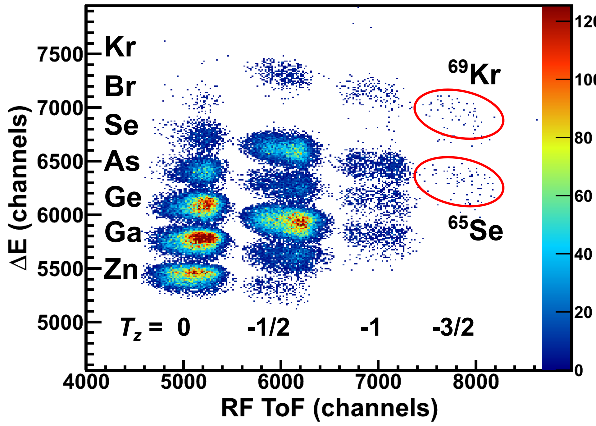


FIG. 2. (color online). Partial particle-identification spectrum for implanted heavy-ions in the DSSD. The energy-loss signal is measured by the silicon $\Delta E$ detector while the RF, gated on the additional timing signals, measures the heavy-ion ToF. Particles are separated based on their charge,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

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/cm$^2$ $^{\mathrm{nat}}$Ni 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 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 ($\Delta E$) measurements allowed event-by-event fragment identification. Decay spectroscopy was performed on fragments implanted into a double-sided strip detector (DSSD), correlated with $\beta$-delayed protons.

The detection setup, shown in Fig. 1, consisted of a set of four silicon detectors: a 300 µm energy-loss ($\Delta E$) 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 $\beta$ 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 $\Delta E$ detector relative to two micro-channel 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 $\gamma$ 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 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 $\Delta E$ detector, were identified via $\Delta E$-ToF where the redundant ToF information reduced the backgrounds in the particle-identification spectrum. DSSD triggered events, without a $\Delta E$ 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-$\alpha$ 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 $\beta$-delayed proton emitter, was also implanted in the DSSD. The $\beta$-decay half-life of $^{65}$Se has not previously been published in a major journal, though Wenxue *et al.* [13], using the reaction $^{40}$Ca($^{28}$Si,3$n$), 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 $^{40}$Ca($^{28}$Si,3$n$) reaction, found evidence of a proton-decay group at an energy of

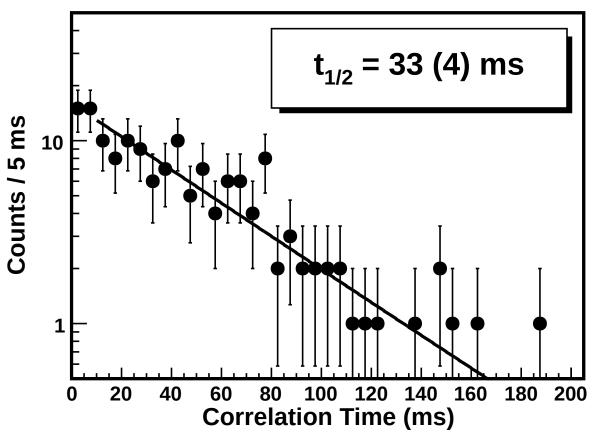


FIG. 3. $\beta^+$-decay correlation-time spectrum for $^{65}$Se.

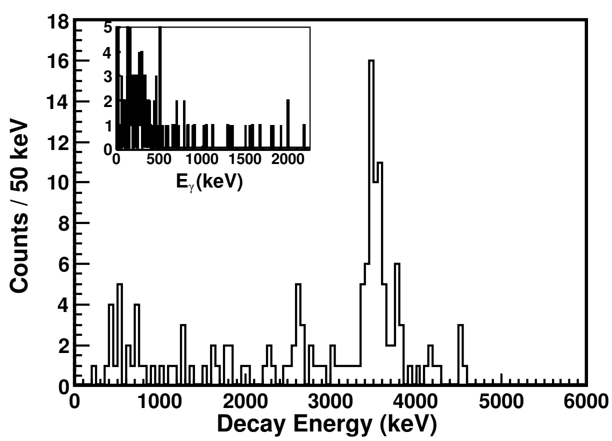


FIG. 4. Charged-particle decay-energy spectrum for time-correlated $^{65}$Se implant events. The $\gamma$-ray spectrum (upper left), coincident with charged particles, does not show clear evidence for any transition in $^{64}$Ge.

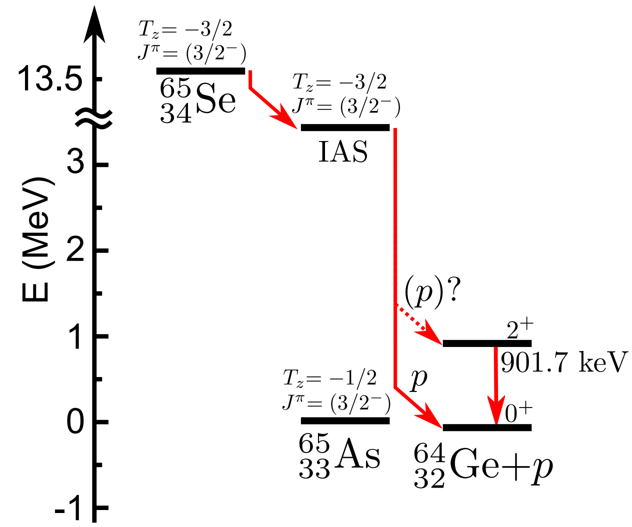


FIG. 5. (color online). Proposed partial decay scheme for $^{65}$Se. The proton decay at 2.62(3) MeV was not in coincidence with any $\gamma$ rays but is consistent in energy with the 901.7 keV $2^+ \to 0^+$ transition in $^{64}$Ge and is tentatively represented by a dashed line.

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 $\beta$ summing. The proton group is not in coincidence with $\gamma$ rays and therefore presumably directly populates the $^{65}$As ground state. Both the half-life 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) MeV and 3.77(3) MeV. The energy of the decay peak at 2.62(3) MeV is consistent with the 901.7 keV $2^+ \to 0^+$ transition in $^{64}$Ge [14], however, we did not observe coincident $\gamma$ rays. In this case, given the $\gamma$-ray detection efficiency and the number of counts in the proton peak, we would expect at a maximum to observe only one coincident $\gamma$-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 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] and [16] the CDE is 10 326(85) keV for the $T = 1/2$ members. This agrees with the Anthony extrapolation of 10 255(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 10 941(111) keV compared to 10 870(50) keV as given by the Antony extrapolation. With this prescription we reach a mass excess for $^{65}$Se of $-33\,358(141)$ keV. The largest contribution to the uncertainty is from the $^{65}$As mass, which is critical in our estimate of the CDE. This

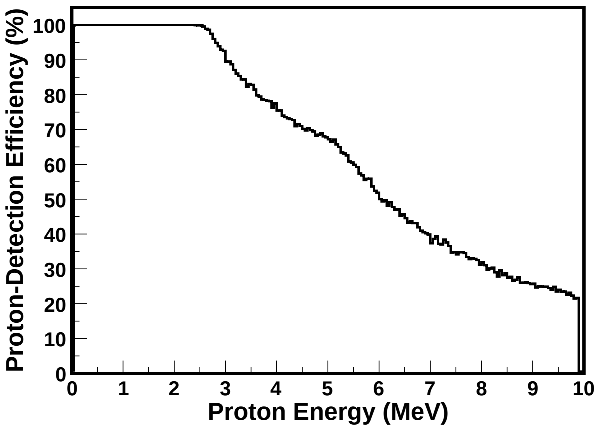


FIG. 6. Proton-detection efficiency in the DSSD as a function of proton-decay energy. The silicon detectors, beam properties, implantation depth, and energy losses were simulated using the GEANT4 toolkit.

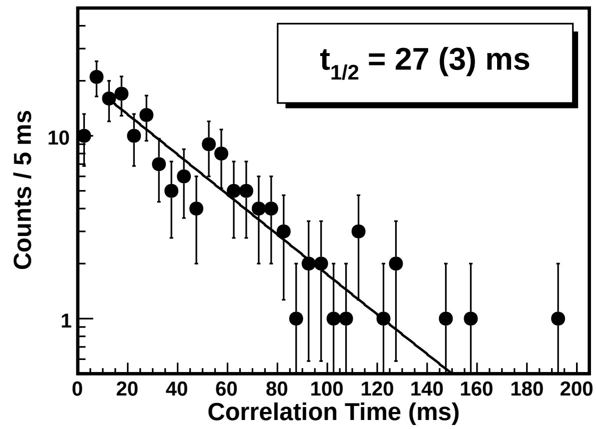


FIG. 7. $\beta^+$-decay correlation-time spectrum for $^{69}$Kr.

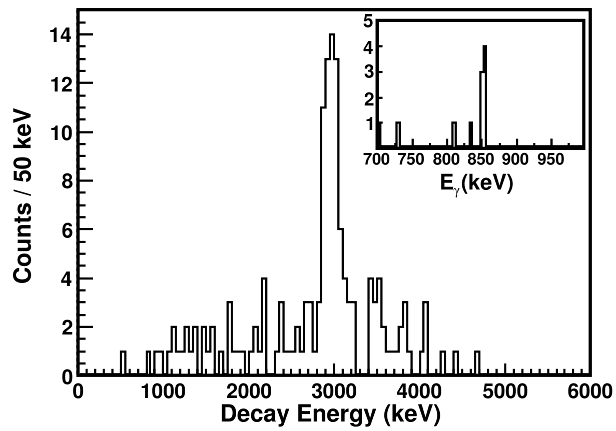


FIG. 8. Charged particle decay-energy spectrum for time correlated $^{69}$Kr implant events. The $\gamma$-ray spectrum (upper right), gated on the 2.97(5) keV proton-decay peak, shows coincident 854.2 keV $\gamma$ rays corresponding to decay from the first excited state in $^{68}$Se.

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 $\beta$-decay properties. The $^{65}$Se–$^{65}$As decay $Q$ value is 13 579(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) MeV 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 used to correct the calculated partial proton-branching ratios. We estimate the $\beta$-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 ($T = 3/2$, $T_z = +3/2$, $J^\pi = 3/2^-$), suggesting that mirror symmetry is not distorted in this system. It is interesting that the spectrum of $\beta$-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 $\beta$-delayed protons from Ref. [9], produced through the $^{40}$Ca($^{32}$S,3$n$) 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 $\gamma$ rays as shown in the spectrum in the upper right of the figure. The 854.2 keV $\gamma$ 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 by $\sim 1$ 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 $\beta$-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 is strikingly different 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 $J^\pi = 5/2^-$

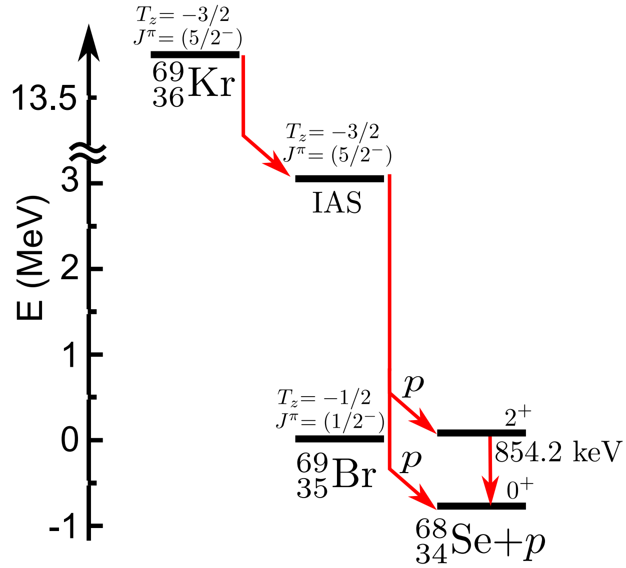


FIG. 9. (color online). Proposed partial decay scheme for $^{69}$Kr.

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

Using the same method for estimating the CDE as for $^{65}$Se, we can analyze the $^{69}$Kr $\beta$-decay properties. Masses from Refs. [21] and [2] result in a CDE of 11 102(40) keV for the $T = 1/2$ members. In this case, the CDE disagrees with the Anthony extrapolation of 10 698(50) keV by 404(64) keV. An adjusted $T = 3/2$ CDE value between $^{69}$Br and $^{69}$Kr of 11 731(81) keV yields a $^{69}$Kr mass excess of $-32\,128(96)$ keV. Compared to AME 2003 [17], $^{69}$Kr is less bound by 312 keV, consistent with the trend in mass excess of both $^{70,71}$Kr isotopes. The $^{69}$Kr–$^{69}$Br decay $Q$ value is 13 987(104) keV where the $^{69}$Br analog state has an excitation energy of 3039(64) keV which, with an estimated 50(19) % $\beta$-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 $88^{+12}_{-13}\%$ and $99^{+1}_{-11}\%$ 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 $\beta$-delayed proton decay, as well as $^{65}$Se. Proton-decay groups corresponding to the population of the IASs were observed at 3.51(2) MeV and 2.97(5) MeV for $^{65}$Se and $^{69}$Kr, respectively. The $^{69}$Kr proton group was found to be in disagreement by $\sim 1$ 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 $\beta$-decay branching. Ground-state decays should be observable given an increase in statistics.

## ACKNOWLEDGMENTS

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