Ground-State Proton Decay of ^{69}Br and Implications for the ^{68}Se Astrophysical Rapid Proton-Capture Process Waiting Point

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We report on the first direct measurement of the proton separation energy for the proton-unbound nucleus ^{69}Br. Bypassing the ^{68}Se waiting point in the rp process is directly related to the $2p$-capture rate through ^{69}Br, which depends exponentially on the proton separation energy. We find a proton separation energy for ^{69}Br of $S_p(^{69}\mathrm{Br}) = -785^{+34}_{-40}$ keV; this is less bound compared to previous predictions which have relied on uncertain theoretical calculations. The influence of the extracted proton separation energy on the rp process occurring in type I x-ray bursts is examined within the context of a one-zone burst model.

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Masses and decay properties of many nuclei along the proton drip line play a key role in the rapid proton- (rp) capture process (see Wallace and Woosley [1]). The rp process consists of sequences of fast proton-capture reactions on proton-rich nuclei near the proton drip line and their subsequent β^+ decays. When the reaction flow reaches weakly bound nuclei at the proton drip line, further proton captures through proton-unbound nuclei are inhibited, and if the β-decay half-life of the bound nucleus is sufficiently long, this nucleus becomes a ''waiting point'' where most of the processed material accumulates.

Type I x-ray bursts provide one important scenario where the rp process may occur [2,3]. There, hydrogen-rich material accretes onto the surface of a neutron star from its stellar companion in a binary system. The accreted material accumulates until highly degenerate conditions are reached. Helium and hydrogen burning ignites a thermonuclear explosion, characterized by a rapid increase (rise time $\sim$1 s) and subsequent decay ($\sim$10–100 s) in x-ray luminosity with a typical energy release of $\sim 10^{36}$ ergs/s [4]. Understanding the energy generation, light curves, and nucleosynthesis in these events depends on measurements of proton-rich nuclei.

One of the largest uncertainties in the astrophysical rp process concerns the ^{68}Se waiting point. The relatively long 35.5 s half-life of ^{68}Se, compared to the time scale of a typical x-ray burst ($\sim$ 10–100 s), and its location on the proton drip line severely limit further progression to heavier masses. It has been shown, however, that $2p$-capture reactions through unbound nuclei such as ^{69}Br can bypass key waiting points if these nuclei are only slightly unbound [2]. Figure 1 illustrates a possible rp-process reaction path which bypasses the ^{68}Se waiting point. Determining whether this waiting point can be bypassed requires precise mass measurements of the relevant unbound nuclei since the $2p$-capture reaction rate depends exponentially on the proton separation energy S_p.

Interest in the phenomenon of proton radioactivity [5–11] and the impact of ^{69}Br on the rp process prompted many studies of its stability. The earliest searches attempted to observe protons emitted from ^{69}Br fusion residues [12,13], but did not observe any proton groups in the expected energy range, corresponding to an upper limit on the half-life of 100 μs. Direct identification of ^{69}Br from the fragmentation of ^{78}Kr was reported in Ref. [14]. This could not be confirmed by improved experiments that followed [15,16], which reduced the upper limit of the ^{69}Br half-life to 24 ns. This limit corresponds to a proton separation energy of $S_p < -500$ keV, represented by the diamond in Fig. 2.

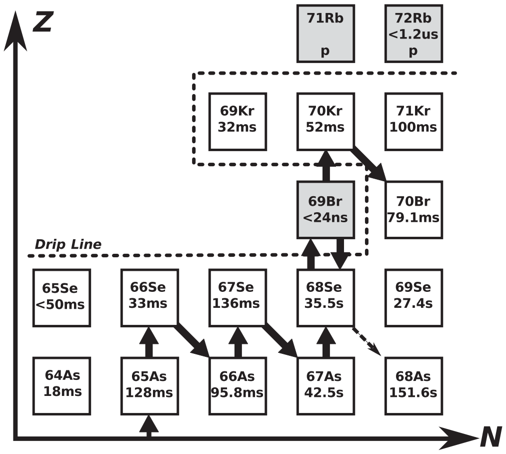

FIG. 1. Illustration of $2p$-capture reactions through ^{69}Br bypassing the ^{68}Se waiting point. The slow β decay of ^{68}Se restricts the rp-process reaction flow in type I x-ray bursts.

More recently, indirect predictions of the proton separation energy, represented by the open circles in Fig. 2, were obtained by combining mass measurements of ^{68,69}Se with estimates for the Coulomb displacement energy (CDE) [17–24] that accounts for the mass difference of ^{69}Br and ^{69}Se. For example, precise mass measurements of ^{69}Se [23] and of ^{68}Se [24] using the Low Energy Beam and Ion Trap (LEBIT) high-precision Penning trap facility [25] have reduced the uncertainties in the masses to negligible values of 1.5 keV and 5 keV, respectively. Combining them with a calculation of the CDE [26] yielded an estimated value of $S_p = -636(105)$ keV where the uncertainty is dominated by the estimated contributions from the theoretical CDE predictions.

In this Letter, we report on the first direct measurement of ground-state one-proton decay from ^{69}Br. This result accurately constrains the $2p$-capture branch of the astrophysical rp-process ^{68}Se waiting point to be $<0.25\%$ (within 1σ), which is sufficient to demonstrate that it can be neglected in present type I x-ray burst models.

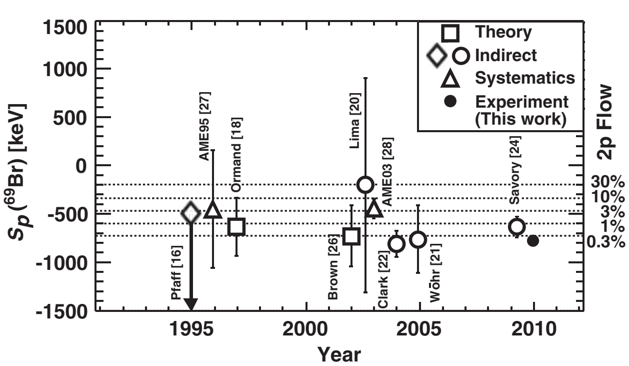

FIG. 2. Comparison of the result from this work, which is the only direct measurement of S_p, showing a reduction in uncertainty to previous predictions. (The size of the data point for this work represents a symmetric uncertainty of ± 40 keV.) Atomic mass evaluation (AME) values are taken from Refs. [27,28].

The experiment was performed at the Coupled Cyclotron Facility of the National Superconducting Cyclotron Laboratory (NSCL) using a secondary beam composed primarily of ^{69}As (23.9%), ^{70}Se (66.7%), and ^{71}Br (9.4%) produced by fragmenting a 140 MeV/nucleon ^{78}Kr primary beam on a 775 mg/cm^2 ^{9}Be target. Fragmentation products were selected using the A1900 fragment separator [29] and directed onto a 5.4 mg/cm^2 polypropylene $(C_3H_6)_n$ reaction target in the S800 spectrograph target chamber [30].

Protons emitted in reactions with the target were detected by 16 ΔE-E telescopes of the High Resolution Array (HiRA) [31], while the heavy projectilelike residues were detected in the focal plane of the S800 spectrograph [32]. Each HiRA telescope was configured with a 1.5 mm thick double-sided silicon 32×32 strip detector backed by four 3.9 cm CsI(Tl) crystals. The array was positioned 50 cm from the target with a gap between the inner telescopes of $\sim$6 cm (3.4°) for the transport of the ^{68}Se to the S800 focal plane.

Projectile-like residues produced in the reaction were identified by energy loss and time of flight (ΔE vs TOF) as shown in Fig. 3. The ΔE signal was taken from the segmented ionization chamber in the S800 focal plane. TOF of the heavy residues was calculated from the known length of the beam-transport system and the measured timing signals from scintillators at the A1900 focal plane and at the object plane of the S800 analysis beam line. The incoming secondary beam was identified by a similar technique. While the inclusive nature of the measurement did not allow a unique identification of the ^{69}Br production mechanism, the kinematics of the residue suggest that neutron emission following proton pickup reactions on ^{12}C or $p + {}^{70}$Se quasifusion can contribute.

A microchannel-plate (MCP) beam-tracking system was used to correct for the 3 cm diameter secondary beam spot on target. One channel-plate tracking detector directly imaged electrons emitted from the reaction target, defining the point of interaction in the target with an accuracy of 1.1 mm FWHM. Additional information about the microchannel-plate tracking detectors can be found in Ref. [33].

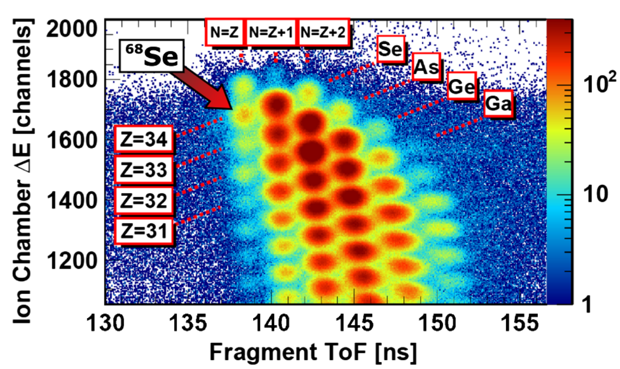

FIG. 3 (color online). Particle identification spectrum of the projectilelike residues detected in the S800 focal plane, in coincidence with HiRA, and produced in reactions with the ^{70}Se secondary beam.

Particle-decaying states were identified within a two-body Q-value (relative-energy) spectrum (with an experimental resolution of $\sim$110 keV FWHM at $Q = 800$ keV) where $Q = \sqrt{P^{\mu}_{\rm tot} P^{\rm tot}_{\mu}} - m_p - m_f$, $P_{\rm tot}$ is the covariant total momentum of the proton and fragment, and m_p and m_f are the proton and fragment mass, respectively. Events were reconstructed from a complete kinematic coincidence measurement of the ^{69}Br $\rightarrow p + {}^{68}$Se decay products for reactions with the ^{70}Se beam [34]. Figure 4 shows spectra for the relative energy Q calculated from the two-body final states $p + {}^{68,69}$Se and $p + {}^{67,68}$As systems detected in this experiment. All spectra display a continuous distribution of proton-emission events at high ($Q > 1.4$ MeV) relative energies, suggestive of statistical nuclear decay following a multistep production mechanism. Only the energy spectrum for $p + {}^{68}$Se (containing possible ^{69}Br decay events) displays a prominent peak at low relative energies of about 0.8 MeV.

This prominent peak results from the decay of one discrete quantum state in ^{69}Br to another in ^{68}Se; a last step simultaneous multibody decay would have a broader peak. The final state must be the ground state for the following reasons. The tunneling decay rate for such low-energy protons through the Coulomb barrier is of the order $\sim 10^{10}$ s^{-1}. If the decay were from an unknown excited state in ^{69}Br to the first-excited state of ^{68}Se at 854 keV, the spectrum should also contain a much larger proton decay peak at about 1.65 MeV corresponding to decay from the unknown excited state to the ground state of ^{68}Se. Such decays would have a $\sim 10^5$ higher tunneling rate but are not observed.

The extremely low proton-tunneling rates for 0.8 MeV protons also explain the very low yields at that energy in the relative-energy spectra for protons coincident with ^{69}Se, ^{67}As, and ^{68}As residues. If a $\sim$0.8 MeV proton were emitted as the last step in the decay process for these spectra, the parent nuclei would be ^{70}Br, ^{68}Se, and ^{69}Se at excitation energies of about 3.2, 3.8, and 5.5 MeV,

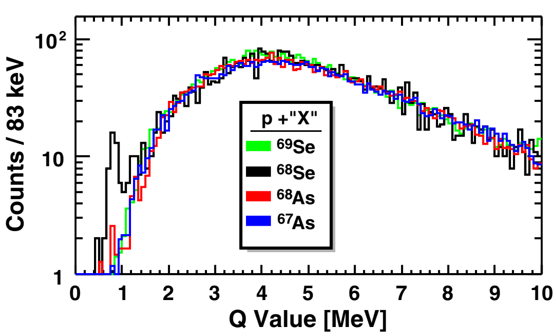

FIG. 4 (color online). Relative-energy spectra for protons coincident with ^{68,69}Se and ^{67,68}As. At the lowest energies, where discrete particle emission is observable, there is a distinct peak at $\sim$0.8 MeV for the reaction ^{69}Br $\rightarrow p + {}^{68}$Se. All other nuclei considered are particle-bound and therefore decay through decay modes other than particle emission. All spectra are normalized to ^{69}Br from 6–10 MeV.

respectively. These states would preferentially γ decay via $E2$ or $M1$ transitions with typical rates that are at least 10^2 larger than the 0.8 MeV proton decay rates.

In our experiment, the unstable ^{69}Br nuclei decay in flight, following their production in the target at the front of the S800 spectrograph. For lifetimes on the order of 100 ps or longer, ^{69}Br, in its ground or excited states, can decay in flight more than 1 cm downstream from the target depending on the spin and proton separation energy. This can create a tail on the decay peak that extends towards lower relative energies. In the following, we take such decays into account by coupling lifetimes, estimated via a WKB calculation, to a simulation of the decay in flight to our detection apparatus.

We employ mirror symmetry to constrain the influence of nuclear structure on the peak shape. Current nuclear structure data for ^{69}Se, which is the $T_z = 1/2$ mirror nucleus of ^{69}Br, indicate that there are three known low-lying levels at $E^* < 150$ keV. The ground state for ^{69}Se has been assigned a spin-parity of $1/2^-$ [35] or $3/2^-$ [36]. This is followed by a $5/2^-$ level at 39 keV [35], and finally by a level with unknown spin-parity at 129 keV [37]. The next highest excited state has a spin-parity of $(9/2^+)$ and an energy of 574 keV [35], being well separated from those at lower energy. Assuming mirror symmetry, we take ^{69}Br to have the same level ordering.

The three low-lying ^{69}Se mirror levels were used to generate spectra in a Monte Carlo simulation for varying proton separation energies, which were compared to the data. For simplicity, we considered these levels to be pure single-particle states with unit spectroscopic factors. The Kolmogorov-Smirnov test [38] was used, with the best-fit results shown in Fig. 5. The final analysis yields a best-fit value for the proton separation energy, assuming a ground state with $J^{\pi} = 3/2^-$ ($\ell = 1$), of $S_p(^{69}\mathrm{Br}) = -785^{+34}_{-40}$ keV corresponding to a mass excess of $\Delta = -46115^{+40}_{-34}$ keV. This result is compared to previous indirect-experimental and theoretical predictions in Fig. 2. The present result is 149 keV more unbound than recent values obtained from Penning trap measurements for ^{69}Se and ^{68}Se combined with CDE shifts to the mass of ^{69}Br from that of ^{69}Se [23,24,26]. This discrepancy could be due to the electromagnetic spin-orbit effect [39,40], for example. We note that the systematic trend of the odd ^{71,73,75}Br isotopes and predictions by shell-model calculations using the GXFP1A interaction [41] favor a ground-state spin-parity assignment of $5/2^-$. If one allows the $5/2^-$ state to lie below the $3/2^-$ state, the Kolmogorov-Smirnov fit yields a proton separation energy for a $5/2^-$ ground-state of $S_p = -735^{+58}_{-72}$ keV. Given that there are no known $T = 1/2$ mirror nuclei where the ground state and first-excited state are inverted, we reject this unlikely possibility in the fit of the Q-value spectrum. There have also been suggestions, as in ^{69}Se, of a long-lived $9/2^+$ isomeric state in ^{69}Br that, if populated, would block decays to the ground and lower-lying states and be misinterpreted as

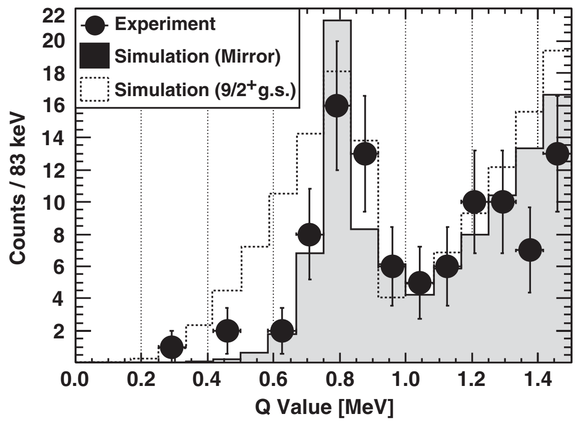

FIG. 5. Comparison of the best-fit results from a ^{69}Se mirror level ordered simulation to the experimental data.

the ground state in experiments relying on the short lifetime [42]. Assuming the observed peak to be the $9/2^+$ level with a pure $\ell = 4$ transition, we have simulated this possibility as the dotted line in Fig. 5. Our simulation of the assignment displays a low-energy tail caused by the long lifetime that is inconsistent with the data. Moreover, if a spin-parity of $9/2^+$ is assigned to the observed peak, then the CDE extracted from our measurement for this possibility would be much smaller than expected from systematics.

To investigate the astrophysical importance of this measurement, one-zone x-ray burst model calculations [43] were performed, using reaction rates from the JINA REACLIB database V1.0 [44], to quantitatively explore the influence of the ^{69}Br proton separation energy on a burst that processes material through ^{68}Se. Dashed lines in Fig. 2 indicate the values for the ^{69}Br separation energy that correspond to 30%, 10%, 3%, 1%, and 0.3% of the reaction flow bypassing the waiting point by $2p$ capture on ^{68}Se. In general, there is a rapid reduction in flow, due to the exponential dependence in the reaction rate on separation energy for $S_p \lesssim -500$ keV. If one used the previous value of $S_p = -636(105)$ keV obtained from Refs. [23,24,26], up to ~2% of the reaction flow could bypass the ^{68}Se waiting point by $2p$ capture. The present value of $S_p = -785^{+34}_{-40}$ keV implies an upper limit of 0.25% on the reaction through $2p$- capture on ^{68}Se which indicates that ^{68}Se remains a significant waiting point in the rp process.

In summary, we report the first direct measurement of the ^{69}Br mass excess, $\Delta = -46115^{+40}_{-34}$ keV, and proton separation energy, $S_p = -785^{+34}_{-40}$ keV. We find from the observed proton separation energy that ^{69}Br is more unbound than previously predicted, restricting the $2p$-capture flow around the astrophysical rp-process ^{68}Se waiting point in type I x-ray bursts.

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