Half-Life Measurement for the rp-Process Waiting Point Nuclide ^{80}Zr

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X-ray bursts have been suggested as a possible site for the astrophysical rp-process. The time scale for the process is governed by β-decay half-lives of several even-even $N = Z$ waiting point nuclei, in particular, $N = Z = 40$ ^{80}Zr. A $4.1(^{+0.8}_{-0.6})$-s β^+/EC half-life for ^{80}Zr was determined by observing delayed 84-keV γ rays depopulating a $T_{1/2} = 4$-μs isomer at 312 keV in the daughter ^{80}Y. As this half-life is lower than many previously predicted values, the calculated excessive production of $A = 80$ nuclides in astrophysical x-ray burst scenarios is reduced, and less extreme conditions are necessary for the production of heavier nuclides.

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More than 40 type I x-ray burst sources have been observed over the last 20 years near the galactic center. These x-ray bursts are interpreted as thermonuclear runaways in the highly electron degenerate envelope of accreting neutron stars [1–3]. The sudden energy release of $\approx 10^{38}$ ergs/s is a result of rapid proton capture reactions and β decays [4–6] that embody the rp-process. The runaway is initiated by the triple α reaction and breakout from the hot CNO cycles [7,8] in the hydrogen and helium enriched atmosphere of the accreting neutron star. After peak temperatures of $T \geq 10^9$ K have been reached, ^{56}Ni freezes out in thermal (p,γ)-(γ,p) equilibrium, forming a ^{56}Ni ocean on the stellar surface [9,10]. A reignition of the ^{56}Ni occurs during the cooling phase of the x-ray burst, driving the rp-process beyond the limits of stability by two-proton capture reactions toward the double-magic Sn region. This process may be a possible contributor to the presently unexplained relatively high observed abundances of light p-nuclei such as ^{92}Mo and ^{96}Ru, if photon driven mass loss were possible from the gravitational potential of the neutron star. A lack of information on masses, β-decay half-lives, reaction cross sections, and nuclear structure for nuclei not easily accessible to measurements gives rise to numerous uncertainties along the rp-process pathway. An important component for understanding both the rp-process and the stellar scenarios that allow it to take place is the ability to simulate the nucleosynthetic process. Extended network calculations [6,7] suggest rp-process nucleosynthesis may be generally delayed by the β decay of several even-even $N = Z$ nuclei, and, in particular, by the β decay of ^{80}Zr. A two-proton capture reaction on this nucleus is hindered by the large negative binding energy of proton-unbound ^{81}Nb [6,11]. Therefore, continuous reaction flow is controlled by the β^+/EC decay of ^{80}Zr alone.

Calculated half-lives for the β decay vary widely due to rapid nuclear structure changes in the $N = Z = 40$ region. Early shell model descriptions based on the strong subshell closures at 40 for both Z (^{90}Zr) and N (^{68}Ni) suggested near-spherical double semimagic character for ^{80}Zr [12]. However, the structure was empirically determined to be highly deformed, with $\epsilon_2 \sim 0.37$ [13]. In Fig. 1 quasiparticle random phase approximation (QRPA) calculations [6] are shown for the ^{80}Zr half-life as a function of deformation using the Q_{EC} value of 6.60 MeV calculated by the finite range droplet model [14]. The half-life sensitivity in the range of the estimated deformation for ^{80}Zr is especially notable. Theoretical estimates of the half-life are also strongly dependent on predicted Q values, as shown in Fig. 1. Both experimental [15,16] and calculated [14,17–21] masses show considerable differences, resulting in a wide variation of calculated half-lives.

Previous network calculations clearly predict a strong production of p-nuclei progenitors [6,7]. Calculations using long half-lives for ^{80}Zr result in a significant overproduction of this nuclide and its great-granddaughter ^{80}Kr, in contradiction to observed solar values [22]. Lower half-life values for ^{80}Zr reduce predicted abundances significantly. This Letter reports the first measurement of the

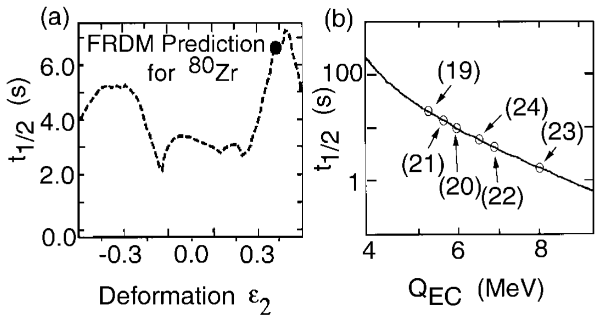

FIG. 1. Half-life sensitivity to the deformation and estimated Q values for ^{80}Zr decay from QRPA calculations. In (a), the calculated curve is based on the mass predictions of the finite range droplet model (FRDM2) [14] used in the previous *rp*-process simulations [6]; the dark circle represents the deformation predicted by the same model. In (b), the half-life is plotted as a function of Q_{EC} values from various mass formulas; references are given in parentheses. The predicted Q_{EC} values range over approximately 3 MeV, resulting in half-life variations from ~1–25 s.

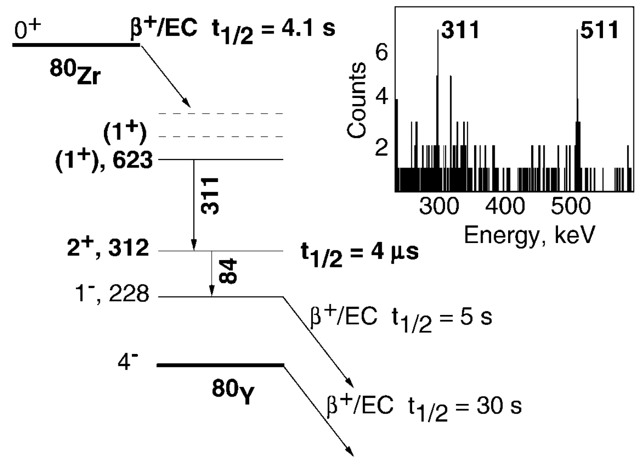

FIG. 2. Partial β^+/EC decay scheme of ^{80}Zr. The figure shows only levels relevant to the present experiment. New data derived from this experiment include the ^{80}Zr half-life and the 1^+ level at 623 keV in ^{80}Y. Also shown are γ-ray energies coincident with delayed 84-keV transitions. The peak at 511 keV arises from positron annihilation, while the peak at 311 keV is assigned as a deexcitation from one of the primary 1^+ levels in ^{80}Y populated in the β decay.

β-decay half-life of ^{80}Zr and the impact of this half-life on the resulting isotopic abundances in an x-ray burst scenario.

Previous attempts to measure the decay of ^{80}Zr with both the Daresbury Recoil Separator and the Argonne FMA were unsuccessful [13,23]. Difficulties arose as a consequence of the small production cross section (10 μb, [13]) and the limited knowledge of γ transitions in the ^{80}Y daughter. Recent structure studies [24,25] of the ^{80}Y nucleus have opened a new possibility for determining the β-decay half-life of the parent. An 84-keV transition was observed in fragmentation reactions to decay from an isomeric state with a 4-μs half-life [25]. A 2^+ spin and parity were later assigned to the isomer [23]. The partial decay scheme for ^{80}Zr is shown in Fig. 2 with levels in ^{80}Y relevant to the present experiment. In designing this experiment, we reasoned that the Gamow-Teller β decay of ^{80}Zr would populate one or more 1^+ levels in the daughter ^{80}Y and that significant branching from these 1^+ levels would populate the 2^+ isomer. Hence, ^{80}Zr events could be uniquely identified, and the half-life determined, by observing delayed coincidence events associated with the decay through this isomer.

The experiment was performed at the Holifield Radioactive Ion Beam Facility of Oak Ridge National Laboratory. Mass 80 nuclei were produced using a 195-MeV ^{58}Ni beam from the Holifield tandem accelerator to bombard a ~500-μg/cm^2-thick enriched ^{24}Mg foil at the target position. Reaction products were subsequently separated by mass-to-charge (A/Q) ratios through the recoil mass spectrometer [26], which was tuned to accept mass 80 recoils. These recoils were then implanted onto the transport tape of a moving tape collector [27] at the focal plane. The tape was advanced at timed intervals to a shielded position surrounded by three large HPGe clover detectors and a low-energy planar Ge detector with a 70-mm diameter × 30-mm thickness. Thin (≈3-mm) plastic scintillators were placed in front of each clover detector to measure β-γ prompt and delayed concidences. The initial bombardment and counting times were 30 s each, with 1.5 s allowed for tape movement. After an estimate of the half-life became available, the time for bombardment and counting was shortened to 20 s.

Coincidence events were sought in which a time-to-amplitude converter (TAC) was started by a positron (in one of the plastic detectors), an annihilation γ, or prompt γ decay (in one of the clover detectors), and stopped by a low energy γ ray in the planar detector. Data written to tape included amplifier outputs of the clover detectors and plastic scintillators whose time signals were used to start separate TAC modules, and the amplifier output for the planar detector whose time signal was used to stop both TACs. A time stamp for each event was provided by a digital time clock that was reset at the end of each tape movement. The half-life of ^{80}Zr was determined by selecting delayed 84-keV events, and noting their time correlation relative to the last tape advance. In this manner, events unique to the decay of ^{80}Zr could be identified in spite of the large background of prompt β-γ and γ-γ coincidence events from the daughter and other nuclides with the same mass-to-charge ratio as ^{80}Zr.

The TAC output versus energy of the stop pulse in the planar detector is shown in Fig. 3. The TAC channel is proportional to the time between the positron start pulse registered in one of the plastic detectors and the stop time registered in the planar Ge detector. The range of the TAC was set to 10 μs, causing prompt events to be condensed near channel 650. Delayed events are observed at both 66 and 84 keV. The 66-keV events arise from a similarity between ^{77}Rb and ^{80}Zr A/Q values which results in the implantation of some $A = 77$ nuclei on the tape. The

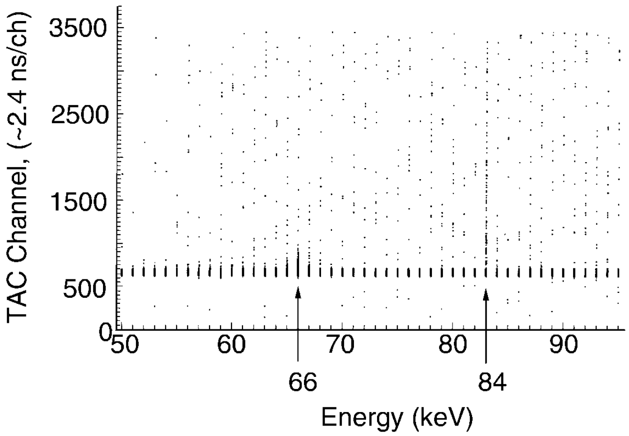

FIG. 3. Two-dimensional display showing the time difference between events observed in the plastic β detectors (TAC start pulse) and events observed in the low-energy planar detector (TAC stop pulse) as a function of the stop-pulse energy in the low-energy detector. Prompt coincidences fall in a band centered at channel 650 with a full width at half maximum of ~60 channels. Events at 66 keV arise from the β decay of ^{77}Rb which populates a level in ^{77}Kr with a 118-ns half-life (~50 channels).

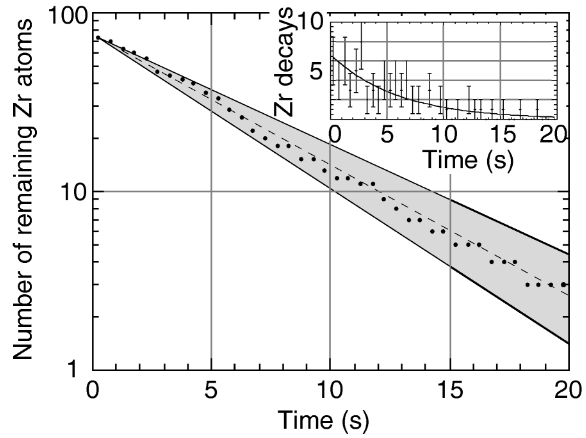

FIG. 4. Number of remaining Zr atoms as a function of time. The straight line represents a 4.1-s decay line, while the shaded areas show the range of error—4.9 s as an upper limit and 3.5 s as a lower. The inset shows the background-corrected counts per 0.5 s.

β decay of ^{77}Rb ($t_{1/2} = 3.77$ m) will populate a 118-ns isomer in ^{77}Kr at 66.5 keV [28]. We sought events in which the 84-keV γ ray was emitted longer than 100 ns after a prompt β or γ decay; these are events shown at 84 keV with a TAC reading above channel 725 in Fig. 3. The time relative to the last tape advance for these events was then analyzed to determine the ^{80}Zr half-life.

A total of 87 delayed 84-keV events were observed, of which 11 events were assumed to arise from Compton background by comparison to adjacent channels. As the half-life is sensitive to the method of background subtraction, several distributions were compared to remove the 11 events. Approaches included various random distributions, even-spaced, fitting to a 30-s half-life (^{80}Y), and fitting to an adjacent channel. The 4.1 s half-life we report for the β decay of ^{80}Zr is an average of maximum likelihood [29] results from the background-subtracted data. All values obtained fell within the $(+0.8/-0.6)$ range of uncertainty calculated with a 4.1-s half-life using a random background subtraction. In Fig. 4 the natural logarithm of the remaining Zr atoms (ln$N$) is plotted as a function of time. The inset shows the compressed decay rate (dN/dt) data, with the solid line representing a 4.1-s half-life.

Figure 2 shows the plot of γ-ray energies from the clover detectors that were start pulses for events in which a delayed 84-keV γ was also detected. One clear peak emerges at 311 keV with the expected annihilation radiation peak at 511 keV. We assign this line at 311 keV to the deexcitation of a primary 1^+ level populated in the β decay of ^{80}Zr which depopulates to the 2^+ isomer at 312 keV. A strongly populated 1^+ level is therefore placed at 623 keV in ^{80}Y.

Döring *et al.* [23] presented two-quasiparticle-plus-rotor calculations for the structure of ^{80}Y showing the lowest 1^+ level dropping in energy with increasing deformation, relative to the energy of the lowest 2^+ level. Specifically, a 311-keV 1^+-2^+ separation would suggest a deformation ϵ_2 between 0.37 and 0.38 for ^{80}Y. This is near the predicted value of $\epsilon_2 = 0.383$ given in the recent tabulation by Möller *et al.* [14].

The ^{80}Y mass has been recently established as 79.932 80(190) in a cyclotron resonance experiment [16]. In addition, a single event for ^{80}Zr was observed from which a mass of 79.940 400(1600) could be determined. Although the uncertainty of this value is large, it is consistent with the calculated mass recommended by Audi *et al.* [18]. If we scale the QRPA-calculated half-life of 6.85 s reported by Ref. [6] to our measured value, a Q value of approximately 7.3 MeV is necessary. We note that this value lies at the upper end of the uncertainty of the experimental 5.7(1.6) MeV Q value in Ref. [16]. A minimum logft value of 4.2 is obtained assuming 100% decay to the level at 623 keV and a total Q value of 7.3 MeV. This value is consistent with the minimum logft value of 4.1 for the nearby $N = Z$ nuclide ^{76}Sr calculated using mass values from Ref. [18].

To test the implications of the measured ^{80}Zr half-life to the rp-process, we calculated the resulting abundances for ^{80}Y and ^{80}Zr within the framework of a one mass zone model for an x-ray burst [7]. In Fig. 5 we show the effect on the total abundance for all mass 80 isobars, and specifically for ^{80}Zr. The shaded areas correspond to the range of ^{80}Zr half-lives predicted by various models prior to the experiment ($2.0 \leq T_{1/2} \leq 20$ s), taking into account only the ground state decay of ^{80}Y ($T_{1/2} = 35$ s). The solid line represents the results calculated on the basis of the newly measured half-life for the ^{80}Zr decay ($T_{1/2} = 4.1$ s), including the effective half-life of ^{80}Y ($T_{1/2} = 25$ s) which incorporates the β-decay component of the 1^- isomeric state [23].

The experimental result for the ^{80}Zr half-life significantly reduces the large uncertainties in the predicted mass

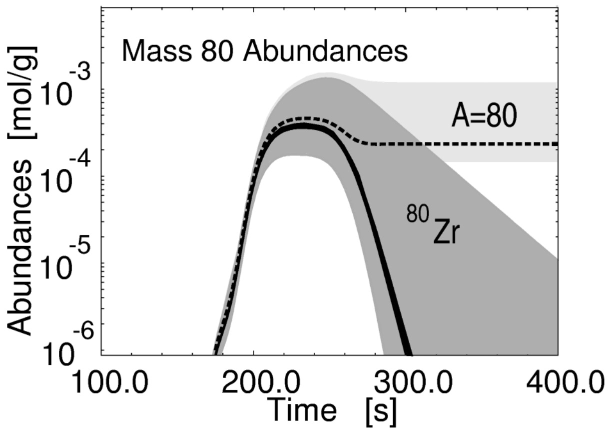

FIG. 5. The total abundance during the burst for ^{80}Zr and all mass 80 isobars. The shaded areas correspond to the range of ^{80}Zr half-lives predicted by various models prior to the experiment ($2.0 \leq T_{1/2} \leq 20$ s), taking into account only the ground state decay of ^{80}Y ($T_{1/2} = 35$ s). The solid line represents the results calculated on the basis of the newly measured half-life for the ^{80}Zr decay ($T_{1/2} = 4.1$ s), including the effective half-life of ^{80}Y ($T_{1/2} = 25$ s) which incorporates the β-decay component of the 1^- isomeric state.

80 abundances. The experimental half-life value is less than the theoretical value used in previous x-ray burst calculations [6]; this results in a reduced production of ^{80}Zr by a factor of 2 during the cooling phase of the burst. The feeding of the ^{80}Y isomeric states by the decay reduces the effective half-life of ^{80}Y significantly and subsequently reduces its abundance during the cooling phase. Fast proton capture on ^{80}Y and ^{80}Sr causes rapid leaking from the mass 80 range toward heavier masses. This constrains considerably the formation of ^{80}Kr during the freeze-out phase, reducing its final abundance in the atmosphere of the neutron star by nearly 1 order of magnitude. The abundances of the heavier p-progenitor nuclei remain largely unaffected as the material is distributed approximately evenly within this mass range. Not included is the possible β-decay contribution of the thermally populated first excited 2^+ state at 290 keV [13] in ^{80}Zr since reliable predictions for its half-life [6] are unavailable. A strong β-decay component of this state may have some influence, but as the temperatures during the cooling phase are presumed to be under 1 GK, this contribution is most likely negligible.

In conclusion, we have measured the half-life of the $N = Z$ waiting point nucleus ^{80}Zr to be $4.1(^{+0.8}_{-0.6})$ s by identifying delayed coincidences with an isomeric transition. The ^{80}Zr lifetime is one of the important bottlenecks in the rp-process and is crucial in x-ray burst simulations. The effect of the measured half-life in comparison to the estimated half-lives for the network simulations of the rp-process is a significant reduction for the production of mass 80 nuclei in the cooling phase of the x-ray bursts.

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