Half-Life of ^{80}Zn: The First Measurement for an r-Process Waiting-Point Nucleus

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A half-life of 0.55 ±0.02 s was measured for the neutron-rich fission-product nucleus $^{80}_{30}$Zn$_{50}$. A Q_β value for the decay of ^{80}Zn of 7.15 ±0.15 MeV and a level scheme for ^{80}Ga have also been deduced. The properties of this $N=50$ waiting-point nucleus are significant for the evaluation of different models of r-process environments and exposure times.

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This Letter reports on the first measurement of nuclear properties of ^{80}Zn. This is a critical nucleus in the calculation of the r process of stellar nucleosynthesis. In the r process,[1–4] nucleosynthesis proceeds through successive neutron captures on a time scale which is shorter than or comparable to the competing β decay. The astrophysical site for this process is not yet known, nor are the precise environmental conditions of neutron density, stellar temperature, and exposure time.[1–7] Apart from these stellar parameters, the most general calculation of the r process would require detailed knowledge of the properties of the nuclides encountered along the path, in particular, β-decay half-lives ($T_{1/2}$), neutron-capture cross sections, binding energies (B_n), and nuclear level schemes (or partition functions).

The waiting-point approximation[2,3] of the classical r process avoids the need for some of these quantities by making two simplifying assumptions: The time scale for neutron capture is assumed to be much shorter than that of β decay, and an $(n,\gamma)\leftrightarrow(\gamma,n)$ equilibrium is envisioned. Then the abundance ratio of two adjacent isotopes depends exponentially, in a nuclear Saha equation,[2,3] on the ratio of B_n to the stellar temperature. For low B_n values, production of the next heavier isotope is inhibited and the continuation of the r process must await β decay to a new element with higher B_n. Since B_n drops precipitously at neutron closed shells, points where the r-process path crosses $N=50$, 82, and 126 specify the three most critical nuclides that determine the nucleosynthetic cycle time from Fe to the actinides. These nuclei[3] are ^{80}Zn, ^{130}Cd, and ^{195}Tm.

The conditions (high neutron density and stellar temperature) under which this approximate description of the production of neutron-rich heavy nuclei is valid have recently been discussed.[8] Even when the waiting-point approximation is poor, β-decay half-lives remain important[9] in determining both the cycle time and the r-process path itself. Moreover, it is clear from the known r-process abundance peaks near $A=80$, 130, and 195 that the above closed-shell nuclei still play a pivotal role.

Unfortunately, for most nuclei in the r-process path and for these waiting-point nuclei in particular, the important nuclear data required for the calculations are unknown, and have had to be extrapolated from existing systematics or calculated under various model assumptions. In particular, to predict unknown β-decay half-lives two models have been used, the gross theory[10] and a microscopic calculation.[11] The two calculations differ by widely ranging factors which attain an order of magnitude in many regions. Moreover, the microscopic calculations, which in general are in better agreement with the data for known nuclei, still disagree with these data by an average factor of ≥ 4. Even for nuclei with $T_{1/2} < 1$ s the average discrepancy factor is ≥ 2.4. The resultant range of possible half-lives for waiting-point nuclei leads to serious uncertainties in the nucleosynthetic cycle time and thus the required neutron exposure time. Clearly, half-life measurements for the three critical closed-shell nuclei would be an essential ingredient in judging the viability of different proposed r-process environments.

The prime purpose of this Letter is to report the results of the first study of the β decay of ^{80}Zn. The measurements give a half-life, a Q_β value, and a decay scheme for ^{80}Zn, the latter comprising low-lying levels and prominent γ rays in ^{80}Ga. Prior to these measurements nothing definitive was known concerning ^{80}Zn, although three γ rays had earlier been tentatively assigned to the level scheme of ^{80}Ga through thermochromatographic techniques.[12] Besides their astrophysical importance, the current results are of considerable nuclear structure interest since they involve a closed-shell region far from stability. This Letter, however, concentrates on the astrophysical aspects. A detailed presentation of the data together with a complete decay scheme and a discussion of the nuclear structure implications will be given elsewhere.

The experiments were carried out at the mass separator TRISTAN on line to the high-flux beam reactor (HFBR) at Brookhaven National Laboratory. Thermal neutrons from the reactor impinged on a 5-g target of ^{235}U situated inside a high-temperature plasma ion source.[13] The resulting fission products were ionized and focused into a beam which was then electromagnetically mass separated and implanted onto an aluminized Mylar tape, in a position viewed by various detector combinations. Time-sequential γ-ray spectra were used for half-life determinations. In addition, γ-γ and β-γ coincidences provided data that ensure that this activity does in fact originate from ^{80}Zn, and that allow the construction of a ^{80}Ga level scheme and yield a Q_β value for the decay of ^{80}Zn.

A first experiment utilized two Ge detectors and a thin plastic β counter, which served as a β gate on the γ-ray data. To measure half-lives, a β-gated Ge detector was used to obtain γ-ray spectra in 32 time-sequential spectra each of 0.1-s duration. The beam was collected for 1.0 s, then electrostatically deflected, allowing the activity to decay for a period of 2.2 s, after which the tape was moved about 10 cm to a shielded location. This cycle was repeated throughout the experiment. Simultaneously, γ-γ coincidence data were accumulated, obtaining a total of about 6×10^7 events.

The mass assignment to $A=80$, obtained via electromagnetic mass separation, was confirmed by the identification of known γ rays from the decays of ^{80}Ga, ^{80}Ge, and ^{80}As. No γ rays resulting from contamination by adjacent masses, either 81 or 79, were observed. Analysis of the time-sequential spectra identified several γ rays as belonging to the ^{80}Zn decay. Strong γ rays of 713 and 715 keV were used to determine a ^{80}Zn half-life of 0.55 ± 0.02 s. Figures 1(a) and 1(b) show γ spectra at early and late parts of the 3.2-s cycle. Figure 1(c) shows the growth and decay of the 713- and 715-keV γ rays. Dead-time corrections were made by use of the scaled output of a pulser. The above half-life was derived from the decay portion only.

The γ-γ coincidence data confirm that the observed γ rays are not new lines from the decay of other $A=80$ nuclei since they are not seen in coincidence with strong transitions in these daughter nuclides. This is illustrated in Fig. 2(a) which shows that the gate placed on the 713-keV γ ray does not show coincidences with the 659- or 666-keV γ rays from Ga and As decay, respectively.

Following these measurements, one Ge detector was

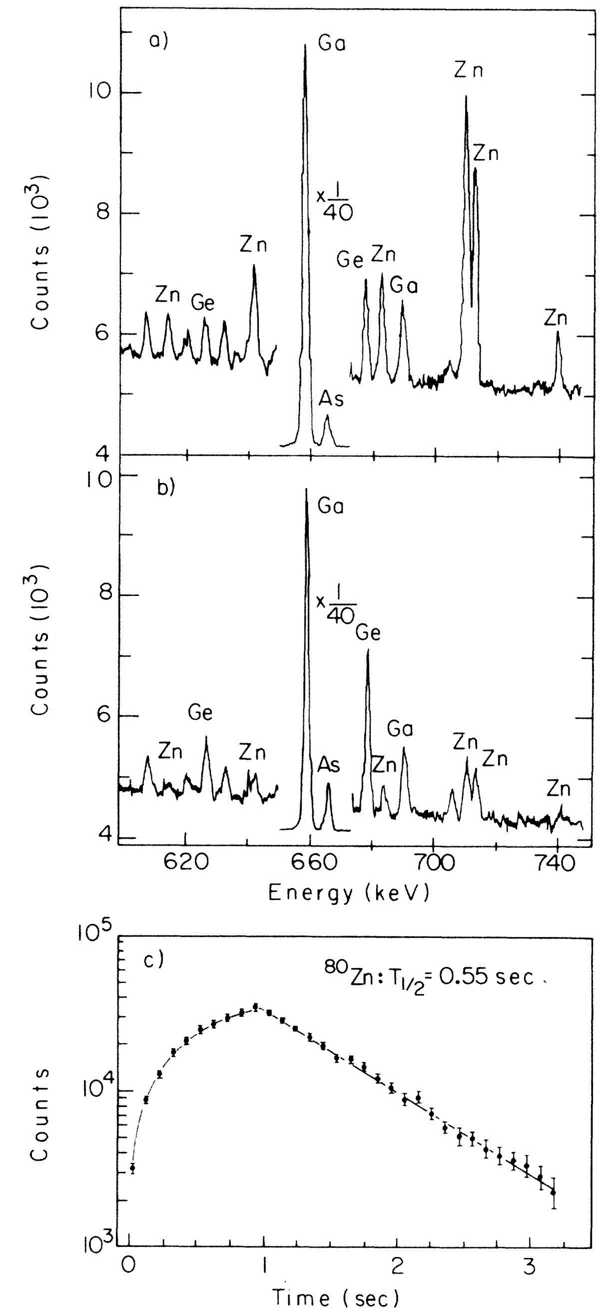

FIG. 1. γ-ray spectra for the $A=80$ decay chain from (a) 0.1–1.2 s and (b) 2.0–3.1 s. The ratio of Zn to Ga activity is a factor of 4 larger in (a) than in (b). (c) The growth and decay of the ^{80}Zn 713- and 715-keV γ rays.

replaced with a hyperpure Ge detector of 10-mm active thickness with a 12-μm Ti window in order to measure the β-decay end point via β-γ coincidences which were repeatedly accumulated for cycles of 1.2-s duration. The β-γ coincidence data were treated with a Fermi-Kurie analysis. The energy calibration was obtained from standard γ-ray sources combined with the high-energy γ lines from neutron capture in Fe,

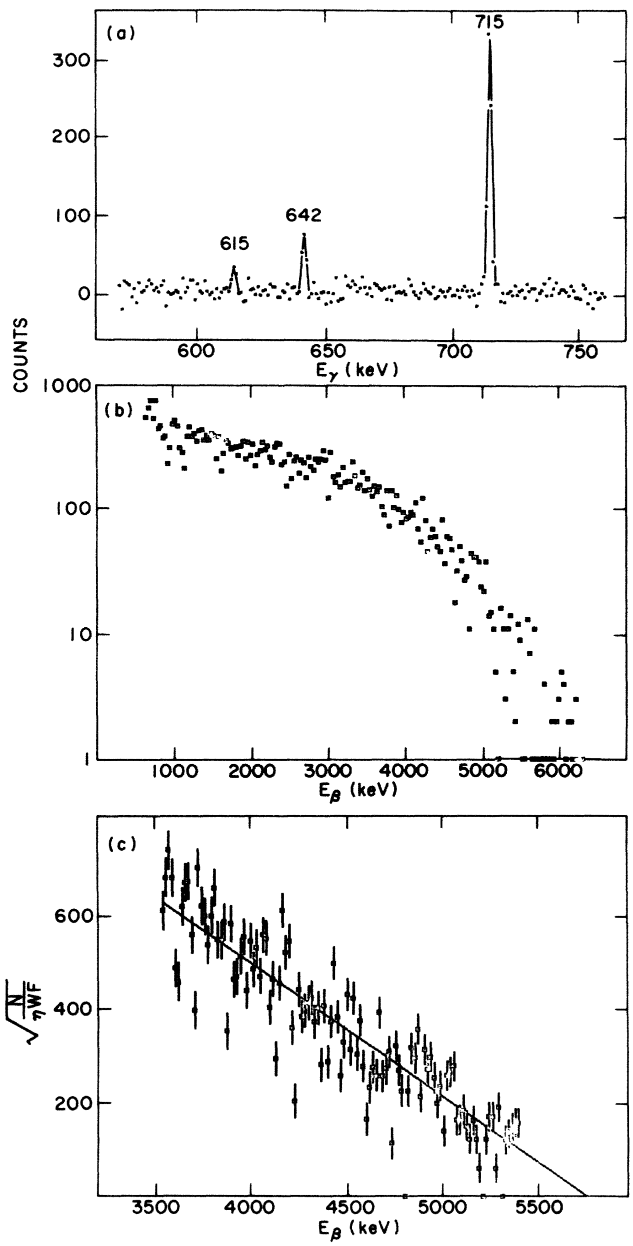

FIG. 2. (a) Portion of the γ-γ coincidence spectrum for the 713-keV gate; (b),(c) raw β spectrum and the end-point region, respectively, of the Fermi-Kurie corrected β spectrum gated on the sum of the 713- and 715-keV γ rays.

which appear as contaminants in the singles β spectra. The correction for the energy loss in the windows, dead layers, etc., was determined in a separate measurement by use of electron sources and known β spectra. Examples of the raw and corrected β spectra are shown in Figs. 2(b) and 2(c). The continuous nature of these β spectra demonstrates that the γ rays do not originate from the internal-conversion decay of an isomeric state in ^{80}Ga but can be assigned to ^{80}Zn decay.

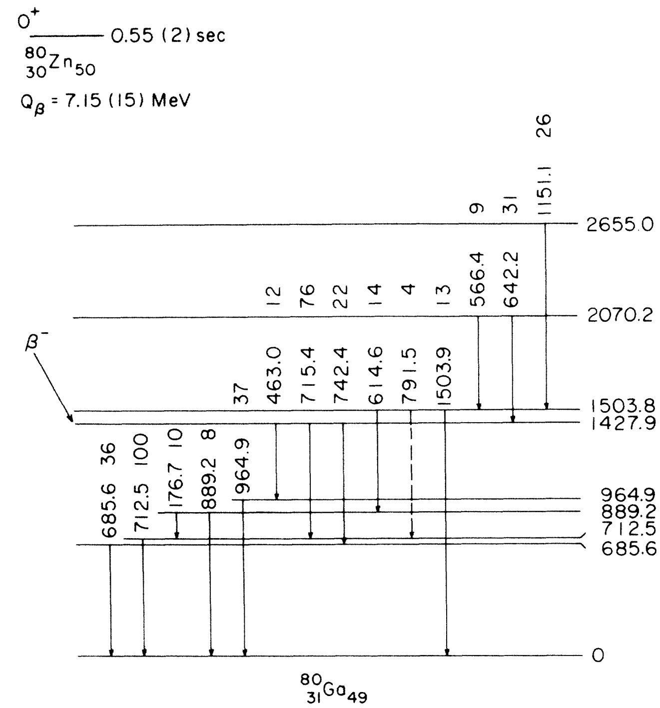

FIG. 3. Decay scheme of ^{80}Zn deduced in these experiments. The γ-ray intensities are normalized to 100 for the 713-keV line. β^- feeding to the 1428-keV level is indicated.

The γ singles and coincidence data were used to construct a partial level scheme for ^{80}Ga which is shown in Fig. 3. From intensity-balance arguments, it would appear that there is significant β feeding to the 1428-keV level. Since there is little β feeding to the 713-keV level (which is fed almost exclusively by the 715-keV γ ray), the β^- spectra gated by the 713- and 715-keV γ rays can therefore be added. Analysis of the end point in Fig. 2(c) then yields a Q_β value of 7.15 ± 0.15 MeV for the decay of ^{80}Zn. This Q_β value is consistent with values obtained from the individual 713- and 715-keV gated β spectra as well as with less accurate values deduced from weaker γ rays. By use of the Q_β value and that[14] for ^{80}Ga and the known[15] mass excess for ^{80}Ge, a mass excess for ^{80}Zn of -52.28 ± 0.46 MeV is obtained. This compares well with the predicted value of -52.40 MeV from the calculations of Moller and Nix.[16] Finally, the data also provide β end points from the decay of ^{80}Ge and ^{80}As which give $Q_\beta = 2.63 \pm 0.02$ MeV and $Q_\beta = 5.47 \pm 0.09$ MeV, respectively, in excellent agreement with the values given by Aleklett *et al.*[17]

Although, as mentioned earlier, both the binding energies and partition functions (level schemes, such as that in Fig. 3) are important input data for *r*-process calculations, the key result here is undoubtedly the $T_{1/2}$ value for ^{80}Zn decay. The predicted values of Takahashi, Yamada, and Kondoh[10] and Klapdor, Metzinger, and Oda[11] are 3.9 and 0.49 s, respectively. The very close agreement with the more microscopic calculation of Ref. 11 is particularly encouraging and results, in the waiting-point approximation, in a much shorter cycle time than would, for example, have been implied by the longer half-lives typical of the gross theory or allowed within the expected accuracy of the predicted half-lives of Ref. 11. In turn, the measured half-life removes a substantial constraint on the neutron-exposure time and thereby provides important information for models of the stellar environments appropriate to the r process.

Follow-up to this work lies in three areas. First, an attempt will be made to measure Q_β for ^{81}Zn and thereby extract a B_n value for the addition of a neutron to ^{80}Zn. This value directly enters the nuclear Saha equation and determines to what extent neutron capture ceases at ^{80}Zn and the r process proceeds with β decay to ^{80}Ga. This yields the temperature regime required to achieve a classical r-process environment. Secondly, the β decay of ^{130}Cd will be studied. Thirdly, a general program to measure an extensive set of $T_{1/2}$ and Q_B values and decay schemes of neutron-rich nuclei, especially for the crucial r-process regions near $A=80$ and 130 and for another important r-process abundance peak near $A=160$, is now feasible with the improved TRISTAN ion sources and will ensue.

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