# Binding Energies in Zr from (d, p) and (d, t) Reactions

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Neutron separation energies in $^{91}$Zr, $^{92}$Zr, $^{93}$Zr and $^{95}$Zr were determined by measurements of relative $Q$-values for (d, p) reactions on Zr isotopes. A comparison is made with separation energies derived from a previous measurement of (d, t) reaction $Q$-values. The neutron separation energy in $^{95}$Zr disagrees by three standard deviations with the adjusted value in the 1977 Atomic Mass Evaluation.

We report here on results for the neutron separation energies in zirconium isotopes of mass numbers $A = 91$, 92, 93 and 95 from measurements of relative $Q$-values for Zr(d, p) reactions obtained by the simultaneous detection of the ground state (d, p) transitions under the same experimental situation. A comparison is made with separation energies derived from a previous measurement [1] of (d, t) reaction $Q$-values and from data in the latest atomic mass evaluation of Wapstra and Bos [2] (WB). We find that the neutron separation energy in $^{95}$Zr obtained in the present work disagrees by three standard deviations with the adjusted value in WB.

The experimental method was essentially the same as that described in [3]. A self-supporting target of metallic zirconium enriched to 89% in $^{91}$Zr was bombarded by a 12 MeV deuteron beam provided by the University of Pittsburgh Van de Graaff accelerator. The scattered protons were analyzed in an Enge split-pole magnetic spectrograph and detected in nuclear emulsion plates placed in the focal surface of the spectrograph. Proton spectra were recorded at seven angles from 8° to 55°. A typical spectrum is shown in Figure 1. Proton groups involving transitions to the ground states of $^{91}$Zr, $^{93}$Zr and $^{95}$Zr are clearly seen among

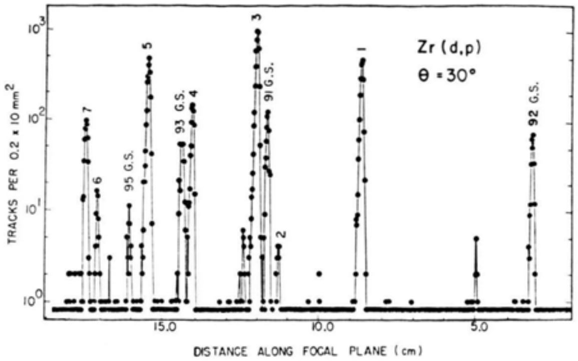


Fig. 1. Typical spectrum for the Zr(d, p) reaction on a target enriched to 89% in $^{91}$Zr at an incident energy of 12 MeV. Numbers 1 to 7 above peaks label transitions to known excited states in $^{92}$Zr.

transitions to known excited states [4] in $^{92}$Zr. A contribution due to the $^{92}$Zr(d, p)$^{93}$Zr (0.267 MeV) reaction may be present in the peak labelled $^{95}$Zr(g.s.) in Figure 1. However, on the basis of known cross-sections for both reactions [5] and the isotopic composition of the target such a contribution should be less than 15% of the peak intensity.

The procedures described in [3] for computing $Q$-value differences and for the evaluation of errors affecting the average values were also used in the present work. The results are presented in Table 1, expressed as neutron separation energies ($S_n$) normalized to a value of (6732.1 ± 1.0) keV for the neutron separation energy of $^{93}$Zr obtained from

Table 1. Neutron separation energies in Zr.

| $A$ | $S_n^{\text{Exp}}$ (keV) [a] | $S_n^{\text{Exp}}$ (keV) [b] | $S_n^{\text{WB}}$ (keV) [c] |
|---|---|---|---|
| 90 | | 11976.8 ± 7.1 | 11976.5 ± 1.7 |
| 91 | 7192.3 ± 2.2 | 7197.9 ± 3.7 | 7199.4 ± 1.5 |
| 92 | 8632.9 ± 4.3 | 8634.8 ± 1.5 | 8635.0 ± 1.4 |
| 93 | 6732.1 ± 1.0 | | 6732.0 ± 1.0 |
| 94 | | 8217.8 ± 2.4 | 8218.6 ± 1.8 |
| 95 | 6459.4 ± 2.6 | | 6470.9 ± 3.8 |
| 96 | | 7853.4 ± 2.8 | 7852.7 ± 2.0 |

[a] Neutron separation energies from (d, p) reaction $Q$-values (this work); the experimental values for $S_n$ were normalized to a value of 6732.1 ± 1.0 keV for the neutron separation energy of $^{93}$Zr (see text).

[b] Neutron separation energies from (d, t) reaction $Q$-values; the experimental values for $S_n$ are from [1], normalized to a value of 8634.8 ± 1.5 keV for the neutron separation energy of $^{92}$Zr (see text).

[c] Neutron separation from the mass tables of Wapstra and Bos [2].

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the experimental $Q$-value for the $^{92}Zr(n, \gamma)^{93}Zr$ reaction [6]. Also listed in Table 1 are the neutron separation energies calculated from the (d, t) reaction $Q$-values of [1] normalized to a value of $(8634.8 \pm 1.5)$ keV for the neutron separation energy of $^{92}Zr$ derived from the experimental $Q$-value for the $^{91}Zr(n, \gamma)^{92}Zr$ reaction [7]. The last column in Table 1 lists the corresponding values for $S_n$ from the WB mass tables [2].

It will be noted that the separation energies listed in column 3 of Table 1 differ from those quoted in [1] in the adoption of a new normalization value for $S_n$ $(A = 92)$ (which is 0.7 keV smaller than that used in [1]) and in the larger uncertainties affecting the measurements. In adopting a new standard, we follow Wapstra and Bos [8] who use the new value as a primary datum in their mass adjustment. The new, larger uncertainties affecting the $S_n$ data derived from (d, t) $Q$-values supersede those quoted in [1] which were found to be in error since only statistical errors had been considered and the systematic uncertainty in the focal plane calibration curve of the spectrograph (see [3]) had not been taken into account [9] in the computation of the total uncertainties.

The new (d, p) data presented here in column 2 of Table 1 complement the revised (d, t) data of [1]. The two sets of data show a good agreement where there is an overlap $(A = 92$ and $A = 91)$. The difference of 1.9 keV for $S_n$ $(A = 92)$ may reflect essentially the difference in the two standards used as reference energies for the (d, p) and the (d, t) data. The two determinations of the separation energy for $A = 91$ while differing by 5.6 keV are in agreement within the limits of the stated uncertainties. If equal weights are given to both measurements, an average value of $7195.1 \pm 2.8$ keV results for $S_n$ $(A = 91)$ which is 4.3 keV lower than the adjusted value of Wapstra and Bos.

The new determination of the separation energy for $A = 95$ fills a gap in the previously existing data and should help in establishing a more precise evaluation of the atomic masses in this mass region. The experimental value differs by 11.5 keV from the adjusted value in WB. The corresponding (d, p) $Q$-value of $4234.8 \pm 2.6$ keV differs by 14.2 keV from the value [10] of $4249 \pm 10$ keV used in WB as a primary datum. The close agreement between the remaining experimental data in Table 1 and the mass table values should cause no surprise since all the data of [1] have been used by WB as primary data in their mass adjustment. The larger, revised, uncertainties affecting the (d, t) data of [1] (and presented in Table 1) will probably lead to an increase in the errors of the adjusted data in a future mass adjustment but will most probably not contribute significantly in modifying the central values of the adjusted masses since the data of Table 1 are among the most precise existing data in this mass region.

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