Neutron Separation Energies of Zr Isotopes *

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(Z. Naturforsch. **31 a**, 393–394 [1976]; received February 25, 1976)

Q values are reported for (d, t) reactions on all the stable isotopes of zirconium. The neutron separation energies of ^{94}Zr and ^{96}Zr differ greatly (by 27.5 and 22.1 keV, respectively) from the values in the 1971 Atomic Mass Evaluation. These results combined with those from other authors seem to indicate that the 1971 values for the masses of ^{93}Zr and ^{95}Zr are in error.

Accurate measurements of reaction Q-values that have been reported since the publication of the 1971 Atomic Mass Evaluation of Wapstra and Gove [1] (WG) have shown that in some particular instances the experimental values can differ from the corresponding ones in the self-consistent set of Q-values (calculated from the adjusted masses) by amounts that are substantially greater than the stated uncertainties. Examples of this will be found in Refs. [1, 2] where discrepancies as big as ~ 20 keV have been found between measured reaction Q-values and neutron binding energies and the tabulated ones in the mass regions of A $\sim 50-60$ and A $\sim 110-120$.

We present here results for the neutron separation energies in the zirconium isotopes derived from a measurement of relative Q-values for the (d, t) reactions on all the stable Zr isotopes. High acuracy results are obtained by the simultaneous detection of the ground state transitions under the same experimental situation. We find that in two cases a considerable disagreement exists between our measured values and the corresponding ones from WG.

The experimental procedure was essentially the same as that described in Reference [3]. A self-supporting target of metallic zirconium enriched to 90% in ^{91}Zr was bombarded by a 16 MeV deuteron beam provided by the University of Pittsburgh three-stage Van de Graaff accelerator. The scattered tritons were analyzed in an Enge split-pole magnetic spectrograph and detected in nuclear emulsion plates placed in the focal surface of the spectrograph. Triton spectra were obtained at seven angles from 12° to 45°. Long exposures were made at all angles in order to ensure the observation with good statistics of weakly populated levels in the ^{91}Zr (d, t) ^{90}Zr reaction [4]. As a result the ground state transitions for the (d, t) reactions on the even natural isotopes (which were present in small percentages in the target) were also clearly observed. Three of these transitions (corresponding to (d, t) reactions on ^{92}Zr, ^{94}Zr, and ^{96}Zr) are the only triton groups which appear between the ground state and the first excited state transitions in the ^{91}Zr(d, t)^{90}Zr reaction. In this region of the spectra, the background contribution is essentially zero and triton groups could thus be easily and unambiguously identified.

The same procedures as adopted in Ref. [3] were used to calculate Q-values differences and in the evaluation of errors affecting the average values. The results are presented in Table 1 where we have normalized the relative Q-values experimentally determined in this work to the Q-value for the ^{92}Zr(d, t)^{91}Zr reaction obtained from the experimental value for the ^{91}Zr(n, γ)^{92}Zr reaction [5], taking into account the neutron separation energy of the triton [1]. The resulting neutron separation energies are also listed in Table 1 together with the corresponding values from WG.

The quite close agreement between the experimental and the mass table values for ^{92}Zr is not surprising since the experimental Q-value for the capture reaction used in the normalization of our results is also the primary datum (with the smallest uncertainty in this mass region) utilized by WG in their mass adjustment. A reasonable agreement is also found between our experimental separation energies of ^{90}Zr and ^{91}Zr and those from the 1971 mass evaluation. Our value for S_n in ^{91}Zr however is 40.3 keV higher than the experimental value of 7158.3 ± 1.5 keV reported by Groshev et al. [6].

A considerable discrepancy is found between our experimental separation energies and the tabulated ones for ^{94}Zr and ^{96}Zr, indicating that some of the tabulated masses in this region may be in error. In the case of $S_n(^{94}\mathrm{Zr})$ the questionable mass appears to be that of ^{93}Zr. In fact, in WG the best primary datum relating this nuclide to its neighbours, namely $Q_\beta(^{93}\mathrm{Zr} \rightarrow {}^{93}\mathrm{Nb}) = 63.4 \pm 2.0$ keV was later found to have been incorrectly assigned to the transition to the ground state of ^{93}Nb rather than the first-excited state at 30.4 ± 0.3 keV of excitation [7]. The adoption of the new experimental value for $Q_\beta(^{93}\mathrm{Zr} \rightarrow {}^{93}\mathrm{Nb}) = 90 \pm 3$ keV [7] should bring the tabulated value of $S_n(^{94}\mathrm{Zr})$ in close agreement with our own. As for $S_n(^{96}\mathrm{Zr})$ it also appears that the mass of the odd-A isotope is in error since while the even isotopes neighbouring ^{95}Zr had their masses based on high-precision mass spectrometer data, the Q-values

* Work partially supported by Banco Nacional do Desenvolvimento Economico, Fundação de Amparo à Pesquisa do Estado de São Paulo, and Conselho Nacional de Pesquisas.

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Table 1. Q-values for the ^{A}Zr(d, t) reactions and neutron separation energies of zirconium isotopes.

A	Q (keV) [a]	S_n^{Exp} (keV) [a]	S_n^{WG} (keV) [b]	Δ (keV) [c]
90	-5719.9 ± 1.8	11977.5 ± 1.8	11983 ± 4	-5.5
91	-941.0 ± 1.7	7198.6 ± 1.7	7202.6 ± 2.7	-4.0
92	-2377.9 ± 1.5	8635.5 ± 1.5	8635.1 ± 1.4	0.4
94	-1960.9 ± 1.9	8218.5 ± 1.9	8191 ± 5	27.5
96	-1596.5 ± 2.1	7854.1 ± 2.1	7832 ± 6	22.1

[a] This work; the experimental values for Q and Sn were normalized to a value of 8635.5 ± 1.5 keV for the neutron separation energy of ^{92}Zr (see text).
[b] Wapstra and Gove, Reference [1].
[c] $\Delta = S_n^{Exp} - S_n^{WG}$.

for the ^{96}Zr(d, t)^{95}Zr and ^{94}Zr(d, p)^{95}Zr reactions [8] used as primary data by WG had a large uncertainty of ± 20 keV.

The authors are indebted to G. Rao for the help with the data acquisition and to E. W. Hamburger and M. J. Bechara for useful discussions.

[1] A. H. Wapstra and N. B. Gove, Nucl. Data Table **A 9**, 265 [1971]; ibidem **A 11**, 127 [1972].
[2] P. L. Jolivette, J. D. Goss, G. L. Marolt, A. A. Rollefson, and C. P. Browne, Phys. Rev. **C 10**, 2449 [1974].
[3] M. J. Bechara and O. Dietzsch, Z. Naturforsch. **30 a**, 356 [1975].
[4] L. C. Gomes, O. Dietzsch, E. W. Hamburger, and G. Rao, to be published.
[5] N. C. Rasmussen, V. J. Orphan, Y. Hukai, and T. Inouye, private communication to G. A. Bartholomew et al., Nucl. Data **A 3**, 367 [1967].
[6] L. V. Groshev, L. I. Govor, and A. M. Demidov, Yad. Fiz. **15**, 625 [1972]; Sov. J. Nucl. Phys. **15**, 347 [1972].
[7] D. C. Kocher, Nucl. Data Sheets **B 8**, 527 [1972].
[8] B. L. Cohen, R. Patel, A. Prakash, and E. J. Schneid, Phys. Rev. **135**, 383 [1964].