Bull. Inst. Chem. Res., Kyoto Univ., Vol. 60, No. 2, 1982

NOTE

Activation Cross Sections of Zirconium and Molybdenum Isotopes for 14.6 MeV Neutrons

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Received March 12, 1982

About 80% of the total energy in the $D+T$ fusion is carried off by the 14 MeV neutrons. The investigations on the interaction of 14 MeV neutrons with structural materials, therefore, are very important for the design of the fusion reactor. Neutron data are needed for the calculations of tritium breeding, radiation shielding, radiation damage effects, neutron multiplication, isotope production, etc.

Zirconium and molybdenum are the expected structural materials that will be used in fusion reactors. Many workers[1] have measured activation cross sections for 14 MeV neutrons on zirconium and molybdenum. However many of their results often show gross disagreements with one another. The gross disagreement seems to result from that most previous measurements have been made with β-ray counting or with γ-ray counting by NaI (TI) detector. This drawback is obviated with the use of a Ge(Li) detector, because its high resolution available for γ-ray identification makes it possible to obtain reliable and precise cross sections. In the present paper, therefore, the (n, p), (n, α) and $(n, 2n)$ reaction cross sections on Zr and Mo have been measured at 14.6 MeV by the activation technique using a Ge(Li) detector.

Experimental procedures were similar to those of a previous investigation,[2] so that they are described only briefly here. Since values for the half-lives of the product activities of interest range from 1 min to 10 d, several samples of Zr and Mo were prepared and each of them was irradiated for periods from 1 min to 2 h, depending on the half-lives of the product activities of interest. Metal samples of about 1 gr were used. Thin Al-foils of about 50 mg were placed in the front and back of each sample. The sample and the monitor Al-foils were covered with Cd-plates of 0.5 mm thick and was then irradiated at about 9 mm behind a Ti-T neutron source.

The neutron-yield variation was monitored by counting the associated α-particles with a Si-detector. After the end of irradiation, the γ-activities of the samples together with the Al-monitor foils were measured with a 60 cm^3 coaxial Ge(Li) detector. The γ-spectra from the Ge(Li) detector were automatically stored on a magnetic tape of a USC-3 on-line computer through an ADC. The activities were identified by both their γ energies and their half-lives. Irradiations and measurements of short-lived activities such as ^{91m}Mo and ^{89m}Zr were repeated for several times in order to obtain good counting statistics.

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The $^{27}Al(n, \alpha)^{24}Na$ reaction with a cross section of 114.5 ± 4 mb[3] was used as the monitor for long-lived reaction products. The $^{27}Al(n, p)^{27}Mg$ reaction with a cross section of 68.0 ± 4.8 mb was used for short-lived reaction products. This cross section for $^{27}Al(n, p)$ reaction has been obtained in the present work.

Typical gamma decay curve is shown in Fig. 1. Table I shows the results obtained from the present work, together with the half-lives of the products, the γ-ray energies and the number of γ quanta emitted per disintegration used in the calculations of the cross sections.

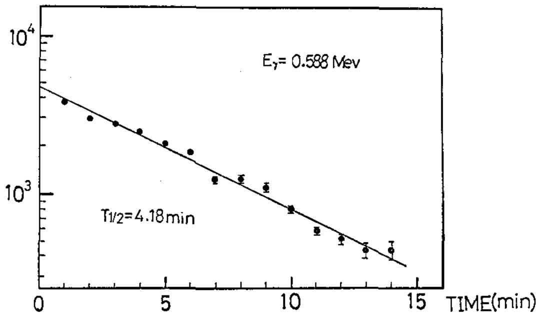

Fig. 1. Gamma decay curve of ^{89m}Zr from $^{92}Mo(n, \alpha)$ reaction

Table 1. Cross sections for (n, p), (n, α) and $(n, 2n)$ reactions with 14.6 MeV neutrons from the present work

Reaction	$T_{1/2}$	E_γ (keV)	η (%)	cross section (mb) experimental	cross section (mb) predicted
$^{90}Zr(n, p)^{90m}Y$	3.1 h	482	91	9.0 ± 0.8	
$^{91}Zr(n, p)^{91m}Y$	50.3 m	551	95	21.4 ± 2.2	
$^{92}Zr(n, p)^{92}Y$	3.53 h	934	14	20.1 ± 1.5	17.9
$^{94}Zr(n, p)^{94}Y$	20.3 m	918	73	10.7 ± 1.1	8.14
$^{92}Mo(n, p)^{92m}Nb$	10.16 d	934	99	68 ± 6	
$^{96}Mo(n, p)^{96}Nb$	23.4 h	569	59	18.1 ± 1.4	24.9
$^{97}Mo(n, p)^{97g}Nb$	72 m	665	98	19.2 ± 1.4	
$^{98}Mo(n, p)^{98}Nb$	51 m	720	75	3.6 ± 0.3	11.6
$^{90}Zr(n, \alpha)^{87m}Sr$	2.83 h	388	80	4.1 ± 0.3	
$^{94}Zr(n, \alpha)^{91}Sr$	9.67 h	1025	30	6.3 ± 0.5	3.91
$^{96}Zr(n, \alpha)^{93}Sr$	8.3 m	888	23.7	2.4 ± 0.3	2.20
$^{92}Mo(n, \alpha)^{89m}Zr$	4.18 m	588	87	5.6 ± 0.5	29.9
$^{92}Mo(n, \alpha)^{89g}Zr$	78.4 h	909	99	20.1 ± 1.6	
$^{90}Zr(n, 2n)^{89m}Zr$	4.18 m	588	87	86 ± 8	
$^{90}Zr(n, 2n)^{89g}Zr$	78.4 h	909	99	805 ± 58	
$^{92}Mo(n, 2n)^{91m}Mo$	66 s	658	54	11.8 ± 1.2	
$^{94}Mo(n, 2n)^{93m}Mo$	6.9 h	685	100	2.4 ± 0.2	
$^{100}Mo(n, 2n)^{99}Mo$	67 h	740	12	1420 ± 100	

η : Intensity of γ-rays per disintegration

The empirical formulas proposed by Levkovskii[4] are perhaps the most successful, or the most widely used formulas for predicting (n, p) and (n, α) cross sections at 14～15 MeV. However rather large discrepancies between experimental cross sections and those calculated by the Levkovskii formulas[4] for both the (n, p) and (n, α) reactions are observed for nuclei with relatively small or large values of asymmetry parameter $(N\text{-}Z)/A$ for a given values of atomic number Z. Kumabe and Fukuda[5] have reparameterized the Levkovskii formulas over three limited mass regions by carring out least-squares fits to experimental cross sections. The empirical formulas are as follows.

$$\sigma_{np}=\begin{cases} 21.8A\exp[-34(N-Z)/A] & (40\leq A\leq 62)\\ 0.75A^2\exp[-43.2(N-Z)/A] & (63\leq A\leq 89)\\ 0.75A^2\exp[-45(N-Z)/A] & (90\leq A\leq 160)\end{cases}$$

$$\sigma_{n\alpha}=\begin{cases} 51.0\sqrt{A}\exp[-30(N-Z)/A] & (30\leq A\leq 60)\\ 55.0\sqrt{A}\exp[-33\ (N-Z)/A] & (61\leq A\leq 105)\\ 7.6\times 10^{-4}A^3\exp[-40(N-Z)/A] & (106\leq A\leq 150)\end{cases}$$

The (n, p) and (n, α) cross section values predicted from above formulas are also shown in Table I. The predicted values except for ^{98}Mo(n, p) and ^{94}Zr(n, α) reactions are in fairly good agreement with the present experimental cross sections.

REFERENCES

(1) CINDA 81, An index to the literature on microscopic neutron data, (May, 1981), IAEA, Vienna.
(2) T. Sato, Y. Kanda and I. Kumabe, *J. Nucl. Sci. Technol.* **12**, 681 (1975).
(3) Y. Kanda and R. Nakasima, JAERI-1207 (1972).
(4) V. N. Levkovskii, *Sov. J. Nucl. Phys.* **18**, 361 (1974).
(5) I. Kumabe and K. Fukuda, NEANDC (J)-56/U, 45 (1978).