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N.I. Molla, M.M. Rahman, Mrs. S. Khatun, A.K.M. Fazlul Hoque,
Rahezuddin Miah and Ayesha Akhter Khan
Institute of Nuclear Science & Technology
Atomic Energy Research Establishment
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Activation Cross Sections for Some Isotopes of Mg, Ti, V, Ni, Zr and Mo at 14 MeV Neutrons.[†]

N.I. Molla, M.M. Rahman, Mrs. S. Khatun, A.K.M. Fazlul Hoque,
Rahezuddin Miah and Ayesha Akhter Khan
Institute of Nuclear Science & Technology
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Abstract:

Cross sections were measured for (n,p) reactions on ^{24}Mg, $^{46-48}Ti$, $^{58,60}Ni$, ^{90}Zr and $^{92,95-98}Mo$, (n,n'p) reactions on $^{47,48}Ti$ and ^{58}Ni; (n,α) reactions on ^{51}V and ^{92}Mo and (n,2n) reactions on ^{90}Zr and ^{100}Mo at 14.6 and 14.8 MeV by the activation technique using HPGe detector γ-ray spectroscopy. Hauser-Feshbach calculations have been performed for ^{47}Ti, $^{92,95-98}Mo$(n,p) and ^{92}Mo(n,α) reactions. The estimated values agree with the experimental cross section values within the factors of 1.5-2 except $^{97}Mo(n,p)^{97}Nb$ reaction.

Introduction:

The investigations of the interaction of fast neutrons with the potential structural materials of nuclear reactors are very important for variety of specific purposes in the development and applications of fission and fusion reactor techniques. The demands on nuclear data for fusion technology are primarily for design calculations pertaining to various areas like tritium production and breeding, nuclear heating, radiation damage, radiation shielding, etc.

The severe radiation environment in fission and fusion reactors cause radiation damage in structural materials. As a result there is an increasing demand for accurate nuclear technology design and reliable assurance of nuclear

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safety which require neutron nuclear data with high accuracy. But recent compilation on nuclear data requirements for reactor technology have shown that cross-section values for fast neutrons particularly at 14 MeV neutron energy are not known with high accuracy. Moreover, cross-section values obtained in different laboratories in many cases differ too much with one another. So the reinvestigations of the interaction of fast neutrons with the potential structural materials of nuclear reactors are now of prime importance. With this objective and in continuation of our work on 14 MeV neutron nuclear data measurements and analysis, we report here (n,2n), (n,α), (n,p) and (n,n'p) reactions cross-section measurements at 14.6 and 14.8 MeV for some isotopes of magnesium, titanium, vanadium,nickel, zirconium and molybdenum. Theoretical calculations following Hauser-Feshbach statistical model have been performed for the $^{47}Ti(n,p)^{47}Sc$, $^{95}Mo(n,p)^{95}Nb$, $^{96}Mo(n,p)^{96}Nb$, $^{97}Mo(n,p)^{97}Nb$, $^{98}Mo(n,p)^{98}Nb$ and $^{92}Mo(n,\alpha)^{89}Zr$ reactions.

Experimental:

High purity target materials ($\geq$99.99% pure) in some cases in the form of enriched samples, sealed in thin polythene bags and sandwiched between two layers of flux monitor materials, were irradiated with 14.6$\pm$0.3 MeV and 14.8$\pm$0.34 MeV neutrons. The neutrons were produced in a J-25 (AID) Neutron Generator of the Institute of Nuclear Science and Technology, AERE, Savar and 3 MeV VDG accelerator of Atomic Energy Centre, Dhaka via $^{3}H(d,n)^{4}He$ reaction.

The main operation parameters of the Neutron Generator were the following:

High Voltage — 120 KV

Beam Current — 350 μA

Beam Diameter — ~1 cm

The diameter of tritium targets (1 mm thick copper backing) was 49 mm with active layer diameter 25 mm and activity 10 Ci. The samples were placed at an angle 0^{o} to the beam direction and close to the back of the water cooled tritium target. The source to sample distance was approximately 5 mm. The sample size was 1 sq. cm and the weight varied from 0.05 gm to 0.4 gm.

The following were the source characteristics with VDG accelerator:

Deuteron beam - 0.8 MeV

Beam Current - 30 μA

Beam diameter - ~1 cm

Tritium target diameter was 25.5 mm with active diameter 14 mm and activity 10 Ci. The target backing was 0.5 mm thick copper. Samples (0.04 gm - 0.5 gm) were irradiated at an angle 70^{o} to the beam direction at a distance of 1.5 cm from the centre of the water cooled target (~1 mm water layer).

The neutron energy and its spread were estimated following Ricci[1]. The neutron flux densities were (0.8 - 4) x 10^{8} n/cm^{2}/sec and (1-6) x 10^{7} n/cm^{2}/sec respectively with neutron generator and VDG accelerator. In each measurement the neutron flux was calculated by using one of the following monitor reactions:

$^{27}Al(n,\alpha)^{24}Na$, $T_{\frac{1}{2}}$=15.08h, σ =115±3 mb and

$^{75}As(n,2n)^{74}As$, $T_{\frac{1}{2}}$=17.7d, σ =970±80 mb

The choice of the monitor reaction for determining the neutron flux depended on the half-life of the product isotope under investigation.

After irradiations the radioactivity of the reaction products was assayed by a co-axial HPGe detector (2.5 keV resolution at 1332 keV γ-ray). Gamma ray spectra were analysed in a Canberra series 40 MCA coupled with CBM 8032 Microcomputer system: The count rates at the end of irradiations were subjected to usual corrections for the dead time loss, pile up loss, efficiency of the detector, gamma transition intensities (f_d) and internal conversion coefficients (α). The correction for counting geometry was avoided by counting the samples under identical conditions to that were done for the determination of detector efficiency. Wherever necessary, before measurements of the activity of the product nuclei, sufficient cooling time was allowed for the decay of the short-lived components.

Results and discussions:

The investigated reactions, enrichment of target isotope, decay data of the product nuclei and the measured cross-sections together with the maximum

TABLE 1

Details of (n,p), (n,n'p)[a], (n,2n) and (n,α) cross-section measurement at 14.8±0.34 MeV

Reaction	Enrichment of target nuclide (%)	$T_{½}$	E_γ (keV)	I_γ (%)	Cross-section (mb)		
					This work	Literature Values	Ref.
$^{24}Mg(n,p)^{24}Na$	99.92	15.08 h	1369	100	122.8±15	181 ±8	2)
$^{46}Ti(n,p)^{46}Sc$	81.2	84 d	889	100	226.2±22.4[b]	166 ±15	2,3)
			1121	100		211.7±8.3	4)
						253 ±24	5)
						230 ±50	6)
$^{48}Ti(n,p)^{48}Sc$	73.7	43.67 h	983	100	61.1±6.7[b]	53 ±6	2)
			1038	100		71.7±2.6	4)
			1312	100		66	7)
						80 ±4	8)
$^{48}Ti(n,n'p)^{47}Sc$	99.25	3.42 d	159	73	13.7±3.9	9 ±2	2,3)
						11.52±0.51	4)
						16 ±2	5)
						14	7)
$^{90}Zr(n,p)^{90m}Y$	51.4	3.19 h	203	97	14.9±2.5[c]	8 ±1	2)
			480	91		9 ±0.8	9)
						12.9±1	10)

$^{97}Mo(n,p)^{97}Nb$	9.5	74 m	665	98	18.2±1.7[c]	14 ±1.8	2)
						11.5±2.4	11)
						17.7±1.5	12)
						19.2±1.4	9)
						14.6±1.2	13)
						8.5±1	10)
$^{98}Mo(n,p)^{98}Nb$	24.4	51 m	720	75	4.2±0.55	2.6±0.7	2)
			787	100		5.2±0.6	7)
						6.7±0.6	12)
						10 ±1.2	14)
						3.6±0.3	9)
						4.1±0.5	10)
$^{90}Zr(n,2n)^{89}Zr$	51.4	78.4 h	910	99	824±78.3	768 ±78	2)
						517 ±47	15)
						805 ±58	9)
$^{100}Mo(n,2n)^{99}Mo$	96.1	66 h	740	12	1418±175	1390 ±60	2)
						1700 ±140	16)
						1389 ±84	17)
						1420 ±100	9)
						1510 ±180	12)
$^{51}V(n,\alpha)^{48}Sc$	99.75	43.67 h	983	100	7.7±1.3	16 ±1	2)
			1038	100		16.1±0.9	8)
			1312	100		21 ±1	18)

a) (n,d) + (n,n'p)+ (n,pn) reaction cross section.
b) Contribution from the (n,n'p) reaction on the neighbouring heavier mass target nucleus subtracted.
c) Includes small contribution of (n,n'p) reaction from the neighbouring heavier mass target nucleus.

TABLE 2

Details of (n,p), (n,n'p)[a] and (n,α) cross-section measurement at 14.6±0.3 MeV

Reaction	Enrichment of target nuclide (%)	Decay data of product nuclides			Cross-section (mb) This work		Literature Values	Ref.
		$T_{1/2}$	E_γ (keV)	I_γ (%)	Measured value	Calculated value		
$^{47}Ti(n,p)^{47}Sc$	68.5	3.42 d	159	73	174.5±13.1[b]	268.0	169.5±6.9	4)
							116 ±14	19)
							114 ±7	5)
							99 ±20	20)
$^{47}Ti(n,n'p)^{46}Sc$	68.5	84 d	889	100	49.7±8.4		55.9±2.3	4)
			1121	100			36 ±4	21)
$^{58}Ni(n,p)^{58}Co$	68.27	70.8 d	811	100	397 ±35.7		338 ±26	22)
							375 ±22	2)
$^{58}Ni(n,n'p)^{57}Co$	68.27	271.3 d	122	85	570 ±49.0		659 ±49	23)
			136	10.6			373 ±20	22)
							526 ±45	24)
$^{60}Ni(n,p)^{60}Co$	26.10	5.26 Y	1173	99.89	144.7±18		171 ±14	23)
			1332	99.98			122 ±12	3)
							112 ±9	6)
							134 ±11	22)
$^{92}Mo(n,p)^{92m}Nb$	14.84	10.15 d	934	99.2	65.9±5.8	88.8	71.8±5.7	22)
							60 ±15	25)
							56.5±4.8	11)
							60.5±4.5	26)

$^{92}Mo(n,\alpha)^{89}Zr$	14.84	78.4 h	909	99	27.3±3.7	18.9	22.5±2.1 25 18.7±1.5 22 ±3 <25 ±3	11) 12) 17) 26) 24)
$^{95}Mo(n,p)^{95}Nb$	15.9	34.97 d	766	99.8	34.4±2.8[c,d]	14.57	41.1±3.6 31 ±3.6 44.8±3.5 37 ±6	11) 24) 22) 26)
$^{96}Mo(n,p)^{96}Nb$	96.76	23.35 h	569	55.66	14.0±1.6	7.4	20.8±2.1 19.0±4 19.2±2.1 16.0±3 12.0±2	11) 26) 24) 12) 14)
$^{97}Mo(n,p)^{97}Nb$	9.5	74 m	658	98.2	21.3±1.7[d]	2.64	11.5±2.4 17.7±1.5 11.7±2.3 14.6±1.2	11) 12) 26) 24)
$^{98}Mo(n,p)^{98}Nb$	24.13	0.85 h	787	93.2	3.26±0.3	1.81	5.2±0.6 6.7±0.6 2.6±0.7 10.0±1.2	11) 12) 26) 14)

a) (n,d) + (n,n'p) + (n,pn) reaction cross-section

b) Contribution from the (n,n'p) reaction on the neighbouring heavier mass target nucleus substracted

c) Contribution from $^{98}Mo(n,\alpha)^{95}Zr$ reaction (via β^--decay of ^{95}Zr) not subtracted

d) Includes small contribution of (n,n'p) reaction from the neighbouring heavier mass target nucleus

TABLE 3

Principal sources of error and their magnitudes (%) considered in the cross-section results

Sources of uncertainty	Magnitude (%)
Sample weight	0.5
Irradiation time	0.5
Irradiation geometry	3
Correction for absorption and scattering of neutrons in the sample	3
Correction for activity induced by background neutrons	1
error in neutron flux	5
Determination of detector counts	1-5
Absorption of gamma rays in the sample	1
Efficiency of the detector	3
Decay data	1

errors are given in table 1 and 2. Each value is based on two to three independent measurements and the quoted error includes statistical and systematic errors. The uncertainities in the cross-section values have been obtained by combining all the estimated random and systematic errors in quadrature. The principal sources of systematic errors considered are given in table 3. For each reaction the recent literature values[2-26] are also given in table 1 and 2.

Statistical model calculation:

In the present work, the emphasis is focussed on the experimental measurements at 14.6 and 14.8 MeV via activation technique. However, theoretical estimation of cross-sections for ^{47}Ti, $^{92,95-98}Mo(n,p)$ and $^{92}Mo(n,\alpha)$ reactions following Hauser-Feshbach statistical model[27,28] calculations have been done using the computer code HELGA at our IBM-4341 computer. A unified set of optical model parameters[29-33] were used in the transmission coefficients calculations.

The composite level density formula of Gilbert and Cameron[34] was used to obtain the energy levels in the continuum region. Cross-sections were calculated for all the discrete levels fed and in the continuum region the calculations were done in energy steps of 0.1 MeV upto the maximum excitation energy of the final nucleus. In the computation six reaction channels, e.g. (n,n'), (n,p), (n,d), (n,t), (n,^{3}He) and (n,^{4}He), were considered and it was also assumed that following the emission of the first particle, if energetically possible, emission of second and third neutrons occurred from the produced nucleus. Gamma rays or charged particles were not included in the second stage decay channels. The calculated values are shown in table 2 along with the experimental results. They agree with the experimental cross-sections results within the factors of 1.5 to 2 except ^{97}Mo(n,p)^{97}Nb reaction where the calculated value is much lower.

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