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Cross-sections of a few (n, α) and (n, p) reactions induced at 14·7 MeV neutrons

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Abstract. Cross-sections of the nuclear reactions $^{27}Al(n,p)^{27}Mg$, $^{30}Si(n,\alpha)^{27}Mg$, $^{52}Cr(n,p)^{52}V$, $^{53}Cr(n,p)^{53}V$, $^{54}Cr(n,p)^{54}V$, $^{54}Cr(n,\alpha)^{51}Ti$ and $^{120}Sn(n,\alpha)^{117}Cd$ at 14·7 Mev neutrons were measured using $^{56}Fe(n,p)^{56}Mn$ and $^{27}Al(n,\alpha)^{24}Na$ as monitor reactions. For comparison, theoretical values of the cross-section for these reactions were also obtained through different approaches of compound nucleus theory and computer code Alice. Accuracies achieved in the present measured values of the cross-sections are better than those available in literature.

Keywords. Nuclear reactions; 14·7 MeV neutrons; activation cross sections; gamma activity; enriched isotopes; HPGe detector.

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1. Introduction

Since the last few decades considerable work has been carried out in the fields of measurement and analysis of cross-sections of nuclear reactions induced at 14 MeV neutrons. This work includes measurements made to generate new data as well as remeasurement to improve accuracies in the reported values. However, in several cases values of cross-sections for a nuclear reaction reported by several authors do not match with each other and as such large discrepancies exist in the literature values. One of the examples is $^{29}Si(n,p)^{29}Al$ reaction, for which the reported values of the cross-sections by different workers are 101 ± 30 mb (Paul and Clarke 1953), 130 ± 16 mb (Ranakumar *et al* 1968) and 115 ± 15 mb (Body and Csikai 1987) and such several examples can be found in literature. With the availability of high efficiency HPGe detectors, modern data acquisition systems, nuclear electronics modules, etc., in addition to precisely known values of cross-sections of nuclear reactions suitable for monitoring neutron flux (Body and Csikai 1987) it has become possible to measure values of cross-section with accuracies much better compared to those obtained a few decades ago. Looking at the importance of the cross-section data, the International Nuclear Data Committee in its report (INDC 1984) recommended measurement of cross-sections of several nuclear reactions at 14 MeV neutron energy. Based on these recommendations, we have measured cross-sections of a few (n, α) and (n, p) reactions.

2. Experimental

Enriched isotopes of elements were used and cross-section for each nuclear reaction was measured separately using $^{27}Al(n,\alpha)^{24}Na$ and $^{56}Fe(n,p)^{56}Mn$ as monitor nuclear reactions (Body and Csikai 1987). For all the samples, the induced gamma-ray activities were measured with a HPGe (30%) detector coupled to a 4096 channel analyser. In a few cases, use of NaI(Tl) was also made to confirm values of the measured cross-sections. The experimental procedure adopted with each monitor reaction was slightly different owing to large difference in the half-lives of the ^{24}Na(15·02 hours) and ^{56}Mn(2·578 hours). For $^{120}Sn(n,\alpha)^{117}Cd$ reaction, powders of Sn-120 and Fe-56, each of 5 mg by weight, were mixed and packed in a polyethylene vial and such three samples were prepared. Each sample was irradiated for 2·5 hours and the induced gamma-ray activities due to ^{117}Cd and ^{56}Fe were measured for 2·5 hours. Similar experiment was repeated by irradiating 5 mg of Sn-120 powder in an aluminium foil ($\sim$ 5 mg) for a period of three hours. The gamma-ray activities due to ^{117}Cd and ^{24}Na were measured for a period of three hours. For $^{30}Si(n,\alpha)^{27}Mg$ and $^{27}Al(n,p)^{27}Mg$ reaction similar experimental procedure was adopted except that the periods of irradiation and counting, were kept 30 min with Fe-56 and 40 min with Al-27. In case of $^{27}Al(n,p)^{27}Mg$ the aluminium foil used for neutron flux monitor also served as sample. For $^{54}Cr(n,p)^{54}V$ reaction, a small quantity ($\sim$ 5 mg) of Fe-56 powder was kept near the irradiation head and was continuously irradiated with 14 MeV neutron for a period of 2·5 hours. The vial containing Cr-54 powder was carried to the irradiation head and back to the detector by a pneumatic transfer system. The sample was irradiated for three minutes and its induced activity was also measured for a period of three minutes. Three such samples were irradiated in sequence, so that in turn the activity of the first sample could decay during the total waiting time of seven minutes which is around ten half lives of the ^{54}V. The induced gamma activities for each sample, for ten activation cycles, was measured and recorded in different memory locations of the multichannel analyser. At the end of 2·5 hours of total irradiation period, the neutron flux was measured from the activity of ^{56}Mn.

Table 1. Details of the (n,α) and (n,p) nuclear reactions and activation cycles.

			Time of irradiation		Time of counting		No. of cycles	
Nuclear reaction	Half life	Energy (MeV)	Al-27 monitor	Fe-56 monitor	Al-27 monitor	Fe-56 monitor	Al-27 monitor	Fe-56 monitor
$^{27}Al(n,p)^{27}Mg$	9·46 min	0·84	40 min	30 min	40 min	30 min	3	5
$^{30}Si(n,\alpha)^{27}Mg$	9·46 min	1·013	40 min	30 min	40 min	30 min	5	5
$^{52}Cr(n,p)^{52}V$	3·76 min	1·434	10 min	10 min	10 min	10 min	10	10
$^{53}Cr(n,p)^{53}V$	1·60 min	1·0	5 min	5 min	5 min	5 min	10	10
$^{54}Cr(n,p)^{54}V$	43·0 s	0·84	3 min	3 min	3 min	3 min	25	25
$^{54}Cr(n,\alpha)^{51}Ti$	5·79 min	0·32	15 min	15 min	15 min	15 min	10	10
$^{120}Sn(n,\alpha)^{117}Cd$	2·40 h	0·434	3·0 h	2·5 h	3·0 h	2·5 h	3	5
			Monitor reactions					
$^{27}Al(n,\alpha)^{24}Na$	15·02 h	1·369	—	—	—	—	—	—
$^{56}Fe(n,p)^{56}Mn$	2·578 h	0·84	—	—	—	—	—	—

Later on Fe-56 was replaced by aluminium foil and the experiment was repeated for a total irradiation period of 4 hours. Similar procedure was adopted to measure cross-section of the reaction $^{52}Cr(n,p)^{52}V$, $^{53}Cr(n,p)^{53}V$, and $^{54}Cr(n,\alpha;^{51}Ti$. The details of the activation cycle used for each nuclear reaction are given in the table 1.

3. Calculations

The cross-section of the reactions were estimated following the method reported earlier (Amemiya *et al* 1981) and the results are shown in table 2. Errors for the measured cross-sections are the root mean square values comprised of uncertainty in estimation of gamma activity under the photopeak, relative detection efficiency, sample weight and time measurements. The correction due to self absorption in the sample was neglected because of small quantity of the sample powder.

The theoretical estimation of the cross-sections was carried out following the method given by Wadhwa and Mohindra (1975). These calculations are based on optical model potential parameters for proton and neutron penetrabilities given by Mani *et al* (1963). The α-induced inverse reaction cross-sections were obtained from literature (Huizenga and Igo 1962). The level densities were calculated using the Lang-LeCouteur and Newton's shell dependent formulae and corrections for pairing and shell were also applied. The Q values for the nuclear reactions were obtained from an earlier reported data (Wapstra and Bos 1977). For comparison, the cross-section values were also estimated using computer Alice Livermore-82 Code, which is a revision of the Alice (Blann and Plasil 1973) and Overlaid Alice (Blann 1975) codes. This code accounts for precompound, compound/statistical calculations in general frame work of the Weisskopf Ewing evaporation model (1940) and hybrid/geometry dependant hybrid model for precompound decay. In addition the cross-sections were also estimated using the evaporation approximation (Cuzzocrea *et al* 1971).

4. Results and discussion

Table 2 shows the measured as well as theoretically estimated values of cross-sections for three (n,α) and four (n,p) reactions. The results shown in the table 2 indicate that theoretically estimated values of cross-sections using Lang-LeCouteur level density formula are close to the corresponding experimental values except for the $^{27}Al(n,p)^{27}Mg$ reaction. For the reaction $^{30}Si(n,\alpha)^{27}Mg$ and $^{53}Cr(n,p)^{53}V$ in which the product nuclei have odd number of nucleons, results obtained with pairing corrections are close to the corresponding experimental values. For $^{52}Cr(n,p)^{52}V$ and $^{54}Cr(n,p)^{54}V$, where both the parent and daughter nuclei have even number of nucleons, the results obtained without pairing corrections are close to the experimental values. However for $^{54}Cr(n,\alpha)^{51}Ti$ reaction though the product nucleus has odd number of nucleons, the theoretical values of the cross-section estimated using both Lang–LeCouteur and Newton's shell dependent level density formulae without pairing corrections are close to the corresponding experimental value. Cross section value obtained for $^{27}Al(n,p)^{27}Mg$ reaction with evaporation model is in agreement with the experimental value.

For the reaction $^{120}Sn(n,\alpha)^{117}Cd$ the experimental values of the cross-section are

Table 2. Experimental and theoretical values of the cross-sections of the nuclear reactions induced at 14·7 MeV neutrons.

	Experimental cross-section		Compound nucleus theory							
	with monitor reaction		Lang-LeCouteur level density formula		Newton's shell dependent level density formula		Alice code equilibrium		Evaporation approximation (mb)	Earlier reported values (experimental) (mb)
Nuclear reaction	$^{27}Al(a,\alpha)^{24}$ (mb)	$^{56}Fe(n,p)^{56}Mn$ (mb)	without pairing (mb)	with pairing (mb)	without pairing (mb)	with pairing (mb)	without pairing (mb)	with pairing (mb)		
$^{27}Al(n,p)^{27}Mg$	$68 \pm 2·0$	$66 \pm 2·0$	80·0	94·0	53·8	58·4	103·0	112·0	73·0	$75·0 \pm 4$ (c)
$^{30}Si(n,\alpha)^{27}Mg$	$81 \pm 5·0$	$85 \pm 5·1$	72·0	83·0	74·0	93·0	30·0	40·0	93·0	$89·0 \pm 27$ (c)
$^{52}Cr(n,p)^{52}V$	$93 \pm 6·0$	$91 \pm 6·0$	88·5	115·7	110·7	142·2	49·0	62·0	135	$80·0 \pm 6$ (c) $102·0 \pm 20$ (c)
$^{53}Cr(n,p)^{53}V$	$48 \pm 6·0$	$46 \pm 5·0$	32·2	50·0	28·1	33·0	16·2	20·4	30	$48·0 \pm 7$ (c) $43·0 \pm 5$ (c)
$^{54}Cr(n,p)^{54}V$	$17 \pm 2·0$	$18 \pm 2·0$	17·3	19·7	20·4	23·8	18·5	23·0	25	$18·0 \pm 3$ (c) $16·0 \pm 3$ (c)
$^{54}Cr(n,\alpha)^{51}Ti$	$27 \pm 2·0$	$28 \pm 2·0$	32·0	41·0	26·0	34·0	12·0	14·0	37·0	$12·4 \pm 3·7$ (c)
$^{120}Sn(n,\alpha)^{117}Cd$	$2 \pm 0·2$	$1·8 \pm 0·3$	2·12 (a) 0·01 (b)	1·96 (a) 0·01 (b)	0·001	0·01	0·01	0·01	0·20	—

(a) Parameter $\delta = 10/A$; (b) Parameter $\delta = 7·9/A$; (c) Body and Csikai 1987.

2 ± 0.2 mb and 1.8 ± 0.3 mb measured using Al-27 and Fe-56 as neutron flux monitor. Theoretically estimated values using different models vary in the range of 0·01 mb to 0·02 mb. We have found that if value of the parameter 'δ' in the following Lang–LeCouteur level density formula (Mohindra and Hans 1963)

$$\frac{1}{W_0} = D_0 = 0.11\, A^2 (U + t)^2 \exp - \{2(AU/11)1/2 + (3/32)(11U)^{2/3}\} \quad (1)$$

where

$$t = (10.5U/A)^{1/2} - \delta \quad (2)$$

is changed from $7.9/A$ to $10/A$, the theoretical cross-section value of the reaction $^{120}Sn(n,\alpha)^{117}Cd$ comes to 2·12 mb without pairing corrections and 1·96 mb with pairing corrections. Variations in the value of 'δ' from $7.9/A$ to $13.3/A$ have been recommended (Vogel *et al* 1983) to match the cross-section value. Alice code-82 values are however not matching with any of the measured values of the cross-sections.

Efforts were made to minimize error in measurement of each parameter because of that the measured value of each cross-section has error smaller than reported earlier (table 2). This was achieved due to use of enriched isotopes, accurately known value of cross-section of the monitor reaction, cyclic irradiation and activity measurement, precise control in operational parameters of the 14 MeV neutron generator, and electronic control for activation cycles. Error in each cross-section was estimated by accounting errors in all the experimentally measurable parameters. For example in the measured value of the cross-section of $^{27}Al(n,p)^{27}Mg$ the error is ± 2 mb. This error is based on the percentage error in activity 0·7%, half life 0·1%, weight of the sample 0·002%, time of irradiation and counting 0·05% and neutron flux 1·42%. Similar approach was adopted for other measured values of cross-sections.

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