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Pre-equilibrium emission effect in (n,p) reaction cross-sections at 14·8 MeV

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Abstract. The influence of pre-equilibrium emission on (n, p) reaction cross-sections at 14·8 MeV has been studied. Cross-sections for (n, p) reactions have been measured by the activation technique at $14{\cdot}8 \pm 0{\cdot}5$ MeV neutron energy. The experimental cross-section values have been compared with the calculated values at 14·8 MeV with and without considering the pre-equilibrium emission. Equilibrium calculations have been performed according to the statistical model of Hauser and Feshbach while the hybrid model has been used to include the pre-equilibrium contribution. Pre-equilibrium emission has been considered only in the first emission step. The comparison of experimental and calculated values clearly indicates the presence of pre-equilibrium emission.

Keywords. (n,p) reactions; measured values; equilibrium and pre-equilibrium calculations.

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1. Introduction

Pre-equilibrium processes play an important role in nuclear reactions induced by neutrons of few MeV (< 50 MeV). Taking into account pre-equilibrium decay, it is possible in general to achieve a better understanding and description of these processes.

Since a large number of experimental measurements of (n, p) reaction cross-sections have been performed around 14 MeV incident neutron energy, it has been observed that there is a large discrepancy between the cross-section values of the same reaction reported by different groups of workers. It has also been observed that unless reliable cross-section measurements using the same technique and the standard reaction are available for a large number of target nuclei, it is not possible to study the trends in the values of reaction cross-sections. With this view a programme of cross-section measurements by the activation technique has been undertaken. The cross-section values have also been calculated theoretically using equilibrium and pre-equilibrium emission models. Experimental and calculated (n, p) reaction cross-sections at 14·8 MeV have been compared. It has been observed that the inclusion of pre-equilibrium emission in the calculations gives better agreement with the experimental ones.

2. Experimental procedure

Reaction cross-sections for 18 nuclei have been measured using the activation technique. The 130 keV deuteron beam of the Cockcroft Walton accelerator of our

laboratory bombarded a thin tritium target to obtain 14·8 MeV neutrons. The samples have been prepared in thin perspex rings sandwiched between two cellulose tapes using spectrascopically pure substances of chemical purity more than 99·9 %. By following activities induced in samples due to neutron bombardment, cross-sections responsible for these activities can be determined. In actual irradiation, various activities due to different reactions were induced in the samples. The residual nuclei of different reactions generally decay with different half-lives. The decay of the irradiated samples were, therefore, followed for sufficiently long times to obtain complete decay curves. Separated decay curves have been extrapolated to get the counting rates ($C_{t=0}$) at zero time after the irradiation. From the observed counting rates at zero time, cross-sections for different reactions (σ_r) have been calculated using the following expression (Gupta 1983).

$$\sigma_r = \frac{C_{t=0}}{G \times \phi \times \varepsilon \times N_0 \times [1 - \exp(-\lambda t_e)]}$$

where, G is the geometrical efficiency of detection, ε is the efficiency of the detector system, ϕ is the incident neutron flux, N_0 is the number of target nuclei in the sample and t_e is the time of irradiation. λ being the decay constant of the induced activity.

The incident neutron flux has not been determined directly, but instead the value of the effective neutron flux ($\phi \times G$) has been determined in each case from the intensity of the activity induced in the standard iron samples due to ^{56}Fe (n, p) ^{56}Mn reaction. The cross-section for the standard ^{56}Fe (n, p) ^{56}Mn reaction has been taken as 102 mb. This value is the weighted average of many reported values (Terrel and Halm 1958; Kern *et al* 1959; Bormann *et al* 1962; Banozzola *et al* 1964; Santry and Butler 1964; Liskien and Paulsen 1965; Hemingway *et al* 1966; Barrell *et al* 1969; Cuzzocrea *et al* 1971; Molla and Qaim 1977). In general, two standard iron samples, one on each side of the unknown sample, have been irradiated simultaneously. All the three samples were then studied by the same detector in identical geometry to keep the geometrical efficiency of irradiation and counting same for all cases including those of the standard samples. Iron as a standard has many advantages. It has a flat excitation function around 14 MeV. As the cross-section for the reaction ^{56}Fe (n, p) ^{56}Mn around 14 MeV is quite large, it gives strong activity even for irradiations of short duration. Moreover, the reaction produces a nearly pure activity of 2.56 hr which could be studied both by the β-particle and γ-ray counting. Thus measurements have been done for all cases in which the residual nucleus of the reaction decays by either the beta and/or γ-emission using the same standard reaction. Activities induced in various samples have been followed by the end-window β-counter and/or by γ-ray scintillation spectrometer. In cases where the residual nucleus decays through β-particles of different energies, the detection efficiency, ε, can be calculated by the relation

$$\varepsilon = a \exp(-\mu_1 d) + b \exp(-\mu_2 d) + c \exp(-\mu_3 d) + \ldots$$

where, $a, b, c \ldots$, etc. are the fractions of β-particles of end-point energies E_1, E_2, $E_3 \ldots$ etc., $\mu_1, \mu_2, \mu_3 \ldots$, etc. are respectively their mass absorption coefficients and d the average thickness (in mg/cm^2) which the β-particle has to travel before entering the counter. In the γ-ray spectrometer, the efficiency is given by the multiplication of the photo-peak efficiency, detection efficiency and the absorption correction. The decay data have been taken from the literature (Lederer *et al* 1978; Nuclear Data Sheets).

3. Results and discussion

The investigated (n, p) reactions, their Q-values and the measured cross-section values are given in table 1. Cross-sections for these reactions have been measured by many workers and the values reported by different groups differ much from each other. To give an idea of the dispersion in the measured values, the maximum and the minimum reported cross-section values for each reaction are listed in table 1. As has been stated, these discrepancies may partly be due to the different techniques adopted by different workers.

The (n, p) cross-sections for the cases presently measured have also been calculated theoretically using two options: (a) pure compound reaction mechanism (denoted by $\sigma_{\text{cal. CN}}$) and (b) with the compound plus pre-compound according to the hybrid model (denoted by $\sigma_{\text{cal. CN + pre}}$).

The pure compound calculations have been performed according to the statistical model of Hauser and Feshbach (1952). For the pre-compound emission the hybrid model (Blann 1971; Blann and Mignerey 1972) option has been chosen. Pre-equilibrium emission has been considered only in the first emission step where the excitation energy is sufficiently large. In these calculations conservation of the parity and angular momentum has been explicitly considered at each step of de-excitation. A computer code on lines of STAPRE (Uhl and Strohmaier 1976, private communication)

Table 1. Results of the (n, p) reaction cross-sections at 14.8 MeV neutron energy.

Reactions	Q-value (MeV)	Measured $\sigma(n,p)$(mb)	Calculated $\sigma_{\text{cal.CN}}$ (mb)	Calculated $\sigma_{\text{cal.CN + pre}}$ (mb)	Literature value $\sigma_{\max}$ (mb)	Literature value $\sigma_{\min}$ (mb)
^{24}Mg $(n,p)^{24}$Na	−4·74	180 ± 20	205·0	188·0	191 ± 40[a]	110 ± 16[b]
^{25}Mg $(n,p)^{25}$Na	−3·023	45 ± 8	18·7	42·6	63 ± 10[b]	40 ± 4[c]
^{27}Al $(n,p)^{27}$Mg	−1·798	76 ± 12	38·3	70·0	132 ± 10[d]	52 ± 10[a]
^{34}S $(n,p)^{34}$P	−4·31	75 ± 8	70·5	70·5	85 ± 40[a]	73 ± 7[c]
^{37}Cl $(n,p)^{37}$S	−4·087	28 ± 5	11·4	24·4	41 ± 4[e]	21·3 ± 3[f]
^{41}K $(n,p)^{41}$Ar	−1·74	53 ± 4	42·0	51·0	88 ± 18[d]	48 ± 10[g,h]
^{48}Ti $(n,p)^{48}$Sc	−3·19	60 ± 5	47·0	59·0	93 ± 33[a]	53 ± 6[i]
^{49}Ti $(n,p)^{49}$Sc	−1·23	40 ± 7	19·5	33·5	97 ± 16[d]	23 ± 5[i]
^{50}Ti $(n,p)^{50}$Sc	−5·65	20 ± 5	13·0	15·0	147 ± 13[d]	9 ± 3[j]
^{51}V $(n,p)^{51}$Ti	−1·68	38 ± 4	14·5	37·0	55 ± 12[g]	20 ± 7[b]
^{52}Cr $(n,p)^{52}$V	−3·19	88 ± 6	144·0	112·0	118 ± 16[e]	74 ± 10[b]
^{56}Fe $(n,p)^{56}$Mn	−2·92	100 ± 6	86·0	97·0	109 ± 10[k]	82 ± 7[b]
^{65}Cu $(n,p)^{65}$Ni	−1·35	21 ± 2	15·0	22·2	31 ± 13[l]	11 ± 1[m]
^{64}Zn $(n,p)^{64}$Cu	+0·21	171 ± 13	220·2	151·0	386 ± 60[a]	160 ± 12[i]
^{66}Zn $(n,p)^{66}$Cu	−1·84	74 ± 6	51·0	68·0	101 ± 17[a]	35 ± 4[b]
^{75}As $(n,p)^{75}$Ge	−0·42	35 ± 3	12·2	29·0	29 ± 2.5[i]	12 ± 2[a]
^{88}Sr $(n,p)^{88}$Rb	−4·41	15 ± 2	1·1	16·3	30 ± 2[n]	13.5 ± 1.5[i]
^{109}Ag $(n,p)^{109}$Pd	−0·369	14 ± 2	5·5	15·3	15 ± 2[o]	10.5 ± 2[p]

[a] Paul and Clarke (1953); [b] Allan (1961); [c] Borman *et al* (1967); [d] Khurana and Hans (1959); [e] Khurana and Govil (1965); [f] Mitra and Ghose (1966); [g] Bramlitt and Fink (1963); [h] Bormann and Lammers (1969); [i] Molla and Qaim (1977); [j] Koehler and Alford (1964); [k] Dyer and Hamilton (1972); [l] Scalan and Fink (1958); [m] Butler and Santry (1961); [n] Strohal *et al* (1962; [o] Levkovskii *et al* (1969); [p] Dzantiev *et al* (1957).

has been developed for these calculations. The code is designed to calculate energy-averaged cross-sections for particle induced reactions. This is based on the statistical compound nucleus model with the consideration of angular momentum and parity conservation. The code considers the evaporation of up-to six particles in sequence and intermediary γ-ray cascades. The code also includes the process of pre-equilibrium decay at the first evaporation step. The hybrid model has been used for the description of pre-equilibrium emission of particles. A detailed description of the parent code is given in report no. IRK 76/01 published by NEA data bank.

The results of calculations depend on many parameters. In the pure compound calculations the value of level density parameter a and the fictive ground state energy Δ for all nuclei have been taken to be consistently equal to that given by Dilg *et al* (1973). It has been observed that the calculated (n, p) cross-section values fail to reproduce measured values with pure compound calculations. As such, there is need to include some other reaction mechanisms for a better agreement between theory and experiment. Pre-equilibrium process is then added to compound nucleus process. In the pre-compound calculations the value of the average squared matrix element $|M|^2$ is

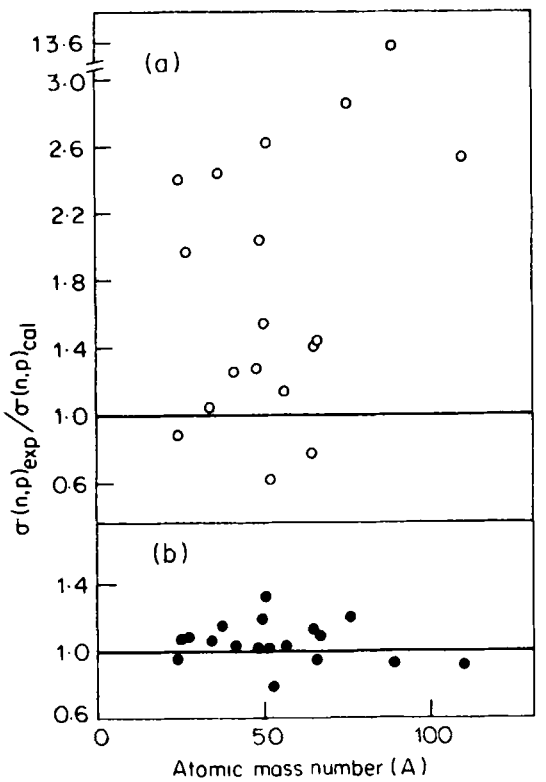

Figure 1. Comparison between experimental and calculated (n, p) cross-sections $[(\sigma(n, p)_{exp})/(\sigma(n, p)_{cal})]$ vs atomic mass number of the target nucleus at 14.8 MeV. **a.** Calculations based on equilibrium statistical theory only. **b.** Calculations include pre-equilibrium emission.

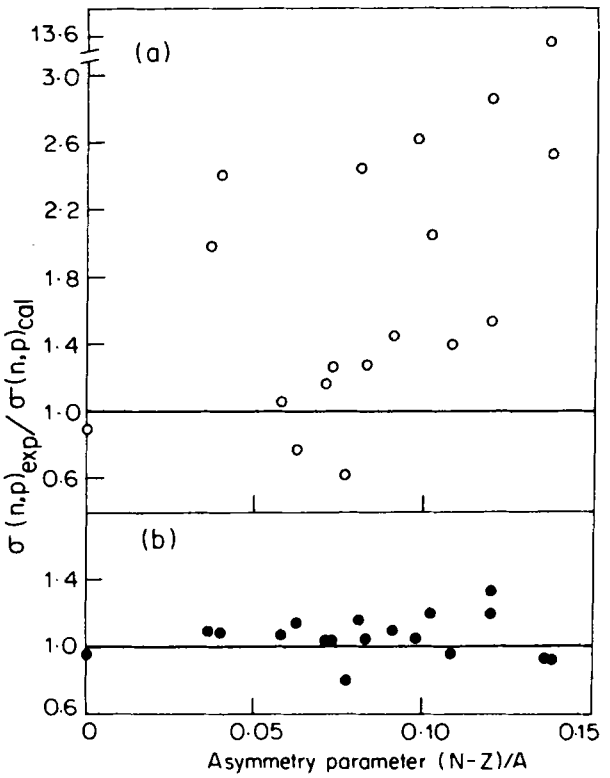

Figure 2. Comparison between experimental and calculated (n, p) reaction cross-sections $[(\sigma(n, p)_{exp})/(\sigma(n, p)_{cal})]$ vs asymmetry parameter of the target nucleus at 14.8 MeV. **a.** Calculation based on equilibrium statistical theory only. **b.** Calculations include the pre-equilibrium emission.

required, it depends sensitively on details of the employed model. The expression

$$|M|^2 = FM A^{-3} E^{-1}$$

proposed by Cline (1973) has been used. In the present calculations FM has been kept as an adjustable parameter to get a better agreement between calculated and measured values of (n, p) reaction cross-sections. In literature, FM values vary from 95 to 7000 MeV^3 (Gudima *et al* 1983). In the present analysis, the best value of FM has been found to be 430 MeV^3, which reproduces the experimental data.

The calculated $\sigma(n, p)_{cal.CN}$ and $\sigma(n, p)_{cal.CN+Pre}$ for 18 nuclei have been listed in columns 4 and 5 of table 1. The ratio

$$\frac{\sigma(n, p)_{exp.}}{\sigma(n, p)_{cal.CN}} \quad \text{and} \quad \frac{\sigma(n, p)_{exp}}{\sigma(n, p)_{cal.CN+Pre}}$$

have been plotted against atomic mass number A and asymmetry parameter $(N - Z)/A$ (figures 1 and 2). It is interesting to see from these figures, except for ^{24}Mg, ^{52}Cr and ^{64}Zn, that the measured cross-sections are higher than their values calculated without consideration of pre-equilibrium emission (figures 1a and 2a). The higher values of the

ratio $(\sigma(n, p)_{exp})/(\sigma(n, p)_{cal.\ CN})$ suggest the presence of some reaction mechanisms, apa from the compound nucleus process, through which the emission of proton is taking place, the ratio $(\sigma(n, p)_{exp})/(\sigma_{cal.\ CN+Pre})$ is also plotted in figures 1 and 2 against A and $(N-Z)/A$ (figures 1b and 2b). As can be seen now the points in these figures lie quite close to unity. This better agreement between the experimental and calculated cross-section values in the latter case strengthens the presence of pre-equilibrium emission process.

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