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EMPIRICAL FORMULAE FOR 14.5 MeV (n,p) CROSS SECTIONS

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Abstract

Six empirical formulae of the (n,p) cross sections for 14.5-MeV neutrons were obtained with respect to even and odd (N-Z) values, depending on the effective Q-Value, the Coulomb barrier height, the threshold and incident neutron energies and the mass number of the target. These formulae were compared with the experimental values. The present calculations fit the experimental results quite well compared to those predicted by the previous workers.

I. Introduction

In general it is quite difficult to measure cross sections of the nuclei with short half-lives. The reliable cross sections of some isotopes are required, especially if the isotopes are formed by neutron fluxes on the order of those found in power reactor cores. There were some discrepancies among the experimental cross sections of 14.5-MeV (n,p) reactions. Therefore empirical cross section equations were required to derive reliable cross sections of some nuclei especially for high energy neutrons. Therefore, in the present study, the experimental cross sections of 14.5-MeV (n,p) reactions were investigated in relation to nuclear evaporation and pre-equilibrium processes.

The (N-Z)-dependence of the (n,p) cross sections at 14 MeV were predicted by many workers [1-6]. First, two empirical formulae were obtained with respect to the odd and even values of (N-Z) by taking the (N-Z)-dependence and L (14.5 MeV less the threshold energy) into account, allowing for experimental errors. It was found that the cross sections which were estimated by these empirical formulae gave better results compared to those in previous work. However, the results deviate from the experimental values for the nuclei with the odd mass numbers in the intermediate region (A=55-91).

The (n,p) cross sections derived by using the nuclear evaporation model have been shown to vary as an exponential function of (Q-the Coulomb barrier) [4,6]. The (n,p) reactions are also strongly dependent on A and L.

Thus, in the present work, both even and odd mass numbers were divided into three separate ranges, for each of which, an empirical cross section formula was obtained by using nuclear evaporation model statistically, as the compound process dominates in the nuclei with intermediate mass numbers and non-compound process plays some role for heavy elements, in which the pre-equilibrium process is dominant, and also there are large differences between even-even and odd nuclei.

II. The Derivation of Empirical Formulae

The (n,p) cross section can be expressed as the sum of the two reaction cross sections

$$\sigma(n,p) = \sigma^{c}_{n,p} + \sigma^{c}_{n,pn} = \sigma_R \frac{\frac{1}{\tau_p}}{\frac{1}{\tau_p}+\frac{1}{\tau_n}+\frac{1}{\tau_\alpha}} = \sigma_R \frac{\tau}{\tau_p} \quad (1)$$

In Eq. (1) σ_R is the reaction cross section, $\sigma_R = \pi r_0^2\left(A^{1/3}+1\right)^2$, where r_o is the nuclear radius constant. Also, τ_n, τ_p and τ_α are the time intervals between the heating of the nucleus and the emission of a neutron, proton or alpha particle, respectively. Finally, $\tau^{-1} = \tau_n^{-1} + \tau_p^{-1} + \tau_\alpha^{-1}$.

τ_n^{-1} and τ_p^{-1} can be derived by performing the integration of the emission rate of neutron and proton for a system in an excited state

$$\tau_n^{-1} = \int_0^{Ec-Bn-\delta n=En(max)} \left(\frac{2s_n+1}{\pi^2 \hbar^3}\right) m_n E_n \sigma_n(E_n)\left[\rho_A(E_A)/\rho_C(E_C)\right] dE_n \tag{2}$$

$$\tau_p^{-1} = \int_{k_pV_p}^{Ec-Bp-\delta p=Ep(max)} \left(\frac{2s_p+1}{\pi^2 \hbar^3}\right) m_p E_p \sigma_p(E_p)\left[\rho_A(E_A)/\rho_C(E_C)\right] dE_p \tag{3}$$

where B, δ, σ, s, k_p, E_n and E_p represent respectively the particle separation energy, the odd-even energy shift, the inverse cross section for formation of a compound nucleus, the spin, a coefficient designed to reproduce barrier penetration approximately, the kinetic energy of a neutron and that of a proton. E_C and E_A are excitation energies of the compound and the residual nucleus, respectively. $\rho_A(E_A)$ and $\rho_C(E_C)$ are the level densities of the residual and compound nucleus at their respective excitation energies. The kinetic energy of proton can not be smaller than the effective Coulomb barrier energy k_pV_p. An expression similar to (3) holds for τ_α^{-1}, which is less than 0.1 times of τ^{-1}.
If the level density [7],

$$\rho(E) = \frac{1}{kT}\left(\frac{2\pi}{k}\frac{dE}{dT}\right)^{-1/2} \exp(S/k),$$

(where S, T and k are the entropy of the nuclear system, the nuclear temperature and the Boltzman constant, respectively) is used by performing the integration (2) and (3), the following equations can be obtained,

$$\tau_n^{-1} \simeq \frac{\pi \hbar^3}{2\, m_n R^2} T^{-2} \exp((Bn + \delta n)/kT) \tag{4}$$

$$\tau_p^{-1} \simeq \frac{\pi \hbar^3}{2\, m_p R^2 \left(1 - \frac{Vp}{Ep}\right)} T^{-2} \exp\left(\frac{Bp + kpVp + \delta p}{kT}\right) \tag{5}$$

where (1 - Vp/Ep) and R represent the probability of barrier penetration for a proton in the classical limit and the nuclear radius, respectively.
Combining Eqs. (1), (4) and (5), the σ(n,p) cross section can be expressed as follows :

$$\sigma_{n,p} \simeq \sigma_R \left[1 + \frac{m_n}{m_p}\left(\frac{Ep}{Ep - Vp}\right) \exp\left(\left(-Bn + Bp + kpVp - \delta n + \delta p\right)/kT\right)\right]^{-1} \tag{6}$$

Q'_{np} = Bn - Bp - δp + δn , the effective Q-value of the (n,p) reaction can be stated in terms of the parameter (N-Z +1) / A or (A-2Z+2) / A [5]. Equation (6) was used for the target nuclei (divided into six different ranges in terms of even and odd mass numbers) to obtain empirical fits to the experimental cross sections [8]. The parameter $(A^{1/3} + 1)^2$ is replaced by either A^a or L^a to get better fitted formulae.
The (n,p) cross section formulae for six ranges of the target nucleus are determined with minimization of the equation

$$\frac{1}{N}\sum_{i=1}^{N}\left(\frac{\sigma^{i}_{exp}}{\Delta\sigma^{i}_{exp}}\right)^{2}\left(\ln\sigma^{i}_{exp}-\ln\sigma^{i}_{(n,p)}\right)^{2} \tag{7}$$

where σ^{i}_{exp} and $\Delta\sigma^{i}_{exp}$ are experimental cross sections and the errors associated with σ^{i}_{exp}, respectively.

III. Results and Discussion

Empirical formulae for 14.5-MeV (n,p) reaction, which are the resulting best-fit parameters, are listed in Table 1.

The ratios between the experimental cross sections and those calculated by the equations in Table 1 are plotted against mass number A in Fig 1. The ratios are closer to unity, compared with Tahar's and with Kumabe and Fukuda's results.

Table 1. Empirical formulae for 14.5-MeV (n,p) reaction.

N-Z	Region	A	Empirical formulae (mb)
0,2,4,6..	1	16-56	$3.5495 \times A^{1.6971} \times e^{-37.580(N-Z+1)/A}$
0,2,4,6..	2	58-76	$0.000067 \times e^{-0.967(N-Z+1)/A}\ L^{5.496}$
0,2,4,6..	3	78-116	$7673.5 \times e^{-27.5418(N-Z+1)/A}\ L^{-0.88897}$
1,3,5,7..	1	19-55	$17.5398 \times A^{1.223} \times e^{-34.63716(N-Z+1)/A}$
1,3,5,7..	2	55-77	$2.09 \times e^{-41.22554(N-Z+2)/A}\ L^{3.1812}$
1,3,5,7..	3	79-91	$13.7138 \times A^{0.026} \times e^{0.02538K}$ $K = -95\left(\frac{N-Z+1}{A}\right) + 0.71\left(\frac{2Z-1}{A^{1/3}}\right) - kpVp$ $kpVp = \frac{1.029\,(Z-1)}{A^{1/3}+1}\left(1-\frac{1.13}{A^{1/3}}\right)$

The deviations of (σexp / σcal) from 1.0, for the last region of the odd (N-Z) in Table 1, are considerably reduced by using the energy Q, derived from the semi empirical mass formula, and the effective Coulomb barrier.

The values of (σexp / σcal) were found to be quite close to unity, when the dependence $\frac{N-Z+2}{A}$ is used instead of $\frac{N-Z+1}{A}$ as the Q value for the range $55 \leq$ odd $A \leq 77$. Most of the deviations of these ratios from unity are within the errors associated with σ^{i}_{exp}.

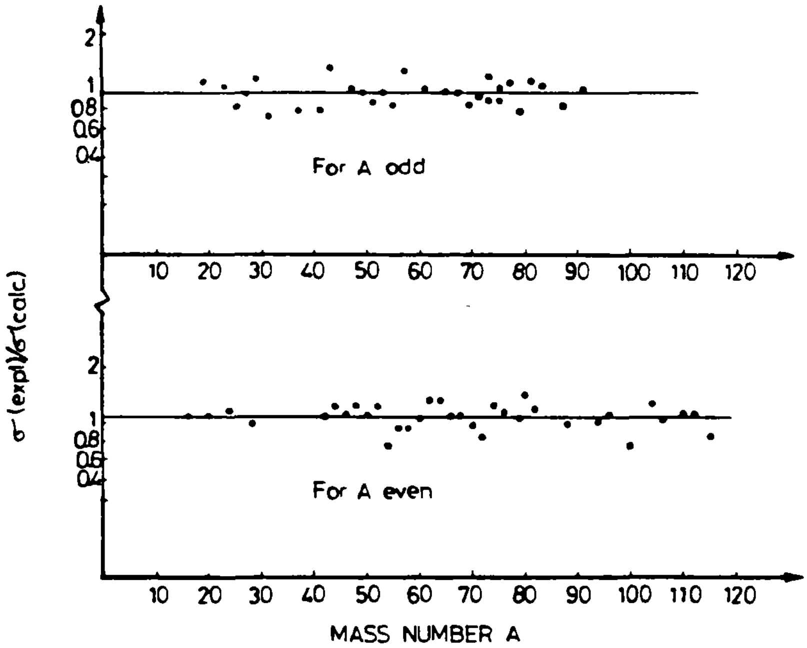

Fig 1. Ratios of experimental-to-calculated (n,p) cross sections for odd and even A derived using formulae given in Table 1.

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