International Atomic Energy Agency

INDC(VN)-006/L

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PREEQUILIBRIUM EMISSION OF PROTONS AND ISOTOPIC EFFECT IN THE FAST NEUTRON-INDUCED (n,p) REACTIONS ON HEAVY ELEMENTS

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December 1987

IAEA NUCLEAR DATA SECTION, WAGRAMERSTRASSE 5, A-1400 VIENNA

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ABSTRACT

The 14 Mev neutron-induced (n,p) reaction cross-sections for the isotopes of Sm, Dy and Er have been calculated using the preequilibrium exciton + compound nucleus evaporation models. For a given element, as the neutron number of the isotopes increases, the (n,p) reaction cross-section decreases exponentially with the reaction Q-value corrected for the pairing energy of the residual nucleus.

More than 85% of the preequilibrium protons are emitted from the exciton state n=3. Based on this result an analytical formula has been found for calculations of the (n,p) reaction cross-sections of the heavy isotopes.

1.INTRODUCTION

It has been found experimentally that the cross sections of the (n,p) reactions induced by 14 Mev neutrons on isotopes of a given element decrease exponentially with increasing mass number A. Some semiempirical formulas which are based on the compound nucleus evaporation model can describe this observed isotopic effect for light and medium nuclei [1,2]. For heavy nuclei the emission of protons in (n,p) reactions is governed by preequilibrium exciton mechanism [3]. The observed cross sections on heavy nuclei also decrease with increasing mass number of the isotope but with markedly less steep than for lighter nuclei. The exponential A-dependence of the (n,p) cross sections on heavy nuclei was shown by Caplar et al. [4] in which the preequilibrium model in combination with the evaporation model with a few input parameters can successfully reproduce both the isotopic trend and the absolute values of (n,p) cross sections for series of Te, Xe, W and Os isotopes. In this paper the (n,p) cross sections, the contributions of both evaporation and preequilibrium exciton mechanisms and the emitted proton spectra have been calculated for series of Sm, Dy and Er isotopes. By fitting the experimental data the exciton model free parameter K characterizing the transition rate between exciton states has been determined for each isotopic chain.

More than 85% of the preequilibrium protons are emitted from the exciton state n=3. Based on this result a rather simple formula has been found and can be used for the evaluation of the (n,p) cross sections on heavy nuclei.

2.CALCULATIONS OF THE (n,p) CROSS SECTIONS

The (n,p) cross sections and the emitted proton spectra were calculated using the preequilibrium exciton model in combination with the Weisskopf-Ewing evaporation model [5,6]. Following the

formalism described in [5] the total (n,p) cross section can be written as a sum of the two components:

$$\sigma_{(n,p)} = \sigma^{PE}_{(n,p)} + \sigma^{C}_{(n,p)} , \tag{1}$$

where the preequilibrium and compound cross sections are determined by the following formulas :

$$\sigma^{PE}_{(n,p)} = \sigma_{CS}(E_c) \sum_{\substack{n=3 \\ \Delta n=+2}}^{\bar{n}} \int_0^{\varepsilon_p^{max}} T_n(E_c)\, W_p^{(n)}(\varepsilon_p)\, d\varepsilon_p , \tag{2}$$

$$\sigma^{C}_{(n,p)} = R_c(E_c)\, \sigma_{CS}(E_c) \frac{\Gamma_p(E_c)}{\Gamma_t(E_c)} , \tag{3}$$

where $\sigma_{CS}(E_c)$ is the cross section for the formation of the composite system at the excitation energy E_c , $W_p^{(n)}(E_c)$ is the emission rate of protons of energy ε_p , $T_n(E_c)$ is the time the system spends in an n-exciton state of energy E_c , $\Gamma_p(E_c)$ and $\Gamma_t(E_c)$ denote the proton and the total emission probabilities of the compound state. The maximum energy of the emitted protons ε_p^{max} in (2) can be written as :

$$\varepsilon_p^{max} = E_i + Q_{np} - \delta , \tag{4}$$

where E_i is the energy of the incident neutron , Q_{np} is the reaction Q-value, δ is the pairing energy of the residual nucleus. The cross section for the formation of the compound nucleus in (3) is expressed as $R_c(E_c)\,\sigma_{CS}(E_c)$, where:

$$R_c(E_c) = 1 - \frac{\sum_x \sigma^{PE}_{(n,x)}(E_c)}{\sigma_{CS}(E_c)} \tag{5}$$

The explicit expressions of the symbols figured in (2), (3), (4) can be found in [5].

In calculating the cross section for the formation of the composite nucleus $\sigma_{CS}(E_c)$ the neutron and proton penetrabilities are taken from the calculations of Mani et al. [7]. The Fermi gas model with pairing correction was used to calculate the nuclear level density. The level density parameter a was chosen as a=A/8 according to the analysis of (n,n´) and (n,2n) reactions [6,8]. In calculating the time $T_n(E_c)$ that the composite nucleus spends in an n-exciton state it is necessary to know the averaged squared matrix element $\overline{|M|^2}$ of the transition rates for the process leading from n to (n+2) and (n-2) exciton states. We use the following phenomenological expression for $\overline{|M|^2}$:

$$\overline{|M|^2} = K A^{-3} E_c^{-1} , \tag{6}$$

where K is a free parameter of the exciton model and can be determined by fitting the experimental data.

The (n,p) cross sections and the emitted proton spectra were calculated for a series of Sm, Dy and Er isotopes. According to formulas (1-3) the calculated cross sections could comprise the contributions from secondary particle emission reactions ((n,pn), (n,pα),...). However, it is known that the cross sections of these reactions are small, except for the case of ^{144}Sm target, their influence on the isotopic behavior of (n,p) cross sections can be neglected. In case of reaction on ^{144}Sm target the maximum excitation energy of the nucleus formed after proton emission (^{144}Pm) is as high as 14.8 Mev and the subsequent emission of neutrons leading to the (n,pn) reaction is favorable. The cross section of the true (n,p) reaction on ^{144}Sm target can be calculated by substracting the low-energy part of the emitted proton spectrum corresponding to the excited states above the neutron separation energy of the ^{144}Pm nucleus. It is worth noting that this approach would give the value higher than the true (n,p) cross section due to the n-γ competition in the decay of the excited unbound state just above the neutron separation energy. The calculated value for ^{144}Sm given in Table 1 and Fig.1 confirm this remark.

3. RESULTS AND DISCUSSION

Figures 1-3 show a comparison between the experimental data and the calculated cross sections for Sm, Dy and Er isotopes. The experimental data were taken from the INDC compilations [9] and [10]. The emitted proton spectra were also calculated, and as an example in Fig.4 are presented the spectra of Dy isotopes. The results of calculations are summarized in Table 1.

The preequilibrium calculations were performed using best-fit K values, namely, K=800 Mev^3 for Er, 600 Mev^3 for Sm and 550 Mev^3 for Dy isotopes. These fitted K values are higher than the corresponding values of Te, Xe, W and Os isotopes in [4] but they agree very well with the "overall best-fit" value K=700 Mev^3 obtained in [6].

The calculated data are in satisfactory agreement with the experimental results and confirm the exponential decrease of (n,p) cross sections with increasing neutron number except for odd-A target isotopes (^{161,163}Dy and ^{167}Er) : the calculated cross sections on these isotopes are markedly higher than those expected from the adjacent even-even isotopes. In Figures 1-3 the calculated data for odd-A isotopes strongly deviate from the straight line drawn through the calculated points for even-even target isotopes. In Ref.[4], such odd-even staggering has been reduced by introducing pairing corrections into reaction Q values. However, in our calculations with pairing corrections, and even in Ref.[4], the odd-even staggering still existed. On the other hand, it is likely that the existing experimental data collected in this work and in [4] do not confirm the odd-even staggering predicted by the calculations. This shows the need for improving the calculation models and the accuracy of experimental data in oder to reveal structure effects in isotopic dependence of cross sections and determine typical parameters figured in nuclear reaction theories.

Table 1

Typical results of calculations

Isotope	K (Mev^3)	$\sigma^{PE}_{(n,p)}$ (mb)	$\sigma^{C}_{(n,p)}$ (mb)	$\sigma^{cal}_{(n,p)}$ (mb)	$\sigma^{exp}_{(n,p)}$ (mb)	$\sigma^{app}_{(n,p)}$ (mb)
$^{144}_{62}$Sm	600	17 6	17	34 6	29 4±3 19 0±4	14
^{148}Sm		7 6	3.2	10 8	9 7±0.8	6 6
^{150}Sm		4.6	1 5	6 1	7 0±0 6 7 19±1 01	3 7
^{152}Sm		3 6	1 3	4 9	3 7±0 2	3 6
^{154}Sm		2.2	1.3	3.5	3.5±0.2	2.6
$^{160}_{66}$Dy	550	7.35	1.44	8.79	9.3±1.0	7.5
^{161}Dy		7.8	0.16	7.96	8.4±0.6	5.8
^{162}Dy		4.96	0.4	5.46	5.2±0.5	5.6
^{163}Dy		5.68	0.024	5.70	3.4±0.3	4.8
^{164}Dy		3.1	0.046	3.15	2.8±0.5	3.6
$^{166}_{68}$Er	800	4.33	0.9	5.23	5.6±0.8 6.7±0.9	4.6
^{167}Er		4.35	0.04	4.39	3.4±0.3	3.5
^{168}Er		2.75	0.1	2.85	2.8±0.4	2.97
^{170}Er		1.5	0.01	1.51	1.8±0.5	1.68

4. APPROXIMATE FORMULA FOR EVALUATION OF THE (n,p) CROSS SECTIONS ON HEAVY ISOTOPES

Results of the numerical calculations show that most of the preequilibrium protons are emitted from the initial exciton states: 85-90% from n=3, 8-14% from n=5 and < 2% from n≥ 7 exciton states. This suggests a further simplification of the calculation model by assuming that all the preequilibrium protons are emitted from the initial state n=3. Then the approximate preequilibrium (n,p) cross section can be written as

$$\sigma^{app}_{(n,p)} = \sigma_{cs}(E_c) \int_0^{\varepsilon_p^{max}} T_3(E_c)\, W_p^{(3)}(\varepsilon_p)\, d\varepsilon_p \qquad (7)$$

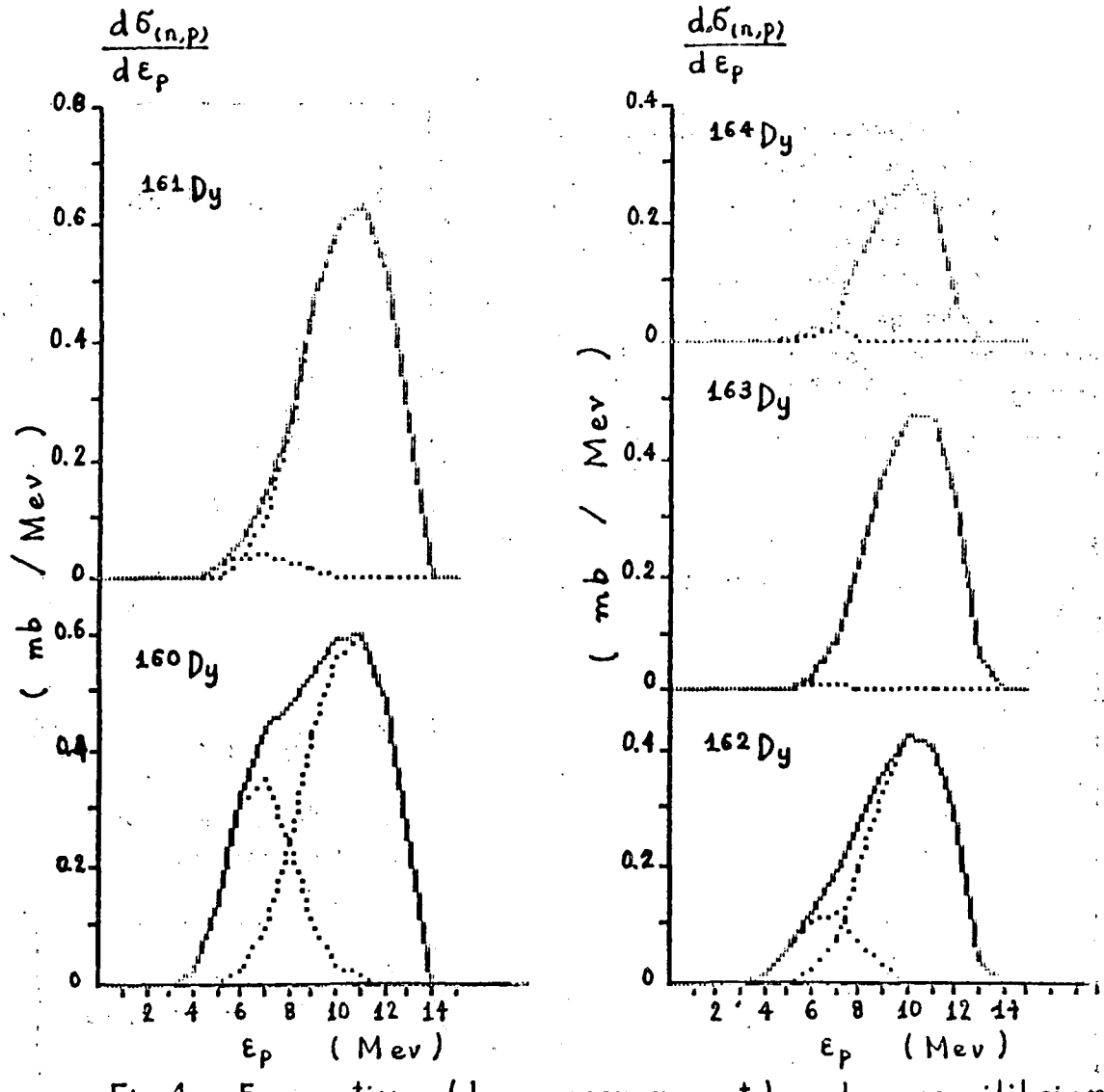


Fig.4 Evaporation (low - energy part) and preequilibrium (high - energy part) proton spectra in 14 Mev neutron-induced reactions on Dy isotopes.

Using approximate formulas for absorption cross sections of neutrons and protons derived from the results of optical model calculations of Mani et al. [11,7] we have :

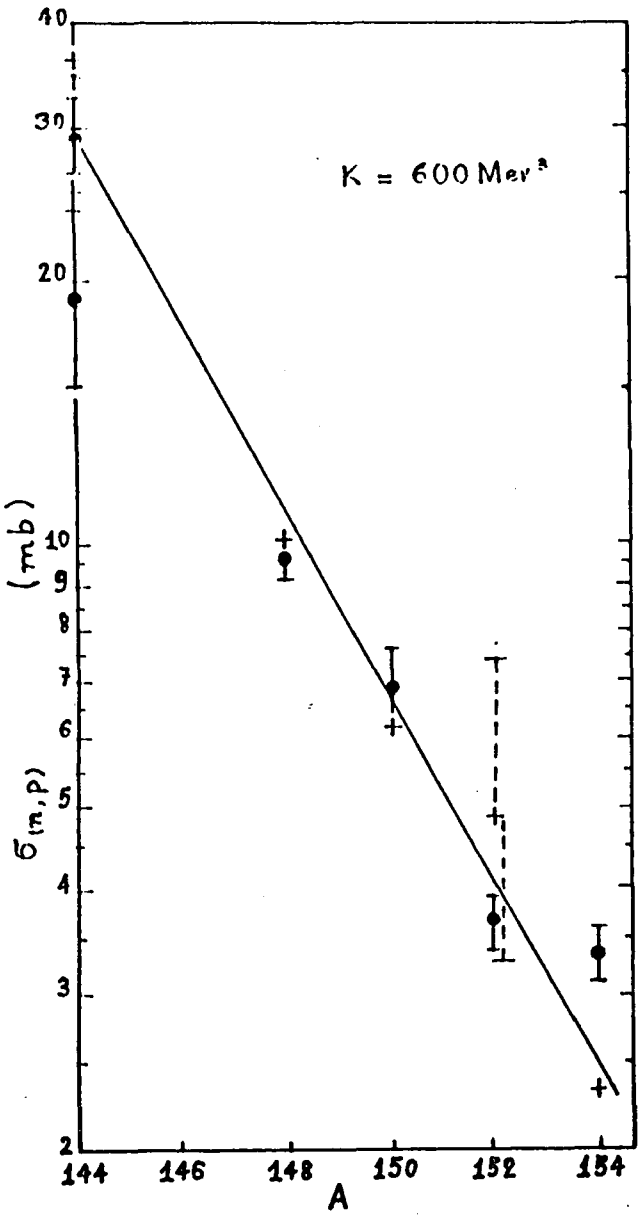
$$\sigma^{app}_{(n,p)}(mb) = 52.5 \frac{(A+100)(7.5A+1000)}{KA}\left(\frac{E_i + Q_{np} - \delta}{E_i + S_n}\right)^3$$

$$\times \left\{ 1 - 25.5\alpha^2 + 78.5\alpha^3 - 13.5\alpha^2(1+3\alpha)e^{-\frac{2(1-\alpha)}{3\alpha}} \right\}, \quad (8)$$

where

$$\alpha = \frac{0.1Z + 0.8}{E_i + Q_{np} - \delta}$$

Fig. 1 Comparison of experimental data (Ŧ) on isotopes of Sm with predictions of the preequilibrium + evaporation models (+). The calculated data on ^{152}Sm exhibits large error due to the error of the proton separation energy $S_p = 8.589 \pm 0.500$ Mev



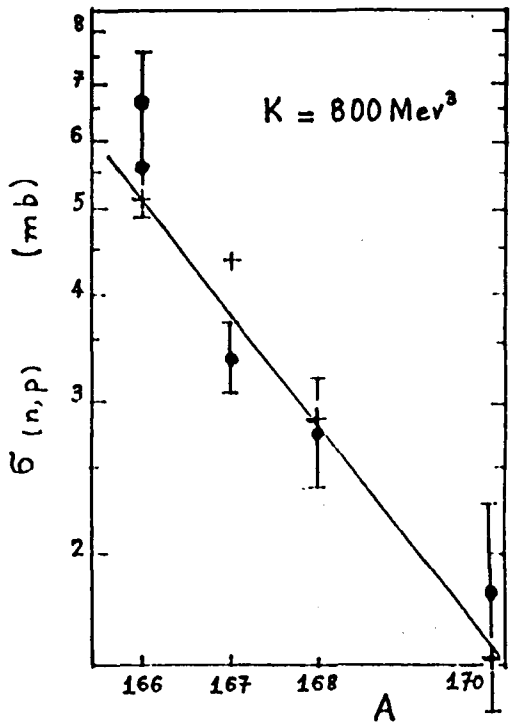


Fig. 3 Same as Fig. 1 for Er isotopes.

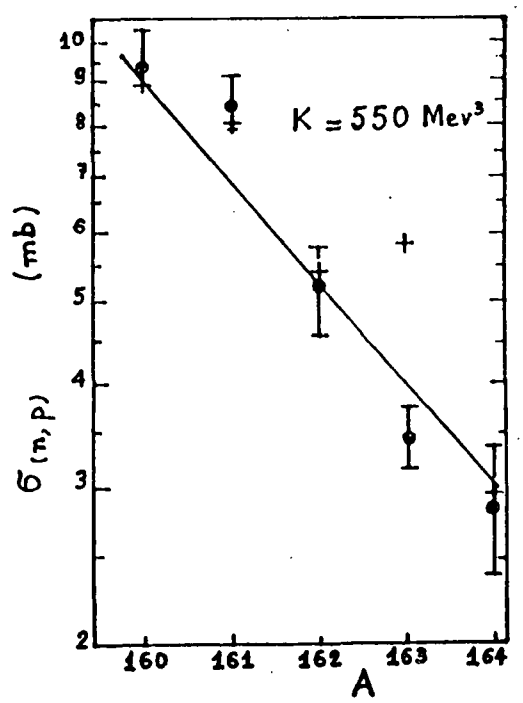


Fig. 2 Same as Fig. 1 for Dy isotopes.

The (n,p) cross sections calculated by using formula (8) are given in the last column of Table 1. Fairly good agreememt with the data calculated in section 3 is obtained, and therefore the approximate formula (8) can be used for evaluation of the precompound part of the (n,p) cross sections or the total (n,p) cross sections on heavy isotopes.

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