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ABSTRACT

Neutron energy distributions for the reactions $^{56}Fe(p,n)$, $^{181}Ta(p,n)$, $^{197}Au(p,n)$ at proton energies of 22.4 MeV were measured in the 150-cm cyclotron of the Institute of Physics and Power Engineering, using a scintillation spectrometer with a stilbene crystal. The neutron emission spectra were analysed in terms of the cascade evaporation model. The contribution of non-statistical neutron emission is taken into account. The data obtained are compared with the results of Ref. [?].

The present paper is a continuation of Ref. [1] and deals with measurements of neutron spectra for (p,n) reactions involving ^{56}Fe, ^{181}Ta and ^{197}Au nuclei at proton energies of 22.4 ± 0.4 MeV and angles of 30°, 60°, 90° and 120°. The measurements were carried out in the 150-cm cyclotron of the Institute of Physics and Power Engineering (FEhI) using a scintillation spectrometer with a stilbene crystal [2] 30 mm in diameter and 20 mm high and an FEhI-93 photomultiplier with a circuit - similar to that described in Ref. [3] - for separating recoil proton pulses from electron pulses. The energy resolution of the scintillation spectrometer was determined from the ratio $\Delta E/E = 0.12/\sqrt{E}$, where E is the neutron energy in MeV.

Metal foils with thicknesses of 25.83 mg/cm^2 for ^{56}Fe (91.7%), 20.66 mg/cm^2 for ^{181}Ta (99.9%) and 18.14 mg/cm^2 for ^{197}Au (99.9%) were used as targets and placed at an angle of 45° to the incident protons. The number of accelerated protons passing through the target was determined by means of a current integrator with a Faraday cylinder acting as a current collector. The neutron detector was placed in the shield used for Ref. [4] at a distance of 261 ± 1 cm from the centre of the target. The procedure for measuring the neutron spectrum for the (p,n) reaction consisted in measuring the amplitude

distributions with and without the target. The measured amplitude pulses were recorded by a 512-channel analyser with a channel width of 20 mV.

The amplitude distributions were converted into energy distributions by a known algorithm involving a smoothing differentiation procedure [5]. The correct operation of the spectrometer and the reliable conversion of amplitude to energy distributions were monitored by measuring the prompt neutron spectrum for spontaneous fission in a ^{252}Cf source and comparing it with a Maxwellian distribution for a temperature T = 1.427 MeV [6], used as the calibration spectrum, and also by measuring the neutron spectra from a ^{239}Pu-Be source.

In determining the errors in the double-differentiated neutron-emission cross-sections obtained, the uncertainties involved in measuring the number of protons incident on the target (about 3%), the target-to-detector distance (about 0.5%), and the number of nuclei per cm^2 of target surface (about 2%) and the errors of conversion from neutron amplitude distriubtions to energy spectra were taken into account [2]:

$$\sigma_\phi/\phi(E) = \sqrt{2\sigma_x^2/x^2 + 2\sigma_{P_x}/P_x^2 + \sigma_\varepsilon^2/\varepsilon^2 + \sigma_{\phi'}^2/(\phi')^2} ,$$

where σ_x/x is the graduation accuracy of the analyser energy scale (about 2%), σ_{P_x}/P_x depends on the accuracy of the known values of the light yield function P(E) (about 3%), $\sigma_\varepsilon/\varepsilon$ is the deviation of the efficiency (in terms of recoil protons), calculated in the approximation of a single scattering event, from the actual function (about 2%), and $\sigma_{\phi'}/\phi'$ is the statistical accuracy.

Integral spectra and angular distributions for neutrons emitted through the interaction of 22.4-MeV protons with ^{56}Fe, ^{181}Ta and ^{197}Au nuclei are given in Figs 1 and 2 using a centre-of-mass system. Table 1 shows emission cross-sections for neutrons with energies greater than 1 MeV obtained in our work and compares them with analogous results from Ref. [7], where the neutron distributions were measured by time-of-flight spectrometry. The compared values, although obtained by different measurement methods, agree closely within the limits of accuracy.

Integral neutron spectra from the $^{56}Fe(p,n)$, $^{181}Ta(p,n)$ and $^{197}Au(p,n)$ reactions at incident proton energies of 22.4 MeV were analysed in terms of the successive particle evaporation model using expressions from

Weisskopf's statistical theory [8] and taking into account the contribution by neutrons from the non-statistical decay process. The data were parametrized for the neutron spectra by means of the expression

$$d\sigma_n/dE = \sigma^{stat} \sum_{i=1}^{N} p_n^i(E) + \sigma^{non-stat} f(E) \Big/ \int_0^{E_{max}} f(E')dE', \qquad (1)$$

where $P_n^i(E)dE$ is the probability of emission of a neutron in the i-th cascade with an energy between E and E + dE (the calculation allowing for competition by open reaction channels), and N is the maximum number of cascades. The function f(E) determines the shape of the neutron spectrum from the non-statistical decay process. The exciton model of pre-equilibrium emission, discussed in Refs [9, 10], for some assumptions gives f(E) in the form

$$f_1 = E \sum_{\substack{n=n_0 \\ (\Delta n=2)}}^{\bar{n}} (U/E^*)^{n-2} (n-1)n(n+1),$$

where E*, U are the excitation energies of the compound and residual nucleus, and n_o is the initial number of excitons after the first interaction. But consideration of the contribution by non-statistical neutrons in terms of the simplest notions of direct process theory [11] gives for f(E) the expression $f_2 = \sqrt{E}U^{n-1}$, where n is the number of excitons in the residual nucleus.

In calculating $p_n^i(E)$ a dependence was used for the level density which was derived from the Fermi-gas model in the form

$$\rho(U) = \text{const}\ (U^*)^{-H} \exp(2\sqrt{aU^*}), \qquad (2)$$

where $U^* = U-\Delta$ is the effective excitation energy of the residual nucleus (Δ being an energy shift explaining the even-odd difference in the level density), H equals 5/4, 3/2 or 2 depending on the assumptions made in deriving the formula, and a is the level density parameter.

The integral neutron spectra were processed by the least squares method. The sum of squares of the deviation

$$\chi_k^2(a, \sigma^{stat}, \sigma^{non-stat}) = \sum_{i=1}^{k} \left[(d\sigma_n^{exp}/dE_i) - (d\sigma_n^{calc}/dE_i)(a, \sigma^{stat}, \sigma^{non-stat}) \right]^2 / \theta_i^2 \qquad (3)$$

was minimized with respect to three selected parameters a, σ^{stat}, $\sigma^{non-stat}$. Here $d\sigma_n^{exp}/dE_i$ and $d\sigma_n^{calc}/dE_i$ are the experimental and calculated

values of the cross-sections in the points E_i [see formula (1)], and θ_i is the error in the experimental values for the points E_i. The method of calculation and of obtaining the optimum parameters is described in greater detail in Ref. [12].

The contriubtion of non-statistical neutrons is determined by the expression $\alpha = \sigma^{non-stat}/[\sigma^{non-stat} + \sigma^{stat}P_1(n)]$, where $P_1(n) = \int_0^{E_{max}} P_n^i(E)dE$ is the probability of emission of a neutron in the first cascade as a result of the statistical decay process.

The relationships of the Weisskopf evaporation model are not entirely accurate, as they do not take into account the laws of conservation of spin and parity in nuclear reactions. Reference [13] gives fairly accurate comparative calculations of neutron emission for the two-cascade reaction $^{56}Fe(n,n')$ for incident neutron energies of 14.5 and 20.6 MeV in terms of the Weisskopf evaporation model, and of the Hauser-Feshbach statistical model, in which those conservation laws are taken into account. It is shown that at energies several MeV below the threshold for the (n,2n) reaction, calculations following these models agree closely, whereas in the incident neutron energy region near the threshold the influence of the spin and parity conservation laws is substantial. As a result, the Weisskopf relationships may be used with full justification in describing the experimental results obtained for the present paper.

In analysing the integral neutron spectra, the required values of the shift Δ, in the first version of the calculations, were determined from the relationship $\Delta = P(Z) + P(N)$, where P(Z) and P(N) are the values of the evaporation energy used in Ref. [14] for the analysis of neutron resonance data in terms of the Fermi-gas model. In the second version, the values of Δ were taken from Ref. [15], where the observed level density was described for a large number of nuclei and over a fairly wide range of energies, the shift Δ being selected as an "inverse displacement" in the Fermi-gas model. In this case the value of Δ is not a physical parameter and cannot be evaluated in terms of any model, but is determined, like the parameter a, on the basis of the best description of the observed level density.

In the minimization of expression (3) the selected parameter a relates to a residual nucleus formed after emission of a neutron in the first cascade (^{56}Co, ^{181}W, ^{197}Hg), and the parameters $a_{N,Z}$ of the residual nuclei formed after

emission of a proton or γ-quantum in the first cascade, or of a neutron, proton or γ-quantum in the second cascade, etc., are determined by means of the relationship $a_{N,Z} = aK_{N,Z}$. The coefficients $K_{N,Z}$ are calculated on the basis of data on the level density parameter taken from Refs [14] or [15], depending on which values of Δ were used in analysing the integral spectra.

When 22.4 MeV protons interact with ^{56}Fe nuclei, two cascades are formed, whereas three particle cascades are produced when such protons interact with ^{181}Ta or ^{197}Au. Calculation of the probability of emission of neutrons, protons and γ-quanta in the cascades shows that competition by protons alone has a strong influence when neutrons emerge from the $^{56}Fe(p,n)$ reaction, whereas in $^{181}Ta(p,n)$ and $^{197}Au(p,n)$ reactions the protons competition is small and that of γ-quanta is appreciable only in the last cascade.

The results of optimizing the integral spectra are given in Fig. 1 and in Table 2, in which the level density parameter values obtained for the nuclei ^{56}Co, ^{181}W and ^{197}Hg are compared with neutron resonance data from Ref. [16]. Table 2 shows that for the integral neutron spectra of the $^{181}Ta(p,n)$ and $^{197}Au(p,n)$ reactions the calcuation using the Δ value from Ref. [14] yields practically the same values for the level density parameter as when using the Δ value from Ref. [15]; these results are in fair agreement with the neutron resonance data. The values for the parameter a corresponding to an index H = 5/4 of the pre-exponential factor in the expression for the level density is somewhat lower than the value of this parameter for H = 2.

Analysis of the integral neutron spectra for the single-cascade reaction $^{181}Ta(p,n)^{181}W$ at initial proton energies of 6 and 7 MeV in terms of the Hauser-Feshbach model in Ref. [17] showed that a satisfactory description of the neutron spectra over the entire excitation energy range, including the region with a known level arrangement, may be obtained for a = 20.3 MeV^{-1} and Δ = -0.25 MeV. For the ^{181}W nucleus Ref. [15] gives values a = 19.99 MeV^{-1} and Δ = -0.39 MeV determined from the known mean distance between levels D_o and the total number of low-lying levels N_o. The values of a found in the present paper from the integral neutron spectrum for the ^{181}Ta (p,n) reaction with an initial proton energy of 22.4 MeV agree very well with the results given above for H = 5/4, as Table 2 shows.

Analysis of the integral neutron spectrum for the $^{56}Fe(p,n)$ reaction with a shift Δ taken from Ref. [14] shows good agreement of the values obtained for parameter a with the data on neutron resonances, while calculation

with a shift Δ from Ref. [15] yields somewhat higher values of a. The neutron emission probability for this reaction in the calculation using Δ from Ref. [14] is 0.76 in the first cascade and 0.50 in the second, whereas with Δ from Ref. [15] the probabilities are 0.73 and 0.28, respectively. Clearly the calculations with Δ from Ref. [15] show stronger competition from protons in the second cascade. Experimental information about the proton spectrum as well as the neutron spectrum would make it possible to analyse the reaction involving ^{56}Fe more fully.

The values of the cross-sections $\sigma = \sigma^{stat} + \sigma^{non-stat}$ obtained in the present paper from the integral spectra are compared with calculation results for the cross-section σ from Ref. [18] in terms of the optical model with a spherically complex potential for which the optimum set of parameters is selected on the basis of the best description of the available experimental information over a wide range of nuclei and energies.

The most widely known systems of optical potential parameters, as Ref. [18] points out, make it possible to describe the experimental data on proton scattering with an accuracy of about 20%. Cross-sections for inelastic interactions of protons at energies of 20 MeV are given in Table 2. Extrapolating the values to proton energies of 22 MeV yields 1.04, 1.6 and 1.6 b, respectively, for ^{56}Fe, ^{181}Ta and ^{197}Au. Considering the accuracy with which the optimum cross-sections for protons are known, the derived values of $\sigma = \sigma^{stat} + \sigma^{non-stat}$ can be made to agree very satisfactorily with the calculated values, given a general tendency for the cross-sections to be lower than the optimum values.

Table 1

Neutron emission cross-section data, mb

Target nucleus	Present paper	Ref. [7]
^{56}Fe	653±49	667±43
^{181}Ta	2118±160	1948±127
^{197}Au	2130±160	-
	171[X]±12	177[X] ±13

X Values for 90° angles are given in mb/sr.

Table 2

Results of analysing integral neutron spectra for (p,n) reactions at proton energies of 22.4 MeV

Target nucleus	Number of cascades	Shape of non-statistical neutron emission spectrum	Value of H in expression (2)	Value of Δ from Ref. [14]			
				a, MeV^{-1}	$\sigma^{non-stat}$, mb	$\sigma = \sigma^{non-stat} + \sigma^{stat}$, mb	α
^{56}Fe	2	$f_1(n_0=3)$	5/4	7,63±0,28	II2±20	698±40	0,20I±0,037
			2	8,75±0,3I	II0±20	69I±39	0,I99±0,036
		$f_2(n=2)$	5/4	7,I3±0,27	88±I6	698±40	0,I60±0,03I
			2	8,32±0,29	87±I6	696±40	0,I58±0,03I
^{I8I}Ta	3	$f_1(n_0=3)$	5/4	20,00±0,76	I93±42	I353±93	0,I43±0,033
			2	2I,50±0,79	I93±42	I309±89	0,I48±0,034
		$f_2(n=3)$	5/4	I9,50±0,74	I69±33	I333±9I	0,I27±0,026
			2	2I,00±0,76	I69±33	I289±86	0,I32±0,027
^{I97}Au	3	$f_1(n_0=3)$	5/4	I9,88±0,7I	I78±30	I460±93	0,I23±0,022
			2	2I,25±0,73	I77±30	I409±89	0,I26±0,023
		$f_2(n=3)$	5/4	I9,88±0,7I	I6I±26	I463±93	0,II0±0,0I9
			2	2I,25±0,73	I6I±26	I4I3±89	0,II5±0,020

Table 2
(continued)

χ_k^2/k	Value of Δ from Ref. [15]				χ_k^2/k	a_{res}, MeV^{-1} [16]	σ^{opt}, (E_r = 20 MeV), mb [18]
	a, MeV^{-1}	$\sigma^{non-stat}$, mb	$\sigma = \sigma^{non-stat} + \sigma^{stat}$, mb	α			
I,69	9,75±0,87	II5±20	793±46	0,I88±0,036	I,33	$7,06^{+0,I9}_{-0,I6}$ ^{55}Fe	I020
I,54	II,I8±0,4I	II5±20	78I±45	0,I9I±0,036	I,37		
I,59	9,I8±0,35	9I±I7	792±46	0,I5I±0,030	I,29	$7,62^{+0,24}_{-0,I9}$ ^{56}Fe	
I,45	I0,38±0,37	9I±I7	778±44	0,I54±0,030	I,35	$8,4I^{+0,23}_{-0,I9}$ ^{57}Fe	
0,64	20,38±0,77	I93±42	I258±86	0,I54±0,036	0,6I	$2I,67^{+0,47}_{-0,37}$ ^{I8I}Hf	I460
0,62	22,00±0,8I	I93±42	I226±83	0,I58±0,036	0,63	$2I,I8^{+I,2I}_{-I,I7}$ ^{I8I}Ta	
I,30	I9,88±0,75	I69±33	I239±88	0,I37±0,029	I,28	$22,28^{+0,23}_{-0,2I}$ ^{I82}Ta	
I,28	2I,63±0,78	I70±33	I2I5±80	0,I40±0,029	I,3I		
0,5I	I9,50±0,70	I76±30	I8I0±84	0,I35±0,025	0,45	$2I,I9^{+0,36}_{-0,30}$ ^{I96}Pt	I440
0,50	20,88±0,72	I76±30	I266±80	0,I40±0,026	0,44	$20,24^{+0,27}_{-0,23}$ ^{I98}Au	
2,04	I9,50±0,70	I60±26	I8I2±84	0,I22±0,022	2,02	$2I,82^{+0,66}_{-0,48}$ ^{I99}Hg	
2,04	20,88±0,72	I60±26	I269±80	0,I27±0,023	2,0I		

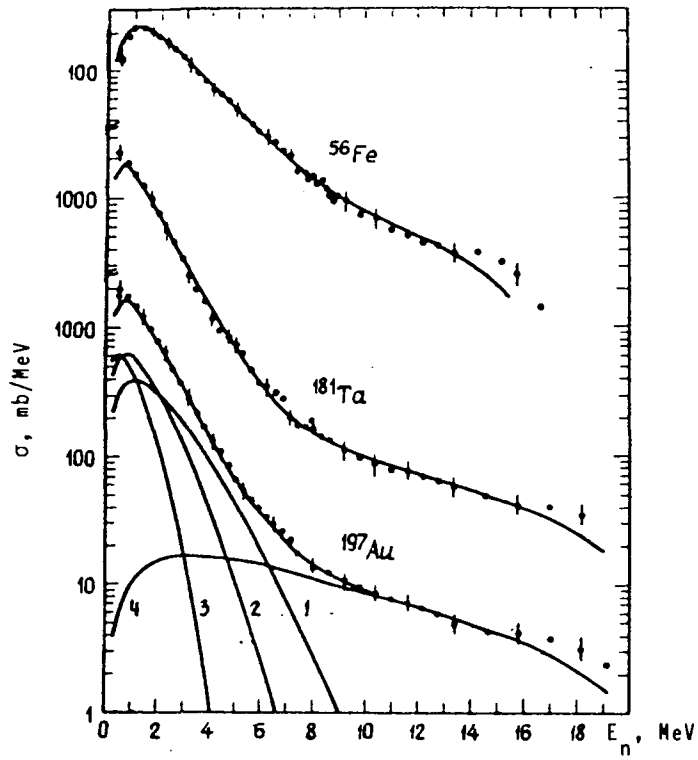

Fig. 1. Integral neutron spectra for (p,n) reactions involving ^{56}Fe, ^{181}Ta and ^{197}Au nuclei: • experimental values; —— calculation by Eq. (1) with $f(E) = r_1(n_o = 3)$. For the neutron spectra for the $^{197}Au(p,n)$ reaction: 1, 2, 3 - statistical-decay neutrons of the first, second and third cascade; 4 - contriubtion of non-statistical emission neutrons.

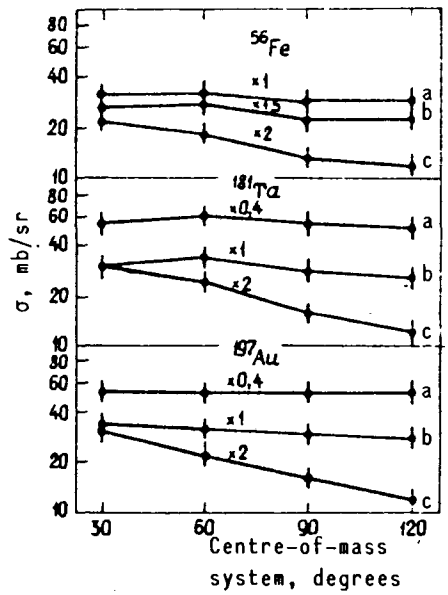

Fig. 2. Angular distributions of neutrons obtained by integrating double-differential cross-sections $(d^2\delta/dEd\Omega)(E,\theta)_{c.o.m.}$ with respect to the following energy ranges: a 1-3 MeV; b 3-6 MeV; c over 6 MeV.

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