acta phys. slov. 25 (1975), No. 2—3

ALPHA PARTICLE EMISSION FROM FAST NEUTRON INTERACTION WITH RARE-EARTH NUCLEI[1]

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In the last years a number of investigations of (n, α) reactions induced by 14 MeV neutrons in deformed rare-earth nuclei have been performed [1—8]. In many cases it is extremely difficult to state a priori what the reaction mechanism should be. If high resolution excitation curves and angular and energy distributions can be obtained, then the particular mechanism involved can generally be determined. But in some cases the experimental difficulties encountered make the acquisition of this type of data nearly impossible. This holds for the study of the (n, α) reaction on heavy nuclei. The cross section for these reactions is quite low, and any attempt to increase the count rate by using thicker targets would lead to a complete loss of the structure of the α-spectrum.

In the past few years we have concentrated our efforts on (n, α) reactions leading to the even-odd, even-even, and odd-odd nuclei from the rare-earth region. The structure of most of these nuclei is reasonably well known from mainly one-nucleon transfer reactions.

In a typical even-odd or odd-odd deformed nucleus in the rare-earth region the average level spacing is below 30 keV at a low excitation energy (<1.5 MeV); at a higher excitation energy the level density increases rapidly due to the excitation of additional degrees of freedom (quadrupole and octupole vibrations, three-particle excitation etc.).

The energy resolution of our measurements does not allow a separation of the single levels except for the ^{147}Sm(n, α) ^{144}Nd reaction where we observe an excitation of the isolated levels.

The experimental method has been described in detail in a previous publication [5], only the main points will be given here. A beam of deuterons accelerated in the 3 MeV Van de Graaff accelerator „LECH“ was used for the production of neutrons from the ^{3}H(d, n) ^{4}He reaction. The neutron flux was monitored by counting the recoil protons from a thin polyethylene foil. The alpha particles were analyzed by a solid state counter spectrometer. The energy resolution was 300—600 keV. The cross sections were measured at the average emission angle of 30°—35°.

The results of the alpha particle spectra measurements from the ^{151}Eu(n, α) ^{148}Pm,

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[1] Contribution delivered at the International Symposium on Neutron Induced Reactions, September 2—6, 1974 at SMOLENICE, Czechoslovakia.

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^{165}Ho(n, α) ^{162}Tb, ^{147}Sm(n, α) ^{144}Nd and ^{163}Dy(n, α) ^{160}Gd reactions, induced by 14.2 MeV and 18.15 MeV neutrons are presented in Figs. 1–3, respectively.

A characteristic feature for most of the observed spectra for the 14 MeV neutron bombarding energy are the sharp initial rise and the broad maximum corresponding to the transitions to the excited states of the residual nuclei. However, some of the spectra show a discernible structure. The shapes of the spectra induced by the 18 MeV neutron bombarding energy are different, mostly in the lower energy part of the spectra, where we observed a higher cross section compared to the 14 MeV spectra. This is probably due to a higher penetrability of the Coulomb barrier.

In Fig. 4 the angular distribution from the ^{165}Ho(n, α) ^{162}Tb reaction induced by 18.15 MeV neutrons is shown. For each emission angle the α-particles spectrum was sumed over a 4 MeV excitation energy. The obtained angular distribution shows a distinct forward peaking and this feature is well reproduced by the knock-on mechanism calculation (solid line in Fig. 4).

We examined and analyzed some of the obtained spectra using the Hauser-Feshbach theory [9]. The calculations performed by means of a Fortran computer program which used a formalism similar to that of the well-known code „LIANA“ [10, 11].

For the high excitation energy region for which the levels of the final nuclei are unknown we used the level density formula given by Cameron [12]. The transmission coefficients were calculated using the Saxon-Woods potential form with the optical model parameters taken from [13].

The results of the calculations for the ^{151}Eu(n, α) and ^{169}Tm(n, α) reactions show that:

— the calculated cross sections for both cases are by a factor of 100 smaller than the experimental ones,

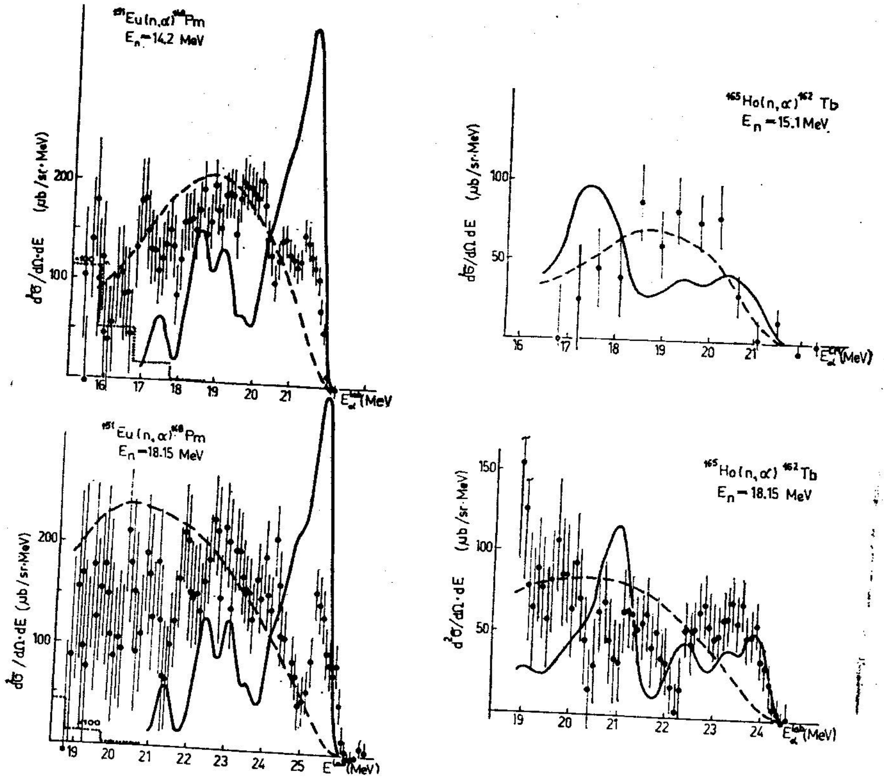

Fig. 1a, 1b. Comparison of the experimental data with the calculated cross section. The solid, dashed and dotted lines are the predictions based on the knock-on, pre-equilibrium and statistical models, respectively.

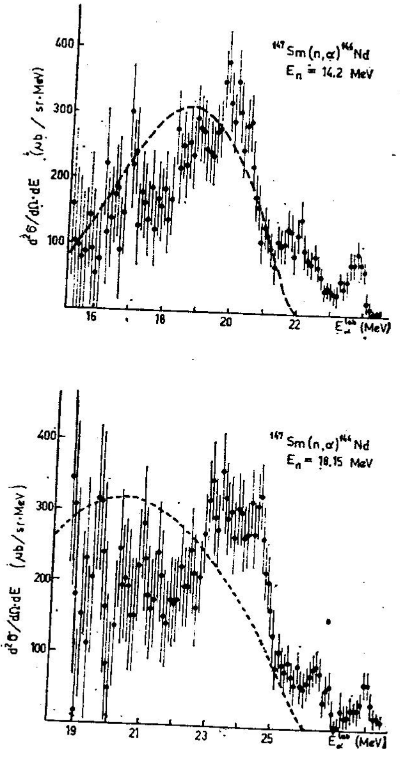

Fig. 2. Comparison of the experimental data with the calculated cross section based on the pre-equilibrium model.

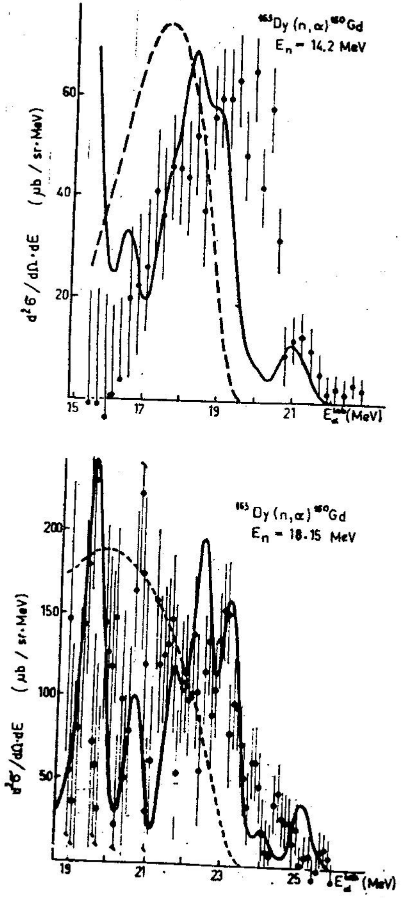

Fig. 3. Comparison of the experimental data with the calculated cross section. The solid and dashed lines are the predictions based on the knock-on and pre-equilibrium models, respectively.

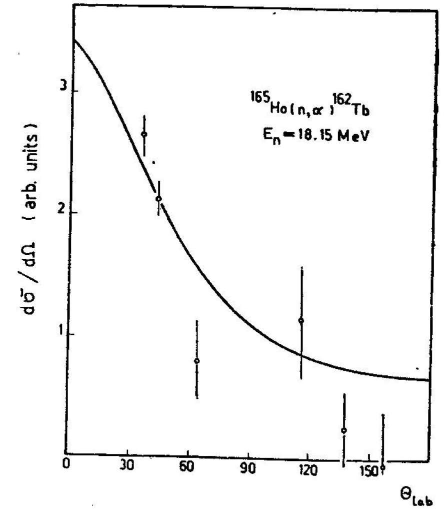

Fig. 4. The angular distribution of α-particles from the ^{165}Ho(n, α) ^{162}Tb reaction. The solid line is the prediction based on the knock-on model.

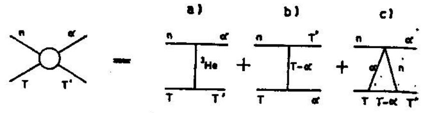

Fig. 5. The Feynman diagrams of the pick-up, heavy particle stripping and knock-on mechanisms.

— the experimental spectra are shifted considerably (about 4—5 MeV) towards higher energies in comparison with the predictions of the statistical theory.

Thus the statistical model is inadequate to describe these reactions.

The preequilibrium formula we used is the following [14].

$$\frac{d\sigma}{d\varepsilon_\alpha} = (2s+1) f\sigma_c \frac{\mu_\alpha \varepsilon_\alpha \sigma_{inv}(\varepsilon_\alpha)}{4\pi^3 \hbar^2 |M|^2 g^4 E^3} \sum_{\substack{n=3 \\ \Delta n=2}}^{\bar{n}} \left(\frac{U}{E}\right)^{n-2} (n+1)^2 (n-1)$$

This implies some probability for four nucleons to be correlated in an α-particle-like structure in the target nucleus. For the excitation energy of even-odd and even-even nuclei the Cameron correction was taken into account [12]. The calculations show that the pre-equilibrium model reproduces the experimental spectra quite well except for the high energy part. This model does not reproduce the structure which we observed in some of our spectra.

The existence of high-energy α-particles in the experimental spectra and the fact that the angular distributions of the emitted alpha particles are strongly forward peaked suggest for the studied reactions a significant contribution from a direct mechanism.

Following **Shapiro** [15], we assume the amplitude of the direct reaction to be described by a set of nonrelativistic Feynman diagrams. When selecting the most important diagrams, both the singularity position and the vertex function magnitude have to be taken into account. For the (n, α) reaction the three diagrams shown in Fig. 5 must be considered. The first diagram describes the pick-up of the helion by the incident neutron. However, because of the large separation energy of ^{3}He, in a first approximation this process can be eliminated. The second diagram describes the heavy particle stripping and gives the maximum of the cross section for backward angles. Since a common feature of the measured angular distributions is a strong forward peaking, this diagram may also be neglected. Hence the third diagram describing the knock-on of an α-particle from the target nucleus was used in the calculations.

The cross section for the knock-on (n, α) reaction described by the triangular diagram may be written as follows [8]:

$$\frac{d\sigma(E, \Theta)}{dE} = \sum_i \sigma(E_i, \Theta) \frac{1}{\sqrt{2\pi}\, a} \exp\left(-\frac{(E-E_i)^2}{2a}\right), \tag{1}$$

where

$$\sigma(E_i, \Theta) = \frac{\mu_{nT}\mu_{\alpha T'}}{4\pi^2} \frac{P_\alpha}{P_n} |F_\Delta|^2. \tag{2}$$

$$F_\Delta = F_{kin}(E_n, \Theta) S \tag{3}$$

In the formula (3) $|F_{kin}(E, \Theta)|^2$ represents the probability of the alpha particle emission with the energy E and under the angle Θ. $S^2 = \gamma_\alpha^2 \gamma_n^2$ denotes the multiplication of the alpha and neutron widths in the target and final nuclei, respectively. The energies and spins of the final states for even-odd and odd-odd deformed nuclei were calculated using the modified Nilsson Hamiltonian and corrected for the pairing effect. The level structures of the doubly-even final nuclei calculated by **Soloviev** et al. [16], were used.

The results of the calculations together with the experimental values are shown in Figs. 1—3. The calculated cross section were smeared out according to the experimental energy resolution and normalized to the total number of counts.

The results of the calculated energy spectra indicate that the model based on the existence of preformed α-clusters and the knock-on mechanism dominance gives the general features of the measured energy distributions.

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Received September 9th, 1974