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A STUDY OF PROTONS AND α-PARTICLES FROM NEUTRON-INDUCED REACTIONS ON ^{40}Ca

D. WINTERHALTER* and M. TURK**

Institute »Ruđer Bošković«, Zagreb

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Abstract: Energy spectra of protons and alpha particles from 14.6 MeV neutron induced reactions on ^{40}Ca have been studied using the nuclear emulsion technique. Angular distributions of protons from the reactions ^{40}Ca(n, p)^{40}K and ^{40}Ca(n, np)^{39}K have been measured. Experimental results have been analyzed in the framework of statistical theory and values for nuclear temperature for various reactions deduced.

1. Introduction

Cross sections for (n, p) and (n, α) reactions on calcium have been measured by several authors[1-6] but the experimental results are not consistent. Eearlier measurements of the (n, p) reaction were performed at a few[1] angles or just at one[2] angle, and the total cross section was estimated. Antolković *et al.*[3] measured the angular distribution of protons at forward angles up to 120^0 from 4 MeV up in search for a direct process. In the paper by Katase *et al.*[4], published in the course of this work, the angular distribution was given in the whole angular range. Although their total cross section agrees with the values from earlier measurements, the ratio $\sigma_{n,\,np}/\sigma_{n,\,p}$ is smaller than that given by Allan[2].

The angular distribution and the total cross sections for the emission of alpha particles from neutron-induced reactions on ^{40}Ca were measured by Bormann[5]. The analysis of the reaction in terms of statistical theory, made by Bormann[5] and by Turkiewicz *et al.*[6], gave different values for the level density parameter *a*.

The present experiment was aimed at obtaining more data on (n, p) and (n, α) reactions on ^{40}Ca and at gathering more information on the reaction mechanisms involved.

* Faculty of Medicine, Zagreb
** Faculty of Science, Zagreb

2. *Experimental procedure*

The 14.6 MeV neutrons were obtained from the T(d, n)^{4}He reaction using deuterons from the Cockcroft-Walton accelerator of the Institute »Ruđer Bošković«, Zagreb. Alpha particles were counted with a scintillation counter for monitoring purposes. Nuclear emulsion plates Ilford K2 and KO 200 μ thick were used as detectors for (n, p) and (n, α) reactions, respectively. In the latter case the separation of alpha particles from singly charged particles was obtained by the temperature method processing[7].

The target was prepared by vacuum evaporation of natural calcium on a gold foil. The evaporation of calcium was followed by evaporation of CaF_2 which formed a thin layer on calcium and served as protection against oxidation. Two gold foils were placed into the evaporation chamber at a time. One of them, shielded during the evaporation of calcium, was used as target for background measurements. The thickness of calcium and of CaF_2 was 2.73 mg/cm^2 and 0.398 mg/cm^2, respectively.

The geometry of the experiment, essentially the same as described earlier[8], allowed run and background tracks to be measured in a single exposure. The length and the angle of emission of each track were measured. To identify particles emerging from the target, the point of emission was determined for each track.

After subtracting the background a total of 822 tracks remained in the case of the K2 emulsion, the run to background ratio being 2. In the case of the KO emulsion the corresponding numbers were 170 and 2.5, respectively.

3. *Results*

3.1. The reactions $^{40}Ca(n,p)^{40}K$ and $^{40}Ca(n,np)^{39}K$. The energy spectrum of protons in the c. m. system is plotted in Fig. 1. Contributions from all measured angles, i. e. from 15^0 to 65^0 and 115^0 to 165^0, were added with appropriate weights corresponding to the solid angle subtended by the target.

Under the assumption of an evaporation process the known relation for the spectrum intensity can be applied

$$N(E) \sim E\, \sigma_c(E)\, \varrho(E)\,,$$

where E is the energy of the emitted particle, σ_c the cross section for the formation of the compound nucleus by the inverse reaction, and ϱ the level density of the residual nucleus.

Both the level density formulae[9] $\varrho(E) \sim \exp(-E/T)$ and $\varrho(U) \sim \sim U^{-2} \exp[2(aU)^{1/2}]$ were used to fit the data in order to evaluate the parameters T and a, respectively. The cross section σ_c was taken from the optical model calculations by Mani *et al.*[10].

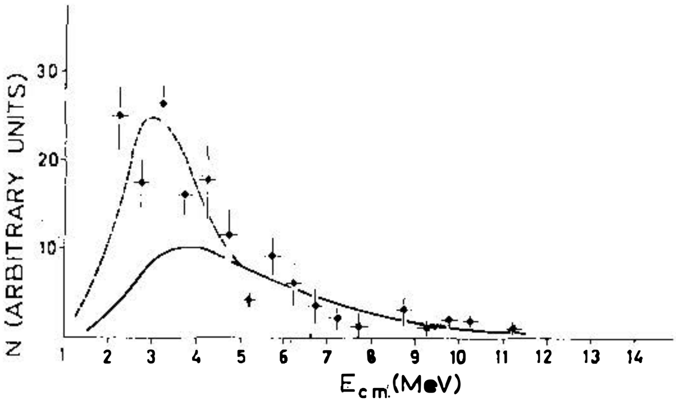

Fig. 1. Energy spectrum of protons. The vertical bars are the statistical errors, the horizontal bars indicate the energy resolution. The full and dashed curves are calculated from the nuclear temperatures for the (n, p) and the combined (n, p) and (n, np) reaction, respectively.

In Fig. 2 ln $(N/\sigma_c E)$ is plotted versus energy E. Because of the contribution of the ^{40}Ca(n, np) reaction the spectrum was analyzed in two parts, from 2 MeV to 5.5 MeV and from 5.5 MeV up. From the least square fit applied to the data above 5.5 MeV a value of $T_{n,p} = 1.55$ MeV was derived for the nuclear temperature of the ^{40}Ca(n, p) reaction. By a similar procedure, plotting ln $(NU^2/\sigma_c E)$ versus $U^{1/2}$, the value for the level density parameter was determined as $a = 5.18$ MeV^{-1}. Below 5.5 MeV the temperature for the combined reactions, ^{40}Ca(n, p) and ^{40}Ca(n, np) is $T_{(n,p)+(n,np)} = 0.86$ MeV. The spectrum was fitted with the above mentioned values of $T_{n,p}$ and $T'_{(n,p)+(n,np)}$

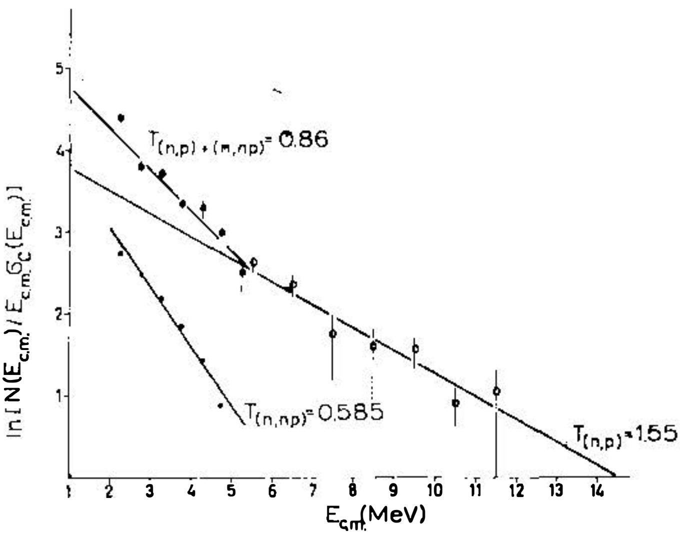

Fig. 2. The relative level density $\ln(N)/\sigma_c E)$ as a function of the proton c. m. energy. The errors are statistical.

as shown in Fig. 1 (full curve and dashed curve, respectively). The curve for the (n, p) reaction was normalized to the experimental points above 5.5 MeV. By extrapolating to smaller energies it is possible to calculate the contribution of the (n, np) reaction. The resulting value for the nuclear temperature is $T_{n, np} = 0.6$ MeV.

From the experimental points the integrated cross section was calculated by extrapolation to the entire angular range. Comparing this value with the areas under the curves in Fig. 2, the cross sections for (n, p) and (n, np) reactions were calculated. The results are summarized in Table 1. For comparison the experimental results by other authors are also given. The first two items in the table are the (n, p) cross sections calculated by Gardner[11, 12] on the basis of a semiempirical formula with shell effects taken into account in the case of the smaller value.

Table 1

Cross sections, nuclear temperatures and level density parameter for the reactions ^{40}Ca (n, p) ^{40}K and ^{40}Ca (n, np) ^{39}K.

Authors	Gardner *et al.* (predicted)	Colli *et al.*[1]	Allan[2]	Antolković *et al.*[3]	Katase *et al.*[4]	present experiment
$\sigma_{n, p}$ (mb)	736[11] 226[12]	∾ 518	298 ± 38		471 ± 21	377 ± 30
$\sigma_{n, np}$ (mb)			205 ± 38		180 ± 32	258 ± 50
$\frac{\sigma_{n, np}}{\sigma_{n, p}}$			0.687			
$T_{n, p}$ (MeV)			1.2 ± 0.1		1.34 ± 0.04	1.55 ± 0.15
$T_{n, np}$ (MeV)			0.3—0.4			0.60 ± 0.03
a (MeV^{-1})			3.48	$5.7 \begin{smallmatrix} +0.5 \\ -0.3 \end{smallmatrix}$	3.69 ± 0.28	∾ 5.18

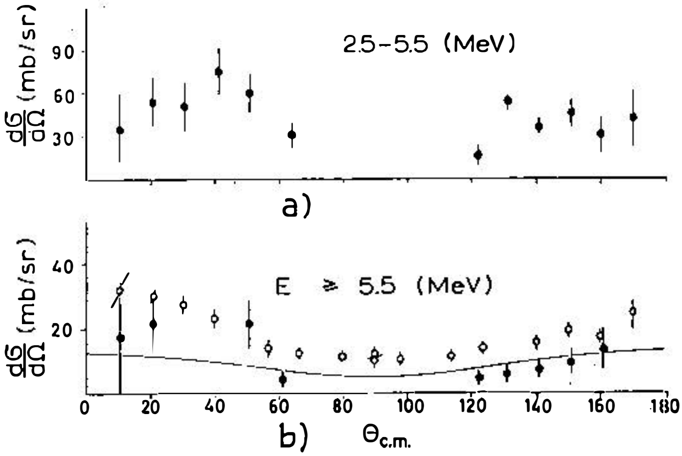

Fig. 3. Angular distributions of protons below a), and above b) 5. MeV. The full curve is calculated from theory[9]).

The angular distribution of protons of energy below 5.5 MeV and above 5.5 MeV are shown in Fig. 3. Our results (full points) are compared with those by Katase *et al.*[4]) (circles). The theoretical curve is calculated from the relation by Ericson[9])

$$W(\Theta) = 1 + [\langle l^2 \rangle \langle I^2 \rangle / (12\, \sigma^4)]\ P_2\,(\cos \Theta),$$

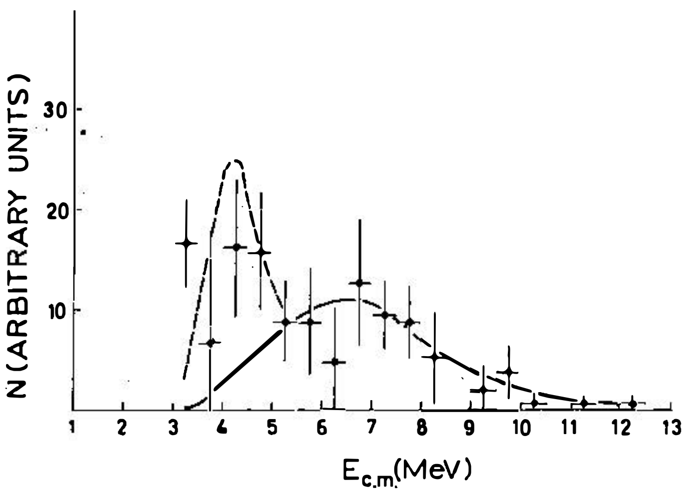

Fig. 4. Energy spectrum of alpha particles. The vertical bars are the statistical errors, the horizontal bars indicate the energy resolution. The full and dashed curves are calculated from the nuclear temperature for the (n, α) and the combined (n, α) and (n, nα) reaction, respectively.

where l and I are the angular momenta of the emitted particle and the compound nucleus, respectively, and σ is the spin cut-off parameter. The average values of l^2 and I^2 were calculated with the aid of the transmission coefficients given by Mani *et al.*[10]. The comparison of the theoretical curve and the experimental data yields for the spin cut-off parameter σ a value of 1.8 and for the moment of inertia a value of $0.3 J_R$.

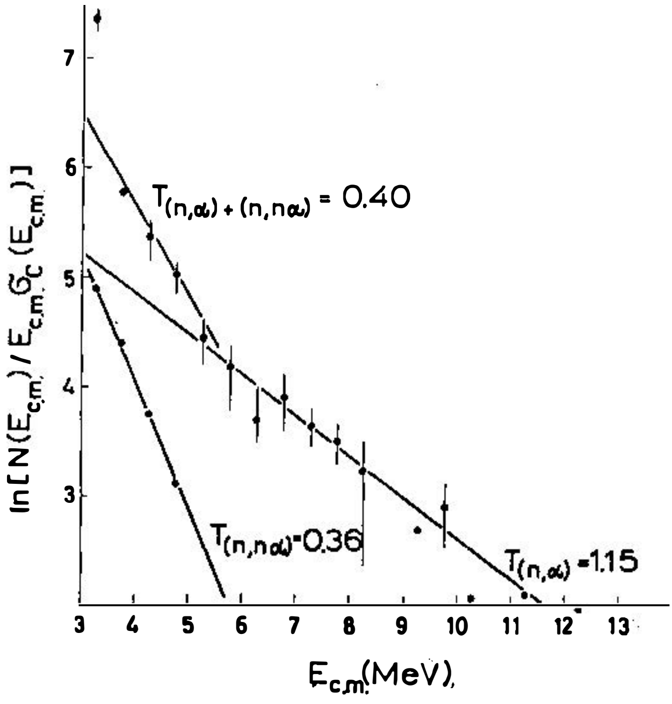

Fig. 5. The relative level density $\ln(N/E\sigma_c)$ as a function of the alpha particle c. m. energy. The errors are statistical errors.

3.2. The reactions $^{40}Ca\,(n, \alpha)\,^{37}A$ *and* $^{40}Ca\,(n, n\alpha)\,^{36}A$. The spectrum of the emitted alpha particles in the c. m. system is shown in Fig. 4. The data were analyzed in a way analogous to that for the (n, p) reaction. The cross section for the formation of the compound nucleus by the inverse process, σ_c, was taken from Huizenga and Igo[13]. The resulting nuclear temperatures are given in Fig. 5 and in Table 2. The pairing energy needed to calculate the parameter a was taken from Cameron[14].

Table 2

Cross sections, nuclear temperatures and level density parameters for the reactions $^{40}Ca\,(n, \alpha)\,^{37}A$ and $^{40}Ca\,(n, n\alpha)\,^{36}A$.

Authors	Bormann *et al.*[5]	Turkiewicz *et al.*[6]	Present experiment
$\sigma_{n,\alpha}$ (mb)	138±20		∾57
$\sigma_{n,n\alpha}$ (mb)	23±6		∾31
$\sigma_{n,n\alpha}/\sigma_{n,\alpha}$	0.167		0.54
$T_{n,\alpha}$ (MeV)			1.15±0.09
$T_{n,n\alpha}$ (MeV)			0.36±0.03
a (MeV^{-1})	5.1±0.4	3.5 4.2*	∾5.1

4. *Discussion*

Our results together with the results obtained by other authors are summarized in Tables 1 and 2. Table 1 shows that our value for the (n, p) cross section is between the values cited in refs.[2] and [4]. The value for the (n, np) cross section is somewhat larger than that obtained by others. This discrepancy may be explained by the fact that in our experiment the lower limit of the proton energy was 2 MeV, whereas in other experiments it was 3 MeV. Concerning the parameter a it should be mentioned that both Katase *et al.*[4] and Allan[2] used for the level density the formula

$$\varrho\,(U) \sim \text{const.}\exp\,[2\,(aU)^{1/2}].$$

* σ_c calculated for the black sphere.

In the present experiment as well as in that performed by Antolković *et al.*[5] the level density formula

$$\varrho(U) \sim U^{-2} \exp[2(aU)^{1/2}]$$

was used. It is therefore expected that our value should be different. The ratio of the parameter a obtained in this experiment to that calculated by Katase *et al*[4] amounts to 1.4 in agreement with theory[15].

In the (n, α) reaction (Table 2.) the value of a obtained from our measurements agrees with the relation deduced from the Fermi gas theory[6]

$$a = A/7.4,$$

where A is the atomic mass of the residual nucleus.

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ISPITIVANJE PROTONA I ALFA ČESTICA IZ REAKCIJA NEUTRONA S JEZGROM ^{40}Ca

D. WINTERHALTER i M. TURK

Institut »Ruđer Bošković«, Zagreb

Sadržaj

Energetski spektri protona i alfa čestica emitiranih bombardiranjem ^{40}Ca neutronima energije 14,6 MeV ispitani su metodom nuklearnih emulzija. Spektri su prikazani na slikama 1 i 4. Izmjerena angularna distribucija protona dana je na sl. 3. Angularna distribucija protona energije veće od 5,5 MeV, koja je dobivena samo iz reakcije ^{40}Ca (n, p) ^{40}K, prikazana je na slici 3b), a slika 3a) prikazuje angularnu distribuciju protona energije manje od 5,5 MeV.

Provedena je analiza eksperimentalnih rezultata primjenom statističke teorije. Dobivene vrijednosti udarnih presjeka, nuklearnih temperatura i parametara gustoće nivoa za reakcije ^{40}Ca (n, p) ^{40}K, ^{40}Ca (n, np) ^{39}K, ^{40}Ca (n, α) ^{37}A i ^{40}Ca (n, nα) ^{36}A nalaze se u Tablici 1 i 2, uporeðeni s podacima drugih autora.