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INELASTIC COLLISIONS BETWEEN DEUTERONS WITH 2.43 GeV/c AND ATOMIC NUCLEI OF PHOTOGRAPHIC EMULSION

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The paper deals with inelastic collisions between deuterons and atomic nuclei during which a high-speed deuteron is emitted as a secondary particle from the nucleus. The particles are identified according to the ionization dependence on $p\beta$. A model of a cascade of interactions of the primary particle and relatively independent static nucleons is used to interpret the observed collisions of deuterons and atomic nuclei. The absorption cross section enables us to evaluate the mean free path of the primary particle inside the nucleus and the probability of single and double interactions in the nucleus. The observed number of secondary deuterons was used to estimate the probability that a deuteron is not disintegrated into its components during a single collision in the cascade inside the nucleus.

I. EXPERIMENTAL MATERIAL AND ITS TREATMENT

All the measurements were performed on a block of nuclear emulsions of NIKFI BR-2 type [$10 \times 20 \times 5$ cm^3], the thickness of one layer being 450 μ. The emulsions had been irradiated in the High Energies Laboratory of JINR in Dubna by a deuteron beam with a momentum of 2.43 GeV/c. The beam characteristics, viz the density of irradiation, the degree of impurity, angular distribution and the properties of the emulsion material, i. e. ionization, spurious scattering etc. were investigated in detail in papers [1] and [2]. The measurements of the track characteristics were performed with a ZEISS KSM 1 microscope using the common technique of measuring.

The interactions were found by means of scanning along the tracks of the primary beam taking into account only interactions with visible secondary tracks. The interactions $(0 + 1)$ were taken into account when the deviation of the secondary high speed particle from the direction of the primary particle was higher than 4°. The choice of the angle of 4° was made in order to eliminate

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the interactions deuteron-nucleus as a whole (Coulomb scattering, diffraction scattering, stripping etc.).

The density of ionization I for 100 μ intervals of tracks together with the density of ionization of the primary track I_0 were measured on all the high-speed secondary tracks by means of counting the gaps between the grains or, eventually, agglomerates of grains of Ag. The total length of a single measured track was ~ 0.5 cm, in order to get a statistical error less than ± 1 gap for 100 μ. Multiple scattering was measured on all secondary tracks for which $I/I_0 \leqslant 1.4$ and the projection length in one emulsion layer was at least ~ 0.5 cm by means of the coordinate method with a basic cell $t = 500\ \mu$. The evaluation of the statistical error in measuring multiple scattering was taken from [3] by the relation $s = 1.09\langle|D|\rangle/n^{1/2}$, where s is the mean square deviation of the measured mean value of the absolute values of the second differencies $\langle|D|\rangle = \sum|D_i|/n$; n is the number of the second differencies D_i of the track coordinates measured perpendicularly to the direction of the particle flight.

The identification of secondary deuterons was performed by means of the dependence I/I_0 on $\ln\langle|D|\rangle^{-1}$ [6]. The results of our measurements are given in Fig. 1. Some points for the values $I/I_0 > 1.4$ were measured on chosen secondary tracks in order to get more easily a semiempirical curve for protons.

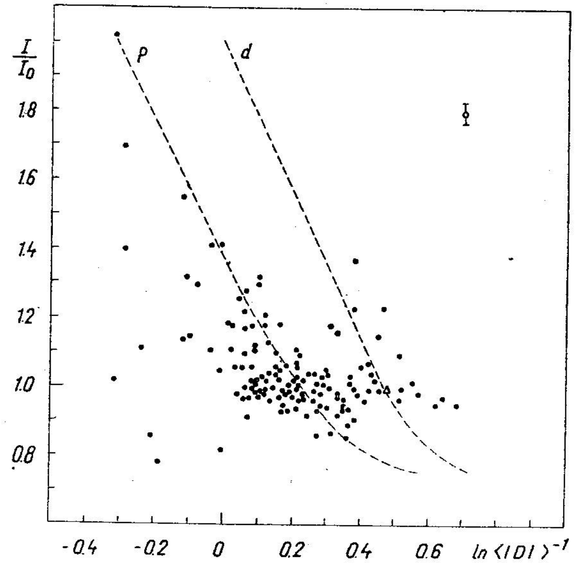

Fig. 1. The dependence of relative ionization I/I_0 on $\ln <|D|>^{-1}$ for secondary particles (Δ marks the primary beam).

The values for a primary deuteron beam are marked by a triangle. The ionization of secondary tracks is related to the values of the primary particles for which β is different from 1 and so our graph is shifted and has another modulus for the axis of ionization than it is usual for primary particles with $\beta = 1$. Semiempirical curves are plotted taking into account the level of noise and errors of measurement [1]. The cases lying nearer to the semiempirical deuteron curve than to the proton curve were identified as deuterons.

II. THE MODEL OF THE PARTICLE-NUCLEUS INTERACTION

To be able to interpret our measurements we use a relatively simple model of interaction as a base. This model appears to be adequate to the amount of information given by our experiment. The atomic nucleus X_Z^A is thought of as a nucleus consisting of relatively independent static nucleons which fill the sphere volume $V_A = 4/3\ \pi R_A^3$, where $R_A = 1.4 \times 10^{-13}\ A^{1/3}$ cm. The decrease in the nucleon matter density near the edges of the nucleus is not taken into account. The interacting particles create a cascade of collisions in the nucleus. Considering the short range and the intensity of strong interaction and the specific properties of nuclear matter (Pauli's principle) we accept the concept of the mean free path of the particle in the nuclear matter. Then the probability that the impinging particle interacts in the nuclear matter just in the interval $(x, x + \mathrm{d}x)$ is given by the relation

$$f(x)\,\mathrm{d}x = \langle L\rangle^{-1}\,[\exp\,(-x/\langle L\rangle)]\,\mathrm{d}x, \tag{1}$$

where $\langle L\rangle$ is the mean free path of the particle inside the nucleus. In the region of high energies $\langle L\rangle$ depends relatively slightly on the energy of the primary particle [4].

We assume that the deuteron impinges on a unit volume of a medium containing one atomic nucleus A. Then the probability that the path of the deuteron centre will intersect the volume of the atomic nucleus is given by the expression

$$\sigma_A = \pi(R_A + \varepsilon_d)^2, \tag{2}$$

where ε_d is the deuteron radius and R_A the nucleus radius. We take the value of 2×10^{-13} cm as ε_d [4], and for all nuclei in a photographic emulsion $\varepsilon_d < R_A$. If there are N nuclei in a volume unit and it is possible to neglect their attenuation (small σ_A), then the total probability $\sigma = N\sigma_A$. Even if the impinging particle passes through the nucleus volume, it does not necessarily mean that a „visible“ interaction will occur. The probability of no interaction of particles passing the nucleus matter with the thickness x is given by

$$G(x) = 1 - \int_0^x f(x)\,\mathrm{d}x = \exp\left(-x/\langle L\rangle\right). \tag{3}$$

For a spherical nucleus we must take into account the distribution of value x, for which we get

$$\eta(x)\,\mathrm{d}x = \frac{1}{2(R_A + \varepsilon_d)^2}\,x\,\mathrm{d}x\,, \tag{4}$$

where x varies in the range from 0 to $2(R_A + \varepsilon_d)$. By means of integrating the expressions (3) and (4) we get the total probability that the particle passes through the nucleus without any interaction

$$P_0 = \int_0^{R_A + \varepsilon_d} G(x)\eta(x)\,\mathrm{d}x = \frac{\langle L\rangle^2}{2(R_A + \varepsilon_d)^2} \times \tag{5}$$
$$\times \left[1 - \{\exp\left[-2(R_A + \varepsilon_d)/\langle L\rangle\right]\}\left(1 + \frac{2(R_A + \varepsilon_d)}{\langle L\rangle}\right)\right].$$

For the case of a complex medium like a nuclear photographic emulsion we get the probability of the interaction

$$P_\Sigma = \sum_i N_i\sigma_{A_i}\left\{1 - \frac{2}{T_i^2}\left[1 + (1 + T_i)\exp\left(-T_i\right)\right]\right\}, \tag{6}$$

where $T_i = 2(R_{A_i} + \varepsilon_d)/\langle L\rangle$, N_i is the number of atomic nuclei A_i in 1 cm^3 of the emulsion. P_Σ depends on the measured mean free path of primary particles in the photographic emulsion $\bar{L}$ according to $P_\Sigma = 1/\bar{L}$. We can measure $\bar{L}$ and we know the composition of the emulsion and, thus, we are able according to (6) to estimate the value $\langle L\rangle$.

By means of an analogous procedure to that used in P_0 we can calculate the probabilities of the single and the double interactions P_1 and P_2. Doing it, we assume that the deviation of the deuteron from the primary direction is small and the value of $\langle L\rangle$ will not change appreciably after the collision. Then we get

$$P_1 = \frac{4}{T^2}\left[1 - \left(1 + T + \frac{T^2}{2i}\right)\mathrm{e}^{-T}\right] \tag{7}$$

and

$$P_2 = \frac{6}{T^2}\left[1 - \left(1 + T + \frac{T^2}{2i} + \frac{T^3}{3i}\right)\mathrm{e}^{-T}\right].$$

When the deuteron collides in the nucleus, it may either continue to be a deuteron or it may be split into its components. If we use X as a symbol of the probability of no splitting, then the probability P_d that a deuteron will be emitted from the struck nucleus is

$$P_d = P_1X + P_2X^2. \tag{8}$$

Since in our case $P_1 > P_2 > P_3 \ldots$ and X is less than 1, the term P_3X^3 and the higher ones are neglected.

III. RESULTS OF MEASUREMENTS

By means of scanning along the track of the total length of the primary track $L = 33\,115.7$ cm, we found $N = 1564$ interactions. After corrections for impurities which constituted on average 8.2 % of the measured tracks [2] and after eliminating interactions (0 + 1) with the deviation of the secondary particle less than 4°, we got the mean free path for the interaction in the emulsion $\bar{L} = 23.4$ cm. On the basis of relations (6) and (2), we can estimate the mean free path of our deuteron inside the nucleus as $\langle L\rangle = 5.2 \times 10^{-13}$ cm. By help of this value we can calculate P_1 and P_2 and we get

$$P_1 \cong 0.30\,, \qquad P_2 = 0.22\,. \tag{9}$$

To be able to solve equation (8) for X we need the value P_d. We identify secondary deuterons on the basis of Fig. 1, yet we must take into account that multiple scattering was measured for angles with a horizontal plane less than ~5°. Since an appreciable quantity of deuterons is emitted at angles higher than 5°, it is necessary to make geometrical corrections. Tab. 1 shows the angular distribution of deuterons with corresponding corrections, separately for interactions (0 + 1) and for the others. We did not measure all the interactions (0 + 1) and, therefore, we had to extend the number of them according to

Table 1

	(0 + 1)		others		
	N	N corrected	N	N corrected	
0– 5	21.1	21.1	6	6	27.1
5–10	21.1	43.6	5.5	11.5	65.1
10–15			4.5	17	17
15–20			4	21.3	21.3
20–25			2	13.7	13.7
together		64.7		69.5	134.2

the total number of interactions $(0 + 1)$ for $\Theta > 4°$. It can be seen from Tab. 1 that the total number of cases with secondary deuterons was estimated as $N_d = 134.2$. From this we get

$$P_d = 0.109 \begin{matrix} + 0.016 \\ - 0.017 \end{matrix}.$$

Fig. 2 shows the distribution of interactions according to the number of evaporating (black) and grey tracks N_h for the whole set of interactions and for the interactions with secondary deuterons. The distribution was normalized to the same area. The comparison is not free from error, because we took the measured deuterons only. Therefore, the number of the interactions with deuterons emitting to high angles was lowered. It is just these stars that give higher evaporation. In spite of this objection it seems to be probable that the interactions with secondary deuterons prefer lower evaporations.

Finally we estimated the lowest limit of energy transferred by deuterons to the nucleus. We measured the range of black tracks and the ionization of high

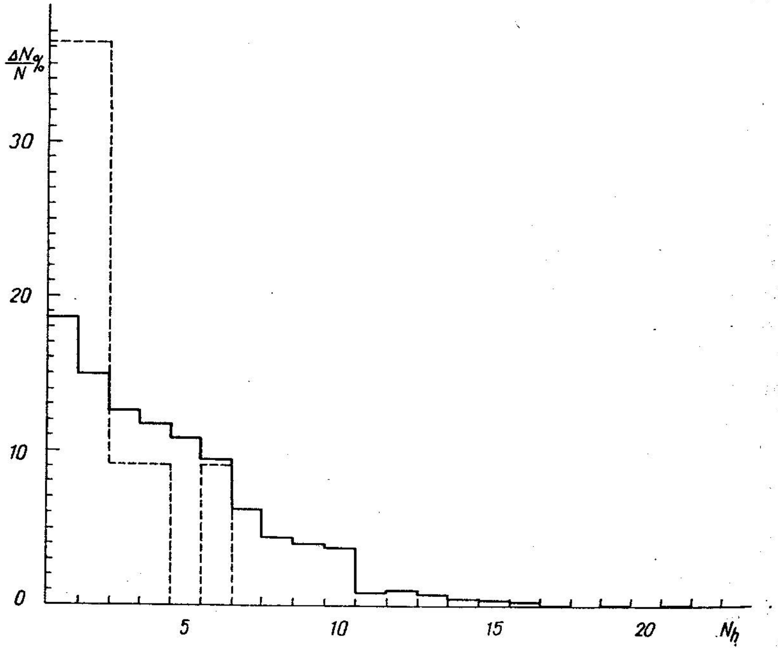

Fig. 2. The distribution of the number of grey and black secondary tracks for the cases of measured interactions and for the interactions with secondary deuterons (dotted line). The distribution was normalized to the same area.

speed tracks and on the assumption that the particles are protons we estimated their energies. This is a rough estimate but even so from 22 stars with secondary deuterons with evaporations in 13 cases the deuterons were transferred to the nuclei at a minimum the energy from 0 to 50 MeV and in 9 cases the energy higher than 150 MeV. The last-mentioned cases correspond probably to double interactions at the primary deuteron inside the nucleus.

IV. DISCUSSION AND CONCLUSION

The main experimental problem of our work was the identification of high-energy secondary deuterons. The high energy of deuterons should be emphasized because it is a factor that reduces the probability that the measured deuteron originated from a cascade and it was struck out of the nucleus. The last-mentioned cases lead to appreciably low values of a secondary deuterons momentum.

The interactions are interpreted by means of a simple model which is only an approximation. Value P_x undoubtedly depends on our model but in our opinion it cannot be very different in reality. From the distribution of the number of secondary particles in the interactions with the secondary deuteron it follows that these interactions occur mainly on light nuclei or on the surface of heavy nuclei. It is in agreement with the assumption that the deuteron interacted only once or at most twice. In spite of this distinctive feature we can see that in some cases an appreciable energy is transferred into the nucleus. Together with a relatively high value of P_x this fact supports the assumption that deuteron in some interactions behave as a whole, despite the low value of its binding energy.

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