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NEUTRON TRANSFER BY THE Be^9 *NUCLEUS*

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The mechanism of Be^8 production in interactions of Be^9 ions of maximum energy 85 MeV with silver and bromine nuclei of nuclear emulsion has been investigated. The angular distribution of Be^8 produced in the ground state has two pronounced peaks in the small-angle region; on the other hand, the angular distribution of Be^8 in the excited states has only a single peak at smaller angles. The Be^8 yield was obtained as a function of the Be^9 ion energy. The collision parameter of the interacting nuclei involved in the formation of the Be^8 nucleus in the ground state is estimated and the value $r_0 \approx 1.95 \times 10^{-13}$ cm is deduced. It is shown that the principal mechanism of Be^8 formation is neutron transfer.

IN the study of interactions of Be^9 ions with emulsion nuclei, the production of Be^8 was rather frequently observed. The Be^8 nucleus is unstable relative to decay into α particles and gives rise, in emulsion, to a characteristic track terminating in two prongs, from which this nucleus can be readily identified.

Owing to energy and momentum conservation, the energies E_1 and E_2 of the α particles produced as a result of the Be^8 decay and the angle between them $\theta_{1,2}$ in the l.s. are related as follows:

$$E_1 + E_2 - 2\sqrt{E_1E_2}\cos\theta_{1,2} = 2Q, \qquad (1)$$

where Q is the excitation energy of the Be^8 nucleus. From the angles and energies of the α particles we can readily obtain the angle and energy of the Be^8 nucleus.

Most likely, the main process leading to the production of Be^8 under these conditions is the process of neutron transfer, although the disintegration process can also make a certain contribution. Since the neutron transfer reactions proceed on the surface of the nuclei, the study of these reactions is of definite interest, since it can be hoped that it will assist us in studying the conditions on the nuclear surface.

Pellicles of NIKFI-D nuclear emulsion 300—400 μ thick were exposed to Be^9 ions accelerated to an energy of 85 MeV in the linear heavy-ion accelerator of the Physico-technical Institute of the Ukrainian Academy of Sciences. The ions entered the emulsion at an angle of 25° to the surface. In the emulsion, α particles could be reliably distinguished from protons.

We selected 284 two-prong stars corresponding to a reaction of the type (Be^9, Be^8) on silver or bromine nuclei. Of these, 146 corresponded, according to relation (1), to the production of Be^8 in the ground state ($Q = 0.1$ MeV, $\Gamma \approx 50$ eV) and 138 corresponded to the production of Be^8 in excited states. The distribution of the Be^8 excitation energies obtained from calculation by relation (1) is shown in Fig. 1.

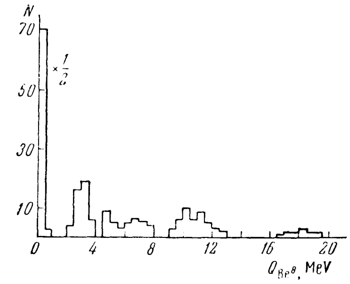


FIG. 1. Distribution of Be^8 nuclei for the energy states Q obtained from two-prong stars according to (1).

The first group on the left corresponds to the production of Be^8 in the ground state. The second and fourth groups correspond to the production of Be^8 in excited states with an excitation energy of $Q = 3$ MeV ($\Gamma = 1.46$ MeV) and $Q = 11.5$ MeV ($\Gamma \approx 6$ MeV), respectively. The fifth group corresponds to energy levels situated close to one another. However, in view of the isospin selection rules, these energy states cannot be obtained by means of the same mechanism as in the case of the other states. Evidently, we have to do here with another mechanism. This group was not included in the considerations that follow. In the 5—8 MeV excitation energy interval, where a third broad group is found, the Be^8 energy level is unknown. Since the initial ion energy was known, then, from the measurements of the Be^9 ion range, we could determine the energy at which the reaction occurred.

The angular distributions of Be^8 produced in the ground and excited states (for the entire interval of Be^9 ion energies) are shown in Figs. 2a and 2b, respectively. Owing to the poor statistics, we were not able to construct the angular distribution separately for each excited state.

In view of the fact that it was impossible to determine whether the reaction occurred on a Ag or Br nucleus, we used a hypothetical nucleus with $Z = 41$ and $A = 94$ for transformation to the c.m.s. and in other calculations.

The angular distribution of the Be^8 nuclei produced in the ground state has two pronounced peaks in the small-angle region. The angular distributions of Be^8 for two energy intervals of Be^9 ions, less than and greater than 65 MeV (not shown in the figures), have the same structure with a slight broadening and shift of the second peak toward the larger angles as the Be^9 energy ion decreases.

The occurrence of two peaks in the angular distribution of Be^8 in the ground state indicates the existence of two mechanisms for the production of this nucleus. In accordance with the theoretical considerations of Breit and Abel,[1] the peak at large angles is apparently due to the tunnel mechanism of neutron transfer, which has the greatest probability when the bombarding ion is as close as possible to the target nucleus without yet penetrating the Coulomb barrier.

The peak at smaller angles is apparently due to the grazing interaction[2], where the bombarding ion penetrates the Coulomb barrier and interacts with the attractive potential of the target nucleus. The attractive potential counteracts the repulsion due to the Coulomb field of the nucleus and decreases the resulting deflection. This leads to a peak in the angular distribution at small angles.

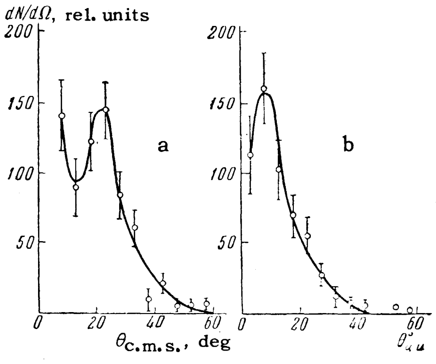
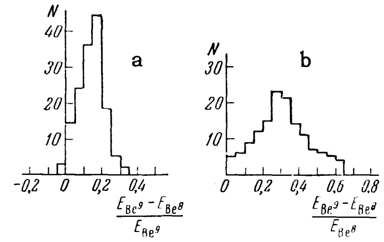


FIG. 2. Angular distributions for Be^8 nuclei in the c.m.s. a) For Be^8 production in the ground state; b) for Be^8 production in excited states (the sum of all excited states). The solid curves were drawn through the experimental points.

In the angular distribution of Be^8 produced in excited states (Fig. 2b) only one peak is observed at small angles. It is apparently due mainly to grazing interactions, although it is not excluded that it is partly the result of the tunnel mechanism. Perhaps this is an indication of a combined effect due to several excited states.

Figure 3 shows the relative energy loss in the interaction. In the case of Be^8 production in the ground state, this nucleus retains 85—90% of the initial ion energy. In the production of Be^8 in excited states, the distribution of the relative energy loss is considerably broader. This is evidence of the more intensive exchange of energies between the interacting nuclei, as a result of which both nuclei go into strongly excited states.

FIG. 3. Relative energy loss in interactions with Be^8 production in the ground state (a) and Be^8 production in excited states (b).



It is probable that when Be^8 is produced in the ground state, the Ag or Br nucleus remains in the ground state or in low-lying excited states, whereas the production of Be^8 in excited states proceeds with a much greater energy exchange between the interacting nuclei, as a result of which the Ag or Br nucleus also remains in a strongly excited state.

In the plot of the energy dependence of the excitation function (Fig. 4), we observe a sharp change in behavior for Be^9 ion energies of 55—60 MeV, and with a further increase in the energy the cross section for the neutron transfer reaction no longer increases. Such a behavior of the excitation function can be explained in the following way. Above the energy threshold, the probability for neutron transfer increases rapidly with increasing energy of the bombarding ion until the interaction distance reaches the absorption radius R_a. This corresponds to a rapid increase in the excitation function above threshold. With a further increase in energy, that is, as the interacting nuclei approach closer to each other, the probability for the neutron transfer process begins to drop rapidly, since for interaction distances less than the radius R_a, the process in which Be^9 is absorbed by silver or bromine starts to compete strongly. This is reflected by the change in slope and the smoothing of the excitation function.

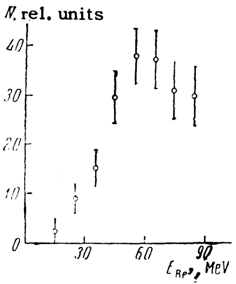


FIG. 4. Yield of Be^8 as function of Be^9 ion energy.

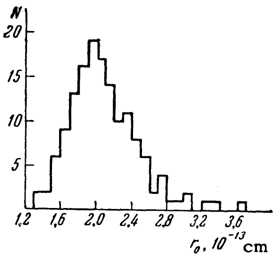


FIG. 5. Distribution of r_0 values for the production of Be^8 in the ground state.

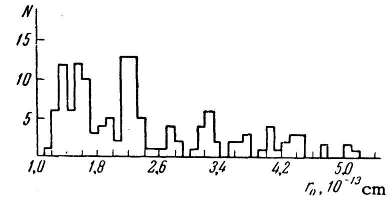


FIG. 6. Distribution of r_0 values for the production of Be^8 in excited states (the sum of all excited states).

It is of interest to estimate the most probable value of the interaction distance (distance of closest approach of the interacting nuclei R_{min}) at which the neutron transfer occurs. If it is assumed that the bombarding ions follow Rutherford trajectories, then the distance of closest approach of the interacting nuclei is given by the following relation:

$$R_{min} = \frac{Z_1 Z_2 e^2}{2E}\left(1 + \operatorname{cosec}\frac{\theta_0}{2}\right), \qquad (2)$$

where $R_{min} = r_0(A_1^{1/3} + A_2^{1/3})$; here Z_1e and Z_2e are the charges of the interacting nuclei, A_1 and A_2 are their mass numbers, E is the energy of the bombarding ion, and θ_0 is the angle of emission of the reaction product (Be^8) (all in the c.m.s.).

Histograms of the values of r_0 are shown in Figs. 5 and 6, respectively, for the production of Be^8 in the ground and excited states. The value $r_0 \approx 1.95 \times 10^{-13}$ cm, obtained in the case of Be^8 production in the ground state if allowance is made for the fact that the present data are averaged over two nuclei (Ag and Br), is in rather good agreement with the value $r_0 = 2.15 \times 10^{-13}$ cm obtained by Newman (private communication) for the case of neutron transfer and the production of both final products in the ground state. Some broadening of the histogram toward large values of r_0 can be explained by the existence of two interaction mechanisms. In the grazing interaction, which occurs at smaller collision parameters, the attractive nuclear potential decreases the resulting deflection of the reaction products, which, with the use of relation (2), leads to an apparent increase in the interaction distance. This obviously leads to the broadening of the histogram.

In the case of Be^8 production in excited states, the quantity r_0 cannot be assigned any definite value (Fig. 6). The histogram has, in fact, two quite definite groups of values of r_0: one in the region $r_0 \sim (1.3-1.6) \times 10^{-13}$ cm and the other in the region $r_0 \sim (2.1-2.3) \times 10^{-13}$ cm. If we start, first, from the assumption that Be^8 is produced in the excited state as a result of grazing interactions, as follows from their angular distribution (Fig. 2b), and, second, that the stronger excitations of the interacting nuclei arise for interactions at smaller distances, then, according to (2), a slight excitation of the final reaction products should lead to a small apparent increase in r_0 as compared to r_0 for the ground state. Consequently, the second group of values of r_0 in Fig. 6 can be explained as being due to the production of the reaction products in states with a small excitation in grazing interactions.

For interactions at smaller distances the attractive nuclear potentials cannot fully offset the Coulomb repulsion of Be^8, but can cause a still greater deflection (which is not observed in angular distribution in Fig. 2b), which, according to relation (2), should give a value of r_0 smaller than for the ground state.

It is doubtful, however, that relation (2) is applicable in the case of such excitations. Moreover, the cross section of such a process should be extremely small, owing to the strongly competitive absorption process. Hence further investigations in which data for each excited state are obtained are necessary for any definite conclusions.

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[1] G. Breit and M. E. Ebel, Phys. Rev. 103, 679 (1956).

[2] R. Kaufman and R. Wolfgang, Phys. Rev. 121, 192 and 206 (1961).

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