THE $O^{16}(\pi, \pi')4\alpha$ *REACTION FOR 80-MeV* π^+ *MESONS*

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Disintegration of O^{16} nuclei into four α particles as a result of inelastic scattering of 80-MeV π^+ mesons by the nuclei was investigated with the aid of photographic emulsions. The cross section for the reaction was found to be 7.3 ± 1.7 mb. A kinematic analysis of the found stars reveals that in more than half of the reactions direct emission of the α particles occurs with formation of an intermediate C^{12} nucleus with excitation energies 9.6 and 13 MeV.

1. INTRODUCTION

THE disintegration of the O^{16} nucleus into four α particles was investigated in several studies, in which the bombarding particles were γ quanta[1-3] and protons[4]. It was established[1,2] that this reaction proceeds in approximately 50% of the cases via an intermediate C^{12} nucleus excited to a 9.6-MeV level and decaying with formation of Be^8 in the ground state. Millar and Cameron[3] found that at γ-quantum energies up to 27 MeV the $O^{16}(\gamma, 4\alpha)$ reaction follows the schemes

$$O^{16} + \gamma \to 2\alpha + Be^8,$$
$$O^{16} + \gamma \to 4\alpha.$$

A similar conclusion was reached by Kolar[4], who investigated in a cloud chamber the disintegration of O^{16}, induced by protons with energy 29 MeV. However, the experimental conditions in[4] were such that there was some probability of missing stars containing tracks of low-energy particles. As shown by Bogatin et al[5], who investigated the reaction $C^{12}(\pi, \pi')3\alpha$, the energy released in such reactions is 10—15 MeV, and it is therefore very important to ensure conditions for the best observation of disintegrations with low-energy particles. We have analyzed the $O^{16}(\pi, \pi')4\alpha$ reaction using a nuclear emulsion method, which is convenient for these purposes. A comparison of the observed decays of O^{16} into four α particles with the data of[5] for the $C^{12} \to 3\alpha$ process has led to several conclusions concerning the mechanism of the former reaction.

2. EXPERIMENT

Plates with PR fine-grain nuclear emulsion sensitive to relativistic particles were bombarded by 80 ± 6 MeV positive pions in the synchrocyclotron of the Joint Institute for Nuclear Research. The experimental conditions were identical to those described in[5]. The total volume of the scanned emulsion was 1.25 cm^3, and contained 170 registered stars with tracks of 4 heavy low-energy charged particles and of one fast particle.

Assuming that these stars correspond to the reaction

$$O^{16} + \pi \to \pi' + 4\alpha, \qquad (1)$$

we made a least-squares check of the compatibility of the four energy and momentum conservation equations using two equations to obtain the momenta of the incident and scattered mesons. All the calculations were made with the Ural-2 electronic computer. The following criteria were used to check on the correct identification of the star with reaction (1):

1. Agreement between the calculated initial meson momentum P_0 and its experimental value 170 MeV/c. Actually some scatter of stars about P_0 was obtained (see Fig. 1), with a greater width than called for by the experimental conditions. This is due to errors in the calculations, and also to a possible dependence of the cross section of the

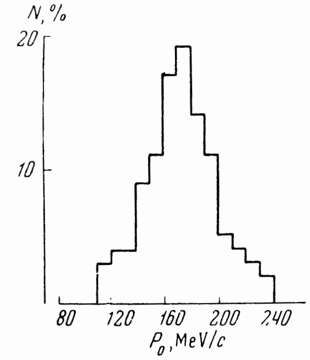

FIG. 1. Calculated meson momentum distribution.

reaction (1) on the meson energy. We excluded from further consideration all cases for which P_0 was outside the interval 110—240 MeV/c.

2. The quantity $D = [(\Delta x)^2 + (\Delta y)^2 + (\Delta z)^2]^{1/2}$ (see [5]), which characterizes the degree of compatibility of all four conservation equations. The form of the distribution of events with respect to D is close to that of $D^2 \exp(-D^2/2\sigma^2)$ with $\sigma = 20$ MeV/c and with an anomalous "train" towards the larger D. An analogous expression in [5] included two coordinates (x and y) with approximately the same value of σ. We discarded stars for which D exceeded 60 MeV/c.

3. Agreement between the grain density in the track of the fast scattered particle and the calculated value of its energy. The comparison was made with the aid of a grain density vs. meson energy plot, obtained from observations of $\pi - \mu - e$ decay and elastic π-p scattering events in the same emulsion.

In addition to stars with four α-particle tracks, a kinematic check was made also on those 3-prong disintegrations which were not attributed to the reaction

$$C^{12} + \pi \rightarrow \pi' + 3\alpha \qquad (2)$$

as a result of the analysis made in [5]. Altogether we checked in our work 160 such stars under the assumption that they belonged to reaction (1). The computation scheme for these stars was as follows: using the four conservation equations we determined the components of the momentum of the "invisible" α particle and the momentum of the scattered meson, specifying the value of P_0 in the interval 110—240 MeV/c. The star was credited to the reaction (1) if the energy of the "invisible" α particle was less than 0.5 MeV and if the last two criteria were satisfied at the same time.

We selected altogether 97 stars (including 17 with three α-particle tracks) satisfying the foregoing criteria. Eighteen of these contained the track of an α particle which did not stop in the emulsion. Calculation of the correction for the emergence of the particles from the emulsion, assuming this emergence to be isotropic, yielded the same result.

Assuming that the oxygen content of the PR emulsion is 0.283 g/cm^3, we obtained a value 7.3 ± 1.7 mb for the cross section of reaction (1). The error includes the inaccuracies in the π^+-meson flux and in the volume of scanned emulsion, and the statistical error in the number of obtained stars.

The angular distribution of the scattered mesons is shown in Fig. 2.

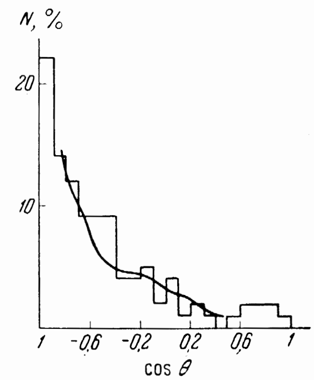

FIG. 2. Angular distribution of scattered mesons in the $O^{16}(\pi, \pi')4\alpha$ reaction. The curve is drawn on the basis of the data of [6] with normalization at the point $\theta = 135°$.

3. ANALYSIS

The presence of C^{12} nuclei as the intermediate product in the reaction (1) can be established from the resonances on the curve showing the distribution of the analyzed events, using the quantity

$$U(C^{12}) = \sum_{k=1}^{3} E_k + 7.28\ \text{MeV},$$

where E_k—kinetic energy of the α particle in the center-of-mass system (c.m.s.) of the three chosen particles. In each star there are four such 3-particle combinations, which leads to four values of $U(C^{12})$; one of these can have a physical meaning—it can characterize the excitation energy of the C^{12} nucleus which decays into α particles. This distribution is shown in Fig. 3, from which it can be seen that two peaks are clearly produced near 10 and 13 MeV. These resonances correspond to C^{12} excitation levels 9.6 and 12.7 MeV.

From the numerous investigations of the disintegration of C^{12} into α particles it is known that the decay from the 9.6 MeV level proceeds with

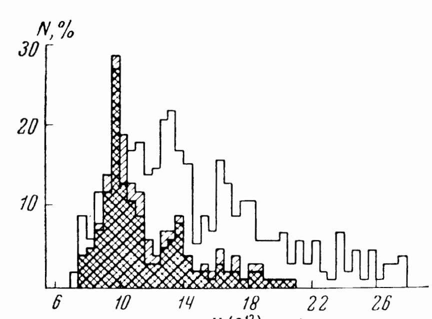

FIG. 3. Distribution of 3α combinations relative to the quantity $U(C^{12})$; single cross hatching—3α combination for stars where there is one state with $U(C^{12}) = 9 - 10.5$ MeV; double cross hatching—3α combination including states with $U(Be^8) < 0.4$ MeV.

formation of Be^8 in the ground state, followed by dissociation into two α particles. From the distribution relative to the quantity

$$U(\mathrm{Be}^8) = \sum_{i=1,2} E_i + 0.1\ \mathrm{MeV},$$

where E_1 and E_2—c.m.s. energies of the two α particles, we can verify that the decay of the 3-particle states with $U(C^{12})$ in the interval 9—10.5 MeV proceeds almost exclusively via 2-particle states with excitation energy lower than 0.4 MeV. The overwhelming majority of these 2α combinations yields $U(Be^8) < 0.2$ MeV, and each 3α state contains only one 2-particle combination with excitation energy lower than 0.4 MeV.

To check further on the correctness of the identification of the first 3α resonance with the 9.6-MeV level of C^{12} we observed the angular correlation of the α particles produced by the decay of this state. In particular, we found that the planes of production and decay of the C^{12} are strongly correlated, in analogy with what was found in [5] for the decay of C^{12} from the 9.6-MeV level, which, as is well known, has spin and parity 3^-

We note also that the form of the distribution relative to $U(C^{12})$ coincides well in the region of the first peak with the analogous distribution obtained in [5]. On the basis of these considerations we conclude that approximately 40% of the reaction (1) proceeds in accordance with the scheme

$$O^{16} + \pi \rightarrow \pi' + \alpha_1 + C^{12*}(9.6\ \mathrm{Mev}),$$

$$C^{12*} \rightarrow \alpha_2 + Be^8, \quad Be^8 \rightarrow \alpha_3 + \alpha_4. \qquad (3)$$

The question of the mechanism of the emission of α_1 can be solved by investigating the angular distribution of these particles. If the α_1 are emitted by the O^{16} nucleus excited by inelastic scattering of the mesons, then the emission of α_1 should be isotropic in the system of the O^{16} nucleus, for at the excitation energies 15—30 MeV realized in our experiment the O^{16} nucleus has many close-lying levels from which emission of an α particle is possible. It was found that the α_1 are emitted forward relative to the direction of the bombarding-meson beam in more than 3/4 of all cases proceeding via scheme (3). We should conclude therefore that a direct interaction takes place between the meson and the nucleus, resulting in the knock-out of the α particle.

An analysis of the 3-particle states with $U(C^{12})$ near 13 MeV was made in similar fashion. It is clear from Fig. 3 that there are a few stars in which two 3α combinations are encountered, giving values $U(C^{12})$ near 10 and 13 MeV. To

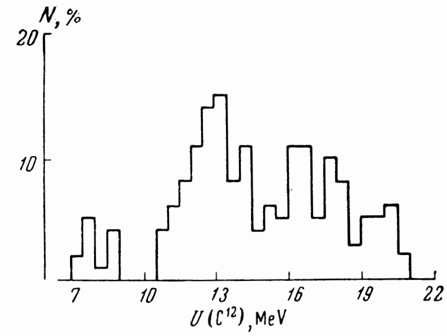

FIG. 4. Distribution of 3α states relative to the quantity $U(C^{12})$ in stars having no 3α states with $U(C^{12}) = 9 - 10.5$ MeV.

separate the 3α states with $U(C^{12}) \sim 13$ MeV, the distribution relative to $U(C^{12})$ was plotted in Fig. 4 for those stars in which 3α states with $U(C^{12}) = 9 - 10.5$ MeV were not realized. The 3α states with $U(C^{12}) = 12 - 13.5$ MeV do not contain 2-particle combinations that give the ground state of Be^8 (see Fig. 3). This is is seen more clearly in Fig. 5. The maximum of the distribution relative to $U(Be^8)$ in the 3 MeV region can be regarded as a resonance of $\alpha\alpha$ interaction with energy 2.9 MeV. The same figure shows the distribution calculated under the assumption of a simultaneous $C^{12} \rightarrow 3\alpha$ disintegration with account of the 2α interaction at a relative-motion energy 2.9 MeV[5].

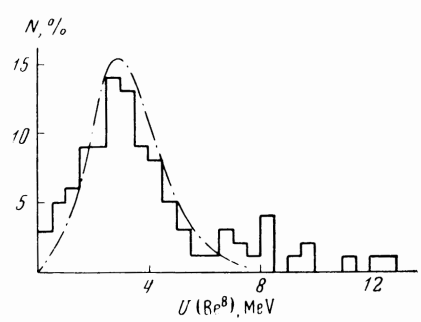

FIG. 5. Distribution of 2α combinations relative to the quantity $U(Be^8)$ in stars where there is a 3α state with $U(C^{12}) = 12 - 13.5$ MeV. The curve is constructed from the formula for simultaneous disintegrations with account of resonant $\alpha\alpha$ interaction at $E_{res} = 2.9$ MeV.

The angular dependences of the α particles from the decay of the 3α system with resonance at 13 MeV are similar to those obtained for the 9.6-MeV state. This can signify that at $U \sim 13$ MeV the spin of the C^{12} state differs from unity, and that the emission of α_1 proceeds via direct interaction of the incident meson with α_1. Consequently, approximately 1/5 of all the disintegrations (1) proceed via scheme (3) with formation of a C^{12} nucleus excited to 12 — 13.5 MeV.

In addition to the indicated two C^{12} states, other levels of this nucleus are apparently also realized in reaction (1), particularly with energy 7.6 MeV, although with much lower probability. The distribution relative to $U(Be^8)$ for stars in which there are no states with $U(C^{12})$ in the 9 − 10.5 and 12 − 13.5 MeV ranges, is described satisfactorily by the model in which O^{16} disintegrates simultaneously into four α particles.

The experimentally obtained disintegrations with four heavy-particle tracks were also checked with an aim to observe among them cases of the reactions

$$O^{16} + \pi^+ \to p + n + 2\alpha + {}_3Li^6 + {}_3Li^6, \qquad (4)$$

$$O^{16} + \pi^+ \to p + \pi^0 + 3\alpha + {}_2He^3. \qquad (5)$$

The check was made in analogy with the main check indicated in Sec. 2, the difference being that the number of unknowns to be determined increased to four (the proton momentum and the three components of the neutral-particle momentum), and the criterion for correct identification of the reaction was only the measurement of the grain density in the proton track. Nevertheless, none of the obtained 4-prong stars could be attributed to reaction (4) or (5). It should be noted, however, that in scanning the emulsion some number of stars corresponding to the absorption reaction (4) or to the charge exchange (5) could be discarded as patently not satisfying the scheme (1).

A sample test was also made of 18 three-prong stars for which D turned out to be larger than 60 MeV/c, with an aim of identifying them with the reactions

$$O^{16} + \pi^+ \to \pi^+ + \alpha + {}_3Li^6 + {}_3Li^6, \qquad (6)$$

$$N^{14} + \pi^+ \to \pi^+ + 2\alpha + {}_3Li^6. \qquad (7)$$

It was found, however, that none of the 18 disintegrations could be attributed to processes (6) and (7) from kinematic considerations.

4. DISCUSSION

The cross section for the disintegration of the nucleus O^{16} into four α particles, obtained in the present work, was almost half as large as the cross section of reaction (2) at the same meson energies. This can be connected with the higher energy threshold and with the larger role of the competing processes in the former case. At the same time, the angular dependences of the cross sections for the reactions (1) and (2) are identical. Figure 2 shows the measured differential cross section for inelastic scattering of 87-MeV π^+ mesons by oxygen, measured in [6] by electronic methods. It is evident that at approximately identical energy losses (12—24 MeV), the angular dependences of the other channels [for example $O^{16}(\pi, \pi'p)$ or $O^{16}(\pi, \pi'n)$] are similar to (1) in the angle range 70—140° c.m.s., in which the measurements of [6] were made; unfortunately the most interesting scattering-angle region ($\theta \sim 180°$) was not investigated there.

Unlike the reaction with C^{12}, the pion-induced emission of an α particle from O^{16} has more clearly pronounced features of direct interaction. This difference might serve as evidence of large spatial localization of the α clusters in the O^{16} nucleus. In such an interpretation, however, we must bear in mind a circumstance connected with the difference in the thresholds of (1) and (2). For process (2) to be realized the meson should leave in the nucleus an energy ~12 MeV, so that the α particle with which the interaction took place would have outside the nucleus an energy less than 3 MeV. This is insufficient for a fast surmounting of the Coulomb and centrifugal barriers, and we therefore observe formation of an excited C^{12} nucleus. In direct collision between the meson and the α group in O^{16}, the latter should acquire, in accordance with the scheme (3), an energy in excess of 8 MeV, enough to leave the nucleus.

Of definite interest are investigations of the reaction $O^{16}(\pi, \pi'\alpha)$ at energy transfers below the threshold of reaction (1), so that the corresponding energy conditions for the direct emission of the α particle from C^{12} and O^{16} are identical. The results of such experiments would help draw more definite conclusions concerning the difference in the degree of overlap of the α-particle configurations in these nuclei.

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