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BREAKUP OF C^{12} INTO THREE ALPHA PARTICLES ACCOMPANYING INELASTIC SCATTERING OF 80-MeV π^+ MESONS

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The breakup of the C^{12} nucleus into three α particles accompanying the inelastic scattering of 80-MeV π^+ mesons is studied in nuclear emulsions. Excitation of C^{12} to the 9.63-MeV level is found to contribute ~ 20% to the reaction cross section. The angular correlation of the decay products indicates that the spin of this level is greater than 1. The experimental data on the energy distribution of the α particles can be explained by assuming simultaneous breakup of the C^{12} nucleus into three α particles with resonance interaction of the particles in the final state.

INTRODUCTION

MANY investigators have studied the breakup of C^{12} into three α particles induced by neutrons or protons.[1-12] Results obtained with low-energy (10—15 MeV) nucleons have shown that this reaction proceeds via a C^{13} or N^{13} compound nucleus. With increasing beam energy direct interactions begin to play an important part. Beginning at 100 MeV the reaction $C^{12}(p, p')3\alpha$ can be regarded as the quasi-elastic scattering of a fast proton on subgroups of nucleons, resulting in the emission of α particles.[10-12]

The breakup of a compound nucleus produced in a low-energy interaction is described by Sachs's model,[13] based on the hypothesis of statistically independent particle emission with an energy spectrum determined only by the corresponding phase volume. However, in many experimental investigations the intermediate formation of a Be^8 nucleus in either the ground state or an excited state has been observed; this conflicts with the foregoing hypothesis. It has been shown in [8,9] that interactions between the emitted particles, resulting in correlated pairs of α particles, must be taken into account. By introducing a correlation function Vasil'ev, Komarov, and Popova obtained good agreement between their calculations and experiments.

At high bombarding energies the model of four-particle breakup becomes unsatisfactory. The $C^{12}(p, p')3\alpha$ process was analyzed in [10] on the basis of Sachs's model without including the scattered proton in the number of particles among which the energy is distributed statistically. A comparison in [10] with the observation of C^{12} breakup induced by 100-MeV protons has shown that this modification of the simultaneous breakup model is unsatisfactory and that we must consider the possibility that an unstable Be^8 system is formed.

It was desirable to obtain data on the $C^{12} \to 3\alpha$ reaction using as projectiles high-energy pions, whose de Broglie wavelength is considerably greater than that of protons having the same energy. Only one previous investigation was known in which C^{12} was split into three α particles by pions;[14] this was done with 60—125-MeV mesons, and did not reveal the presence of a Be^8 nucleus as an intermediate state. It was therefore concluded that the three-particle breakup of C^{12} is a suitable model. However, this conclusion was based on small statistics (only 25 emulsion events were observed) and is therefore not entirely convincing.

In the present work we aimed to obtain a large amount of data on the $C^{12}(\pi, \pi')3\alpha$ reaction as a basis for conclusions regarding the reaction mechanism. Nuclear emulsions are very suitable for this kind of problem.

EXPERIMENT

Plates bearing a type-PR fine-grain nuclear emulsion were irradiated with a beam of π^+ mesons from the synchrocyclotron of the Joint Institute for Nuclear Research. A beam of mesons having 170 ± 8 MeV/c momentum was defined by

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means of a magnetic field and a collimator system. The meson beam entered the emulsion at a 4° angle.

The scanners selected stars produced by pions and containing tracks of three α particles plus the scattered meson. The geometric parameters of visible tracks in the selected stars satisfied momentum conservation for the reaction

$$C^{12} + \pi = \pi' + 3\alpha. \tag{1}$$

Track lengths and angles were measured conventionally under a microscope with 100×15×1.5 magnification. Vertical projections were measured with a lever-type micrometer having 1-μ scale divisions; horizontal projections were measured to within 0.3 μ.

EXPERIMENTAL RESULTS

The scanned emulsion volume was 1.17 cm^3; 393 stars were selected for further analysis. The next step consisted in a qualitative check that these events had been identified correctly as the breakup of C^{12} into three α particles. A system of equations based on energy and momentum conservation was applied to each star:

$$p_{0x} = p_{1x} + \sum p_{\alpha x}, \tag{2a}$$

$$p_{0y} = p_{1y} + \sum p_{\alpha y}, \tag{2b}$$

$$p_{0z} = p_{1z} + \sum p_{\alpha z}, \tag{2c}$$

$$\sqrt{p_0^2c^2 + \mu^2c^4} = \sqrt{p_1^2c^2 + \mu^2c^4} + \sum E_\alpha + Q. \tag{2d}$$

Here p_{0x}, p_{0y}, and p_{0z} are the momentum components of the incident pion; p_{1x}, p_{1y}, and p_{1z} are those of the scattered pion; $\Sigma p_{\alpha x}$, $\Sigma p_{\alpha y}$, and $\Sigma p_{\alpha z}$ are the combined components for the α particles, which have the combined kinetic energy ΣE_α; Q = 7.28 MeV is the reaction energy. The x axis is the horizontal-projection direction of the incoming meson track; the y axis lies in the emulsion plane; the z axis is the line of sight.

In order to simplify the calculations, Eq. (2d) was linearized with respect to p_0 and p_1 with good accuracy in the momentum range 100–200 MeV/c. Since the incoming and outgoing meson directions are known, the only unknown quantity in the system (2) is the scattered meson momentum p_1. The first test to determine whether any given star fitted the carbon breakup interaction (1) was the agreement between the values of p_0 obtained experimentally and by solving the equations (2).

The method of least squares was used to solve for p_0 and p_1 in (2). Straight lines representing the equations in (2) were plotted on the (p_0, p_1) plane. Since vertical momentum projections are ordinarily measured less accurately, Eq. (2c) was usually dropped from these calculations. It was also required for simplicity that the desired point $(p_0; p_1)$ should lie on a straight line representing (2d). This is based on the fact that energy values are determined with considerably greater accuracy. The position of a $(p_0; p_1)$ point was therefore determined by minimizing the quantity $(\Delta x)^2 + (\Delta y)^2$, where Δx and Δy are the respective deviations for (2a) and (2b). Figure 1 shows the distribution of events with respect to the calculated values of p_0. We excluded stars for which the calculation yielded a value of p_0 lying outside the interval 100–250 MeV/c. The calculated momentum distribution in the meson beam was approximately twice as wide as the experimental distribution; this can be attributed, of course, to inaccuracy of the measurements.

The second selection criterion was based on the magnitude of $D^2 = (\Delta x)^2 + (\Delta y)^2 + (\Delta z)^2$. Figure 2 shows the star distribution with respect to D. Stars for which D > 50 MeV/c, which corresponds to the emission of a 1.3-MeV neutron, were also rejected. The distribution of D resembles a Maxwellian curve[15] with the parameter 18 MeV/c.

Since Eq. (2c) was often not taken into account in solving for p_0 and p_1, the distribution with re-

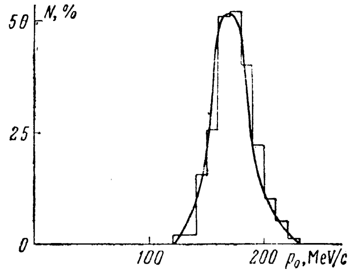

FIG. 1. Calculated momentum distribution of incident pions.

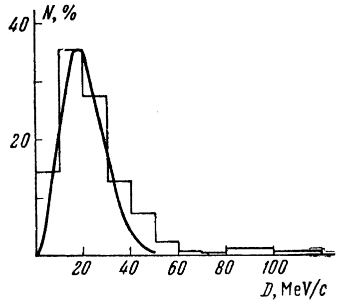

FIG. 2. Star distribution with respect to the deviation $D = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}$. The curve is a Maxwell distribution with the parameter 18 Mev/c.

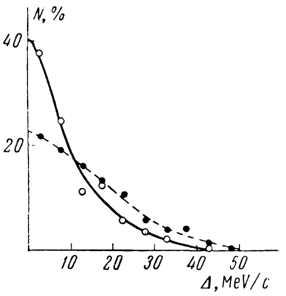

FIG. 3. Star distribution with respect to the deviations Δx, Δy, and Δz. Open circles – Δx and Δy; solid circles – Δz.

spect to Δz was broader than those with respect to Δx and Δy (Fig. 3). Distributions for which Δz was unusually large (greater than 40 MeV/c) were also excluded from our statistics.

The foregoing selection procedure left us 233 stars, which we assigned to the reaction (1). Some of the originally selected stars included α-particle tracks not stopping in the emulsions. These stars were subjected to a similar kinematic analysis, with the difference that three quantities (p_0, p_1, and the momentum of the escaping α particle) were determined. The system (2) was solved and the aforementioned criteria were applied. We found 24 stars with a single escaping α particle; these stars were included in the total statistics of 233 events. A correction for the escape of tracks from the emulsion can also be determined geometrically from the known energy spectrum of α particles in C^{12} breakup. This correction was found to be 12%, thus agreeing with the directly observed number of stars having an escaping α particle.

The pion flux was determined to be $(1.00 \pm 0.11) \times 10^6\ \text{cm}^{-2}$ from the track count of particles in the incident beam. The indicated error includes the statistical spread of the number of tracks and inaccuracy in evaluating the muon admixture.

The muon content of the beam was taken to be 15 ± 5%.[16] Assuming that the carbon content of the PR emulsion was 0.27 g/cm^3, the cross section for the reaction (1) was 14.6 ± 3.6 mb. The indicated error includes the statistical error and inaccuracies in determining the scanned emulsion volume and the flux. By rescanning we found that the efficiency of star detection was close to 100%. The distribution of C^{12} breakups with respect to the azimuthal angle of meson scattering exhibits some anisotropy; there is a reduced number of events with pion emission at small angles to the emulsion plane. This is obviously associated with smaller registration efficiency for inclined tracks of lightly ionizing particles. An estimate indicates that the cross section obtained for (1) should be increased by about 10% to account for the omission of stars lacking a visible scattered meson track.

The foregoing value of the cross section does not include some inelastic scatterings of mesons on C^{12} with the excitation of the 7.66-MeV level since a considerable fraction of such stars can be overlooked in scanning as a result of small energy release.

While collecting approximately half of the statistics (209 stars out of the total initial number 393) we also noted stars containing only two α-particle tracks and a scattered meson track. These 15 stars were also tested for conservation of energy and momentum.

Equations (2) were solved for p_1 and for the three momentum components of the "invisible" α particle. An event was assigned to (1) whenever the calculated energy of this α particle did not exceed 0.2 MeV (which represents approximately the conditions for observing the track in the emulsion). We thus selected and included in the total statistics 5 stars with two α-particle tracks. According to a rough estimate in [15], 5–10% of the $C^{12} \rightarrow 3\alpha$ stars lack one α-particle track; this agrees with our data.

The angular distribution of scattered pions is characterized by pronounced backward peaking (Fig. 4) which varies very little with changing energy loss through scattering.

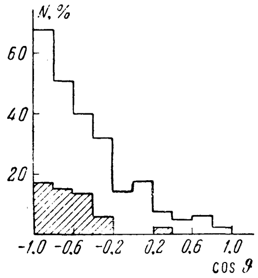

FIG. 4. Angular distribution of scattered pions. The shaded histogram represents events satisfying the condition $8.5 < U_C < 10.5$ MeV.

Figure 5 shows the distribution of events with respect to U_C, determined from the relation

$$U_C = \sum T_\alpha + Q,$$

where ΣT_α is the total kinetic energy of α particles in the c.m. system.

If inelastic pion scattering by carbon results in excited C^{12} nuclei, Fig. 5 should exhibit peaks corresponding to known C^{12} levels. The experimental data clearly indicate the 9.63-MeV level.

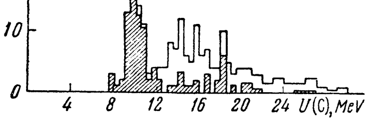

FIG. 5. Star distribution with respect to U_C, the excitation energy of C^{12} nuclei. The shaded histogram represents events where $U_{Be} < 0.5$ MeV.

The 7.66-MeV level is also probably excited, although only few of the corresponding events were registered, as a result of experimental difficulties.

Above 12 MeV the C^{12} levels are very close and can be resolved only with extreme difficulty in our experiment. We can assume that the 14-, 16-, and 18-MeV peaks in Fig. 5 correspond to C^{12} levels at 14.05 and 15.62 MeV and to a series of levels in the interval 18—19 MeV.

The fact that the distribution over U_C terminates at ~ 8 MeV is additional evidence of a clear-cut selection of events. Stars incorrectly identified with $C^{12} \rightarrow 3\alpha$ events would be represented by an unlimited range of U_C beginning with zero.

Figure 6 shows the distribution of all possible α pairs in the observed stars with respect to U_{Be} (the Be^8 excitation energy), obtained from the relation

$$U_{Be} = U_C - {}^3/_2 T_1 - Q_1$$

in which T_1 is the energy of the α particle not included in Be^8, and $Q_1 = 7.38$ MeV.

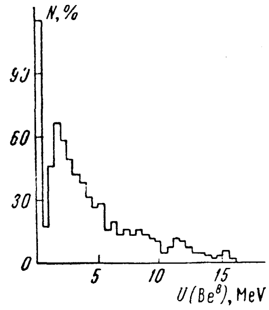

FIG. 6. Distribution of α-particle pairs with respect to U_C for all stars.

The sharp peak at $U_{Be} = 0$ indicates that when C^{12} breaks up into three α particles a Be^8 nucleus is formed as an intermediate system. Most of the events in which Be^8 appears pertain to low-lying C^{12} states; in Fig. 5 the shaded histogram represents events with $U_{Be} < 0.5$ MeV.

In order to give a clearer picture of the formation of excited Be^8 nuclei, Figs. 7 and 8 show the distribution of α pairs with respect to U_{Be}, taken in the stars that did not include α-α combinations giving $U_{Be} < 0.5$ MeV. It should be noted that besides the few events corresponding to the 7.66-MeV level of C^{12}, in each of all the remaining stars there is only one combination out of three (or none at all) giving U_{Be} close to zero. Figure 5 shows that the breakup of excited C^{12} nuclei having excitation energy ~ 10 MeV proceeds via an intermediate $Be^8(0^+)$ state:

$$C^{12} + \pi = \pi' + C^* \qquad \hookrightarrow \alpha + Be^8. \qquad (3)$$

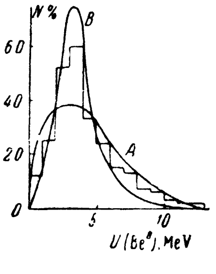

FIG. 7. The same as in Fig. 6, for stars where $U_C < 20$ MeV and there are no combinations with $U_{Be} < 0.5$ MeV. Curve A was plotted from Sachs's model; curve B was plotted with account of resonance interactions of α particles.

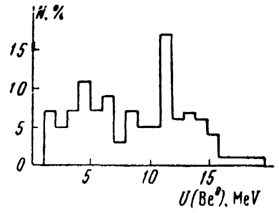

FIG. 8. The same as in Fig. 6, for stars where $U_C > 20$ MeV and there are no combinations with $U_{Be} < 0.5$ MeV.

Then the energy spectrum of α particles emitted from C^{12} according to the scheme (3), which we shall call "first" particles, must correspond to a definite excitation level.

Figure 9 shows the energy distribution of "first" α particles in stars where U_C lies in the range 8.5—10.5 MeV. The peak of this distribution (T_m = 1.5 MeV) is in good correspondence with U_C = 9.6 MeV; the disintegration of C^{12} from the broad 10.1-MeV level[17] would yield T_m = 1.8 MeV. It is therefore reasonable to assume that in our events the 9.6-MeV state of C^{12} is realized.

We attempted to determine the angular momentum of this level by investigating different angular correlations of C^{12} breakup products. Figures 10—12 show the results obtained from calculations of different angles for C^{12} breakup according to (3) from the 9.63-MeV level (with U_C in the range 8.5—10.5 MeV).

Figure 10 shows the strong correlation between the direction of an emitted "first" α particle in the excited C^{12} system and the polarization vector

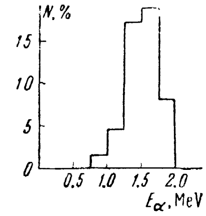

FIG. 9. Energy spectrum of "first" α particles in disintegrations where $8.5 < U_C < 10.5$ MeV and there are combinations with $U_{Be} < 0.5$ MeV.

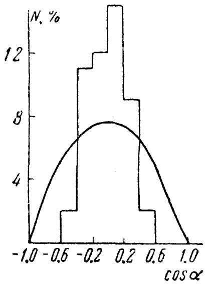

FIG. 10. Distribution of excited C^{12} decay events over the angle of "first" α-particle emission relative to the normal on the pion scattering plane. The theoretical curve represents decay of a nucleus with spin and parity 1^-.

of this nucleus. The distribution is symmetric around the plane of meson scattering; this indicates the absence of a contribution from the interference of two neighboring levels differing in parity. If the spin of an excited C^{12} nucleus disintegrating according to (3) were 1 with negative parity, the angular distribution of decay products in the rest system of an excited C^* nucleus would be [18]

$$w(\alpha) \sim |Y_{11}(\alpha, \varphi)|^2 \sim \sin^2\alpha.$$

For zero spin of C^* the decay probability is of course independent of α. The experimental data therefore indicate that the spin of the 9.5-MeV level exceeds 1.

Figure 11 shows the distribution of C^{12} disintegration events from the 9.6-MeV level over the angle between the normals to the plane of C^{12} formation and the plane of its disintegration. The same figure includes curves representing the breakup of nuclei with different spin S, calculated from the formula [19]

$$w(\beta) = \sum_{0,2,\ldots}^{2S} A_k \cos k\beta. \qquad (4)$$

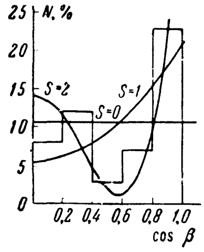

FIG. 11. Angular correlation between formation and decay planes of excited C^{12}. The theoretical curves represent decay of nuclei with spin S = 0, 1, and 2.

The coefficients A_k in (4) were selected by least squares. This obviously enables us to determine only the minimum spin. Pearson's test shows that the variants with S = 0 or 1 are in poor agreement with observations; $P(\chi^2) = 10^{-4}$, 10^{-2}, and 0.2, respectively, for S = 0, 1, and 2. Figure 12 shows that there is a correlation between the direction of excited C^{12} motion (in the 9.63-MeV level) and the line of its decay. The curves were plotted from (4). The discrepancy between the experimental and theoretical curves for spins 0 and 1 cannot be accounted for by statistical fluctuations [$P(\chi^2) = 0.015$]; at the same time $P(\chi^2)$ for distributions with S = 2 and 3 lies within acceptable limits (0.04 and 0.73, respectively).

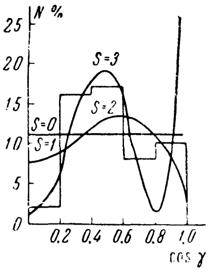

FIG. 12. Distribution of excited C^{12} decay events over the angle between the direction of C^* motion and the line of its decay. The theoretical curves represent decay of nuclei with different values of the spin S.

A special check showed that errors incurred in measuring track dip angles did not seriously distort the experimental histograms in Figs. 10—12.

DISCUSSION OF RESULTS

Unlike the data in [14], which did not include a peak in the distribution of U_{Be} near zero, our measurements indicate a strong correlation between α particles which are the breakup products of C^{12}. According to Sachs's model the distribution over U_{Be} has the form

$$w(U_{Be}) = \text{const}\cdot[U_{Be}(E_{max} - U_{Be})]^{1/2}. \qquad (5)$$

This distribution (curve A in Fig. 7) clearly disagrees with experiment even for disintegrations not involving the ground state of Be^8. Following [8], we calculated the function $w(U_{Be})$ taking into account α-particle interactions in the final state with resonance at $E_0 = 3$ MeV having the width $\Gamma = 3$ MeV. The excitation function was taken to be

$$\Psi = \sum_{k,l}\left[(E_{kl} - E_0) + \frac{i\Gamma}{2}\right]^{-1}, \qquad (6)$$

where E_{kl} is the energy of relative motion of the k-th and l-th α particles. The resulting theoretical distribution over U_{Be} (curve B in Fig. 7) is in considerably better agreement with experiment.

No similar calculation was performed for α-α interactions at zero energy, since the experimental data are interpreted satisfactorily by the simple scheme (3). A more exact calculation introducing the function Ψ would undoubtedly yield a similar picture.

It should be noted that the form of the energy spectrum of α particles is less sensitive to the selected breakup model. Figure 13 is the spectrum of α particles (in the c.m. system of three α particles) for stars where $U_C < 20$ MeV, $U_{Be} > 0.5$ MeV; the curve was calculated on the model of statistically independent α-particle emission.

For disintegrations where the meson loses con-

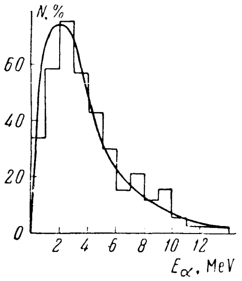

FIG. 13. Energy spectrum of α particles (in the c.m.s. of three α particles) in stars for which $U_C < 20$ MeV and $U_{Be} > 0.5$ MeV. The curve is the spectrum according to the Sachs model.

siderable energy we should probably take into account a second resonance in the α-α interaction ($E_0 = 11.7$ MeV). This can be seen, for example, in Fig. 8, which gives the experimental distribution of U_{Be} for stars with $U_C > 20$ MeV.

The spin of the 9.63-MeV level of C^{12} was determined by several investigators; a brief review can be found in [20]. Since this excited state is unstable against breakup into three α particles, from the conservation of parity and angular momentum the spin and parity of this level can be any of the following: 0^+, 1^-, 2^+, or 3^-. The authors of [20], after a critical analysis of the experimental results, concluded that $S = 3^-$ is most likely. Recently Carlson[21] established from the observation of C^{12} γ emission (the transition to the 9.63-MeV level) in the reaction $B^{11}(p, \gamma)C^{12*}$ that the angular anisotropy of γ rays agrees with $S = 3^-$. This method is free of any model assumptions regarding the nuclear structure and therefore has greater weight than conclusions derived from preceding investigations of this level. It should also be noted that Carlson's results permit more confident rejection of $S = 0^+$ or 2 than of $S = 1^-$. Our conclusion based on the observed angular correlation of α particles, according to which the 9.63-MeV level has spin 2 or 3, permits us, in agreement with Carlson, to fix the value $S = 3^-$

Since the spin of pions participating in (1) is 0, in inelastic scattering on C^{12} a considerable contribution must come from initial states with orbital momentum equal to 2 or 3. The minimum number of partial waves participating in the scattering was calculated as in [22]; it was found that waves up to $l = 4$ participate in the process.

The strong interaction between particles in the final state, which is revealed in the breakup of C^{12}, conceals the possible direct knocking-out of a single α particle by the meson, analogous to that observed in reactions with high-energy protons.[10-12] The angular distribution of "first" α particles (in the meson + nucleus system) plotted for stars with $U_C > 10.5$ MeV and $U_{Be} < 0.5$ MeV is peaked backward relative to the meson direction; however, in the simple knock-on model the forward-to-backward ratio should be greater than 1, as in reactions with protons. On the other hand, when all α particles from C^{12} decay are considered we observe forward peaking (the forward-to-backward ratio is 1.37 ± 0.20), which can indicate the existence of direct processes.

The most probable explanation lies in different degrees of participation by the broad ($\Gamma \sim 6$ MeV) third resonance (11.7 MeV) in α-α interactions associated with proton-meson reactions. If considerable energy, $U_C \sim 20$ MeV or greater, is transferred to the nucleus a considerable contribution comes from the second level of Be^8. However, the level is so wide that a correction for this resonance does not appreciably change the simple breakup scheme (neglecting the interaction).

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