# *DECAY OF RESIDUAL NUCLEI PRODUCED IN THE INTERACTION OF 660-MeV PROTONS WITH CARBON NUCLEI*

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Experimental and calculated excitation yields and energies of residual nuclei produced after termination of the cascade process in the $C^{12}$ nucleus are presented. Decay of residual nuclei is considered under the assumption that the frequencies of occurrence of various final states are proportional to their statistical weights. The calculations agree satisfactorily with the experiments.

We have considered in earlier communications [1,2] the data on the disintegration of carbon nuclei by 660-MeV protons, pertaining to the cascade stage of the interaction. Comparison of the calculated and experimental characteristics due to this stage shows that the use of the ideas of Serber and Goldberger in the calculation of the intranuclear cascade on light nuclei leads to satisfactory quantitative agreement between calculation and experiment.

The purpose of the present communication is a study of the characteristics connected with the decay of residual nuclei produced following the completion of the cascade process in the carbon nucleus.

To investigate the decay of the residual nuclei it is necessary above all to know the nature of the residual nucleus and its excitation energy.

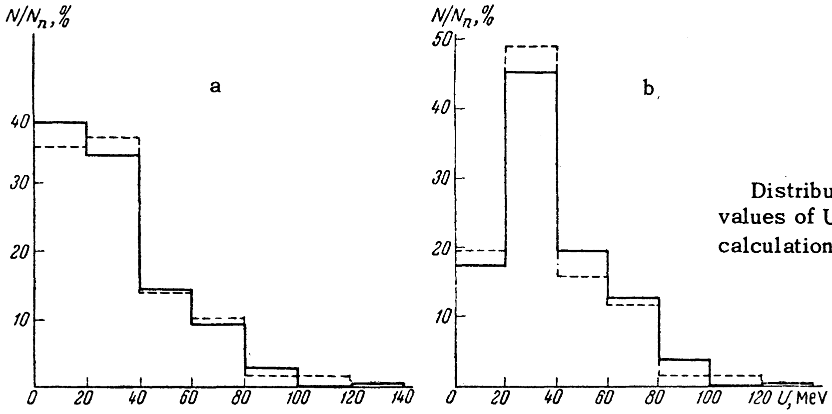
The yields of the residual nuclei and their excitation-energy distributions have been obtained from the analysis of disintegrations on diamond particles introduced in nuclear emulsions [3]. Two types of emulsion were used, those registering protons with energy to 20 MeV (type D) and those for particles with ionization down to minimum value (type S). The type D emulsion ensures reliable identification of the alpha particles and protons, and also permits an appreciable increase in the yield of the investigated reactions due to the increase of the emulsion irradiation time. The type S emulsion contains much fewer stars, but permits observation of the total picture of the investigated disintegrations on carbon.

The charge of the residual nucleus and its excitation energy were determined by studying the stars produced on carbon in the D emulsion. It was assumed that the particles registered by the D emulsion arise essentially as a result of the decay of the residual nuclei produced after completion of the cascade process in the carbon nucleus. Among the particles that result from the decay of the residual nuclei there are apparently protons with energy higher than 20 MeV, which are not registered by the D emulsion. However, as shown in several investigations [4-6], the fraction of such protons is very small, so that the insensitivity of the D emulsion to protons with energy higher than 20 MeV does not distort in practice the distributions under consideration. A correction was introduced for the admixture of cascade alpha particles and protons. The cascade particles amounted to 14% for alpha particles and 16% for protons with energy higher than 20 MeV.

Table I lists the calculated and experimental yields of the residual nuclei from carbon. The yields are in per cent of the total number of residual nuclei. Since we could not distinguish between isotopes of different elements in the emulsion, the experimental data in Table I are total yields over all isotopes with given charge. As follows from the table, the experimental data

**Table I**

| Nucleus | Yield, % | | | Nucleus | Yield, % | | |
|---|---|---|---|---|---|---|---|
| | theory | | experiment | | theory | | experiment |
| $C^{12}$ | 3.8 | 28.1 | 26.7±3.0 | $Be^{10}$ | 8.8 | 26.8 | 29.6±2.5 |
| $C^{11}$ | 17.7 | | | $Be^{9}$ | 7.6 | | |
| $C^{10}$ | 6.6 | | | $Be^{8}$ | 6.3 | | |
| | | | | $Be^{7}$ | 4.1 | | |
| $B^{11}$ | 16.5 | 34.0 | 28.9±2.5 | $Li^{9}$ | 1.3 | 11.1 | 14.8±2.0 |
| $B^{10}$ | 10.1 | | | $Li^{8}$ | 3.7 | | |
| $B^{9}$ | 5.1 | | | $Li^{7}$ | 3.6 | | |
| $B^{8}$ | 2.3 | | | $Li^{6}$ | 2.5 | | |




Distribution of disintegrations by excitation energy: a – all values of U, b – $U > U_p$. Solid line – experiment, dashed – calculation.

agree with the calculated yields of the residual nuclei.

The experimental and calculated excitation energies of the residual nuclei are compared in the table. The distribution of Fig. b does not contain the excitation energies that are not sufficient to cause a given residual nucleus to decay and produce a disintegration capable of being registered in the emulsion. The distributions of Fig. a include all the excitation energies. The correction for the unregistered disintegrations in the experimental excitation-energy distribution was obtained on the basis of data which we have published previously [3]. It is obvious that this correction changes only the number of distributions with excitation energy in the 0—20 MeV interval, for with an excitation energy $U \geq 20$ MeV any residual nucleus produced after the completion of the cascade in the carbon nucleus decays with production of a reliably identifiable star.

It follows from the figures that for all distributions, whether they include all the excitation energies or only the energies $U > U_p$ (where $U_p$ is the excitation energy necessary for decay of the residual nucleus with production of a disintegration that can be registered in the emulsion), the agreement between experiment and calculation is good.

The theoretical calculation for the intranuclear cascade was carried out for interaction between 300-MeV protons with carbon nuclei [7] assuming both Gauss and Fermi momentum distributions of the nucleons in the carbon nucleus. In the case of the Gaussian distribution calculation results in negative values of U in the excitation-energy distribution, which of course is physically meaningless but expected, for a Gaussian momentum distribution signifies indeed the existence of an interaction between the nucleons in the nucleus, a fact not considered in the Fermi gas model. The presence in the Gaussian distribution of nucleons with energy appreciably exceeding the depth of the potential well for the Fermi gas does indeed lead to the appearance [7] of negative values of U, unless the distribution is suitably cut off on the high-energy side.

How does a residual nucleus with excitation energy U, produced after the termination of the intranuclear cascade, decay? Attempts to apply the particle evaporation to light nuclei, in analogy with the heavy ones, cannot be regarded as valid, in view of the small number of nucleons in the light nucleus.

We have attempted to consider this question by starting from considerations advanced by Fermi, namely that the energy released in any volume V containing n particles (n can be also a small number, on the order of a few units), is statistically distributed among the emitted particles. The possible final states then appear with frequencies proportional to their statistical weights. Account of the momentum and energy conservation laws and of the dependence of the statistical weight on the particle spin leads to the following expression for the statistical weight [8]:

$$\rho_k = \left\{V^{n-1} \prod_{i=1}^{n} (2I_i + 1) \prod_{i=1}^{n} m_i^{3/2} T^{(3n-5)/2}\right\}$$
$$\times \left\{(2\pi)^{3/2(n-1)} \hbar^{3(n-1)} \Gamma\left[\frac{3(n-1)}{2}\right]\left(\sum_{i=1}^{n} m_i\right)^{3/2} \prod_k n_k'!\right\}^{-1}, \quad (1)$$

where $I_i$ — spin of i-th particle, $m_i$ — its mass, $T = U - B$, U — excitation energy of the residual nucleus, B — binding energy corresponding to the given decay of the residual nucleus, and $n_k'$ — number of identical particles of sort k.

At a given excitation energy U, the residual nucleus can have several allowed final states, into which it goes over by decay into n particles. Using (1), we have calculated for several types of residual nuclei the transition probabilities into various final states for several values of the excitation energy. The yields of the residual nuclei were taken from Table I (theory). For each residual nucleus with excitation energy U we wrote the corresponding probabilities of transition to some final state which, together with the cascade particles produced during the course of development of the given cascade, determines the type of disintegration (type of reaction). Summation of all the probabilities for the production of a given type of disintegration over all the cascades yields the calculated distribution by reaction type, which is given in Table II together with the corresponding experimental distribution (see [3]).

Our calculations explain the relatively high yield of type $2p2\alpha$ disintegrations. Analysis of (1) shows that at sufficiently large T and for several possible final states with nearly equal T the transition to the state with the larger number of particles is more probable. However, if T is small, then the transitions to a final state with large n are either forbidden or have low probability.

Calculation of the intranuclear cascade in $C_6^{12}$ shows that approximately half the residual nuclei are $C_6^{11,10}$ and $B_5^{11,10}$. Let us consider, for example, $B_5^{10}$. A disintegration of the type $2p2\alpha$ is produced in the case of the decay

$$B_5^{10} \rightarrow 2\alpha + p + n. \tag{2}$$

From (1) we find that for U = 40 MeV such a transition has approximately 10 times the probability of the transition

$$B_5^{10} \rightarrow Li_3^6 + \alpha, \tag{3}$$

which is characterized by approximately the same energy as (2). For U = 30 MeV the transition (2) is still about four times more probable than (3). Only for U = 20 MeV do the two probabilities become equal. At the same time, even for U = 40 MeV transitions to a final state with more particles than in (2) involve the breakup of at least one more alpha particle in (2) and are practically forbidden because of the sharp decrease in T. An analogous result is obtained also by comparing (2) with other possible decay schemes of $B_5^{10}$. Since U > 20 MeV in most cases (disregarding the nondecaying $B_5^{10}$), it is obvious that interactions that lead to the formation of the residual nucleus $B_5^{10}$ will give essentially disintegrations of the $2p2\alpha$ type. An approximately similar situation arises also in the case of formation of the residual nucleus $C_6^{10}$. For $B_5^{11}$ and $C_6^{11}$ the probability of decay with production of two alpha particles will

**Table II**

| Type of disintegration | Percentage of total number of disintegrations | |
|---|---|---|
| | experiment | theory |
| $C_6^{12}\left(p; {p,\ n \atop p,\ 2n}\right) C_6^{11,10}$ | 13.4±1.0 | 10 |
| $C_6^{12}\left(p; {2p \atop 2p,\ n}\right) B_5^{11,10}$ | 12.2±1.0 | 11 |
| $2p^*2\alpha$ | 33.8±3.6 | 28 |
| $4p\alpha$ | 12.2±2.2 | 15 |
| $3\alpha$ | 7.0±2.0 | 11 |
| $p\alpha Li$ | 7.0±2.0 | 10 |
| $2pBe$ | 6.5±2.0 | 5 |
| $3\alpha p\pi^-$ | 3.2±1.0 | 4 |
| $6p$ | 2.4±0.8 | 1 |
| $3pLi$ | 1.7±0.7 | 3 |
| $5p\alpha\pi^-$ | 0.6±0.5 | 2 |

*The letter p denotes all positive singly-charged particles (p, d, t, $\pi^+$).

be much smaller, owing to the rather large value of B. A considerable contribution is made to disintegrations of the $2p2\alpha$ type by interactions that lead to the residual $Be_4^9$, for practically all the nuclei with U < 30 MeV will decay into two alpha particles and a neutron.

The results listed in Table II show that the calculations and experiment are in satisfactory agreement. This is an apparent confirmation of the advantage of the indicated approach to the decay of residual nuclei produced after completion of an intranuclear cascade in a light nucleus.

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