THE INTERACTION OF 660-Mev PROTONS WITH CARBON, NITROGEN, AND OXYGEN NUCLEI

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Sandwich emulsions (a 2μ gelatin layer between two 100μ emulsion layers) were used to record 1044 disintegrations of C, N, and O nuclei induced by 660-Mev protons. Analysis of the disintegrations indicates that the process involves a two-stage mechanism. The excitation energy, mean charge $\overline{Z}$, and mean mass $\overline{A}$, are estimated for the residual nucleus, which is formed after the cascade stage of the disintegration. The angular distributions of the charged particles are obtained. The mean lifetime of α-particle substructures inside light nuclei is estimated.

1. INTRODUCTION

THE disintegration of carbon, nitrogen, and oxygen nuclei by protons and neutrons with energies over 100 Mev has been studied in a series of papers.[1-10] The mechanism for this phenomenon has been experimentally obtained for the energy region ~ 100 Mev. It was found that when the incident particles have such energies, the C, N, and O nuclei disintegrate in two states, [1,2] as in Serber's disintegration mechanism.[11] The first stage consists of the development of an intranuclear cascade of nucleon-nucleon collisions leading to the direct emission of nucleons with the residual nucleus being left in an excited state, and the second stage consists of the decay of the excited residual nucleus. In a number of articles[8-10] it has been shown that among the ejected particles are a significant number of complex particles: H^2, H^3, He^3, and He^4. The idea is presented in these articles that nucleons inside nuclei apparently form for a certain time groups such as quasideuterons, quasitritons, and quasialpha particles (intranuclear substructures).

Fewer articles[4-8] have dealt with the disintegration of C, N, and O nuclei by nucleons with energies over 500 Mev. These articles supply only preliminary data and are mostly of a descriptive nature.

The results available in the preceeding articles are insufficient for extrapolating the two-stage disintegration mechanism to cases where the bombarding nucleons have energies substantially greater than 100 Mev. Not all the data are reliable enough for such an extrapolation. On the other hand, it can be assumed that such factors as the participation by the nuclear substructures in the nuclear cascade process, the increase in the number of ejected particles with an increase in the energy of the incident nucleons,[12] and the increase in the role played by meson absorption within the nucleus can cause complete fission of C, N, and O nuclei in the first stage at sufficiently high energies. A suggestion of this sort was made by Hodgson in an endeavor to explain some results observed in disintegrations of these nuclei by cosmic rays.[5] Such an assumption also follows from Messel's theory for nuclear cascade showers induced in the atmosphere by cosmic rays.

The present work was concerned with obtaining more detailed experimental data on the disintegration of C, N, and O nuclei by protons with energies over 500 Mev with the object of specifying more precisely the fission mechanism.

2. EXPERIMENTAL TECHNIQUE

Sandwich emulsions[3] consisting of a thin layer of gelatin (2μ) between two layers of P-9 emulsions,* each 100μ thick, were used to detect the fission of C, N, and O nuclei. This technique permitted a more complete collection of the disintegrations than would have been possible by using other criteria[7] to differentiate the disintegrations of light nuclei from all the disintegrations occurring in the emulsion.

The P-9 emulsion used was found to be sensitive to protons with $E_p < 30$ Mev by measurements of the visible postions of π^--meson tracks. Consequently, only charged particles with so-called

*The P-9 emulsions and sandwich emulsions were prepared in Prof. N. A. Perfilov's laboratory in the Radium Institute, Academy of Sciences, U.S.S.R.

"black" tracks (including α-particles with energies below ~500 Mev) were recorded.

Sandwich emulsions were exposed to a beam of 660-Mev protons extracted from the synchrocyclotron of the Joint Institute for Nuclear Research. The proton beam was incident parallel to the surface of the emulsion (with an accuracy of 1 to 2°).

All disintegrations centered in the gelatin layer of the sandwich (stars without visible centers) were ascribed to disintegrations of C, N, and O nuclei. Among these (about 1,000 stars), not a single star with 8 or more "black" prongs was discovered. This means that any possible contamination by disintegrations of Ag and Br nuclei which have diffused from the emulsion into the layer of gelatin amounts to less than 1%, since, according to Ostroumov's data,[12] stars with eight or more "black" prongs comprise about 13% of all the stars when Ag and Br nuclei are disintegrated by 660-Mev protons.

The charged particles emitted by C, N, and O nuclei were assigned into singly-charged, doubly-charged, or multiply-charged ($Z > 2$) categories by a method previously described.[13] The singly-charged particles were considered to be protons and the doubly-charged ones α particles.

The kinetic energy E of a charged particle was determined from the particle's total range in the gelatin and emulsion by using the relation

$$E = E(R_1) + 0.6\,[E(R_1 + R_2) - E(R_1)], \qquad (1)$$

which takes into account the difference in stopping power of the emulsion and gelatin. In Eq. (1) R_1 and R_2 are the ranges in the emulsion and gelatin respectively, and E(R) is the particle energy corresponding to a range R in the emulsion.

The experimental data (with the exception of angular distributions) were corrected for the loss of particle tracks within the gelatin layer and for the emergence of tracks from the emulsion into the backing and air. Corrections were computed on the basis of an isotropic distribution of particles. In our case allowance for anisotropy would have reduced the magnitudes of the corrections by no more than 3%.

When stars centered within the gelatin layer are selected, false multiple-prong stars may be recorded if the centers of two disintegrations are near each other (up to 5 μ apart). We estimate that the probability of recording such false multiple-prong stars did not exceed 1%.

3. EXPERIMENTAL RESULTS

Altogether 1,044 C, N, and O disintegrations were recorded. The corrected distribution of the number of stars with various numbers of "black" prongs, N_h, is given below. In correcting for the losses it was assumed that the number of tracks lost in the gelatin was proportional to the total number of particles for each type of star.

N_h	1	2	3	4	5	6	7
Number of stars	28	245	383	257	101	26	4

Here the mean number of "black" prongs per star is 3.25, of which 1.94 were attributed to α particles and 1.29 to protons. Thus the α/p ratio is 1.5. According to references 3, 6, and 7 the average number of charged particles emitted by C, N, and O nuclei varies slightly with the energy of the bombarding nucleons and can be assumed to be 4.0 for energies of 500 - 600 Mev. Consequently, because of the sensitivity of the photographic plates used in our experiments, an average of ~0.75 fast protons ($E_p > 30$ Mev) per disintegration were not recorded.

The fraction of stars having recoil nuclei with $A > 4$ amounted to 25% after correction for losses in the gelatin. In the remaining 75% of the cases the C, N, and O nuclei were completely disintegrated into their component particles with masses $A < 4$.

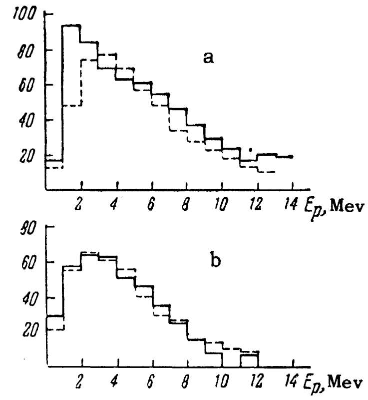

FIG. 1. Energy distribution (in l.s.) of secondary protons emitted into the forward (a) and backward (b) hemispheres measured relative to the direction of the bombarding protons (the ordinate represents the number of protons for 1 Mev energy interval). The solid lines represent the experimental distributions, $N_1(E)$ and $N_2(E)$, and the broken lines the calculated distribution $N_1'(E)$.

Figures 1 and 2 show the experimental energy distributions in the laboratory coordinate system for the secondary protons and α particles for both forward and backward hemispheres $N_1(E)$ and $N_2(E)$, measured relative to the direction of the bombarding proton beam.

The distributions of the emission angles projected on the plane of the emulsion are shown in Figs. 3 and 4. A separate distribution is given for protons with energies $0 < E_p \leq 3$ Mev, and simi-

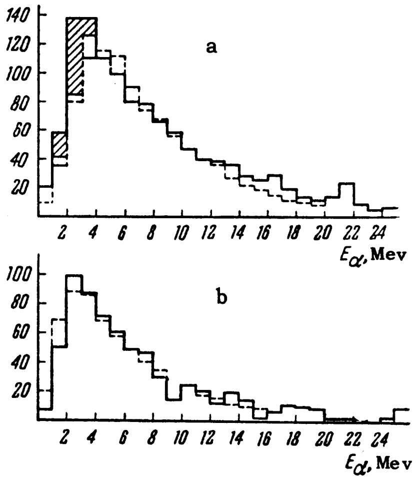

FIG. 2. Energy distributions (in l.s.) of α particles emitted into the forward (a) and backward (b) hemisphere (the ordinate represents the number of particles for 1 Mev energy interval). The solid lines represent the experimental distributions, $N_1(E)$ and $N_2(E)$, and the broken lines the calculated distribution, $N_1'(E)$. The correction for contamination by Li nuclei is indicated by the shaded area.

larly for α particles with energies $E_\alpha \leq 8$ Mev. The α particles for which $E_\alpha < 2$ Mev have not been incorporated in Fig. 4a, because of the shortness of their tracks in the emulsion and the consequent uncertainty in the emission angles.

4. ANALYSIS OF THE EXPERIMENTAL DATA

1. Mechanism for the disintegration of C, N, and O nuclei by 660-Mev protons. If all of the particles are emitted by decaying nuclei moving with some mean velocity v in the direction of the pro-

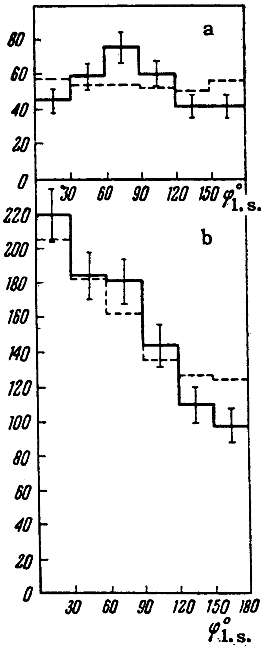

FIG. 3. Angular distributions of protons, $N(\varphi)$: a) energies in the range $0 \leq E_p \leq 3$ Mev, b) energies $E_p > 3$ Mev. The solid lines represent the experimental distributions, while the broken lines show calculated distributions, $N'(\varphi)$, for the same energy intervals and normalized to the same total number of protons. The ordinate gives the number of protons per 30° angular intervals.

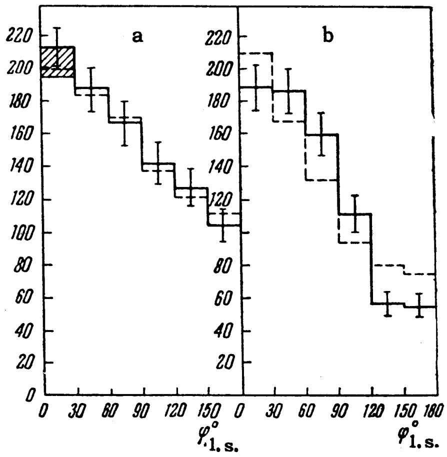

FIG. 4. The angular distributions for α particles, $N(\varphi)$: a) energies $2 \leq E_\alpha \leq 8$ Mev, b) $E_\alpha > 8$ Mev. The solid lines represent the experimental distributions, while the broken lines show the calculated distributions, $N'(\varphi)$, for the same energy intervals and normalized for $E_\alpha > 8$ Mev to the same total number of α particles; for $2 \leq E_\alpha \leq 8$ Mev, the $N'(\varphi)$ distributions have been plotted without normalization. The correction for contamination by Li nuclei is indicated by the shaded area. The ordinate gives the number of α particles per 30° angular intervals.

ton beam, then in the laboratory coordinate system the energy distribution of the particles in the backward hemisphere $N_2'(E)$ is related uniquely through the quantity v with the distribution in the forward hemisphere, $N_1'(E)$ and with the angular distribution of the particles $N'(\varphi)$. In other words, if v and $N_2'(E)$ are known, then $N_1'(E)$ and $N'(\varphi)$ can be uniquely computed.

We have looked for such correlations in our data. From the ratio of the number of α particles with energies $E_\alpha < 4$ Mev emitted forward to those emitted backward the value of v was found to be $\sim 3.5 \times 10^8$ cm/sec. In this calculation it was assumed that for those disintegrations of the residual nuclei in which α particles occur with energies below the Coulomb barrier for C, N, and O nuclei (~ 4 Mev) the contamination by knock-on α particles must be a very slight (because of the opacity of the Coulomb barrier). From the experimental values for $N_2(E)$ and v the corresponding $N_1'(E)$ and $N'(\varphi)$ distributions were computed (within the limits of the model for the disintegrating nucleus) for both α particles and protons. In the computation it was assumed that the angular distribution of the emitted particles would be isotropic in the center-of-mass system of the decaying residual nucleus. The calculated distributions $N_1'(E)$ and $N'(\varphi)$ are shown by the broken lines in Figs. 1a, 2a, 3, and 4. In Figs. 1a, 2a, and 4a the calculated distributions are given as computed (i.e., without normalization) whereas in Fig. 3 and 4b,

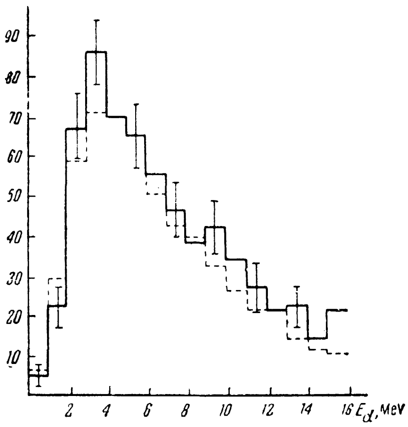

FIG. 5. The energy distribution $N_1(E)$ (in l.s.) for α particles emitted within the angles $45° \leq \Theta \leq 90°$. The solid line represents the experimental distributions and the broken line the calculated distribution $N_1'(E)$ for the same angular region. The ordinate gives the numbers of α particles for 1 Mev energy interval.

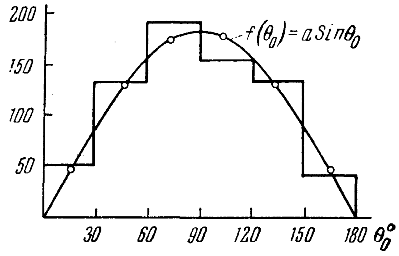

FIG. 6. The angular distribution (histogram) for α particles (with $4 \leq E_\alpha \leq 8$ Mev in the l.s.) in a coordinate system moving in the direction of the proton beam with a velocity of $3.5 \cdot 10^8$ cm/sec. The solid line shows the isotropic angular distribution, which has been normalized to the same number of particles. The ordinate gives the number of particles per 30° angular interval.

for convenience in comparing form, the calculated distributions have been normalized to the same total number of particles observed experimentally.

When the $N(\varphi)$ and $N'(\varphi)$ distributions for the α particles are compared for the different energy intervals, it is found that they practically coincide for all $E_\alpha \leq 8$ Mev (Fig. 4a), i.e., when $E_\alpha \leq 8$ Mev there exists a correlation between the $N(\varphi)$ and $N_2(E)$ distributions. This fact is in conflict with the lack of correlation between $N_1(E)$ and $N_1'(E)$ for $E_\alpha < 8$ Mev (Fig. 2a). However, allowance must be made in Fig. 2a for the distortion of the experimental distribution due to contamination by tracks of Li nuclei (nuclear fragment), which, since their range in the emulsion is less than $30\,\mu$, could not be satisfactorily distinguished from α-particle tracks. To minimize this effect we made use of the fact that the probability of emission of Li fragments decreases sharply for increasing emission angles.[14] Thus the $N_1(E)$ and $N_1'(E)$ (unnormalized) distributions were formed for α particles emitted within the angle of $45° \leq \theta \leq 90°$ in the l.s. (Fig. 5). From Fig. 5, it is evident that a correlation also exists between the $N_1(E)$ and $N_2(E)$ distributions for α particles with $E_\alpha < 8$ or 9 Mev.

From Figs. 1 and 3 it is evident that such a clear partial correlation between distributions does not occur in the case of protons. Nevertheless, the comparison of the $N(\varphi)$ and $N'(\varphi)$ distributions in Fig. 3 reveals that at low proton energies these distributions have some characteristics in common (Fig. 3a).

Besides the attempt to find a correlation in the distributions in the l.s., a study was made of the energy and angular distributions of particles in a coordinate system moving in the direction of the proton beam at a velocity of 3.5×10^8 cm/sec. It was found that when the energies and angles of emission had been converted into this coordinate system, the angular distribution for α particles with $E_\alpha = 4$ to 8 Mev (in the l.s.) agreed quite satisfactorily with the isotropic distribution (Fig. 6). In the moving coordinate system the energy distributions for the particles in the forward $N_1(E_0)$ and backward $N_2(E_0)$ hemispheres (in relation to the direction of the proton beam) proved to be quite close to one another. Indeed, the ratios of the ordinates of these curves for the same energies E_0 are quite close to unity for proton energies $0 < E_{0p} < 11$ Mev and for α-particle energies $2 < E_{0\alpha} < 13$ Mev.

Thus, the experimental characteristics in a coordinate system moving at a velocity of 3.5 $\times 10^8$ cm/sec are in some respects like the characteristics in the center-of-mass system of the disintegrating nucleus.

On the basis of the above results it can be inferred that apparently the disintegrations of C, N, and O nuclei produced by 660-Mev protons pass, in most cases, through two stages with the residual nucleus making the main contribution to particle emission.

A different mechanism may come into play when C, N, and O nuclei are completely disintegrated into singly-charged high-energy particles ($E > 30$ Mev) and neutrons. Our detectors did not record these disintegrations. According to Philbert's data[6] they probably comprise no more than a few percent of the total events.

2. Characteristics of knock-on particles. As a rule the ordinates of the experimental distributions $N_1(E)$ and $N(\varphi)$ exceed those of the unnormalized calculated distributions $N_1(E)$ and $N'(\varphi)$. It is natural to attribute this to the presence of knock-on particles. After correction for contamination by Li nuclei (the shaded areas in Figs. 2a and 4a, which correspond to about 0.09 Li nuclei per disintegration), the difference between the experimental

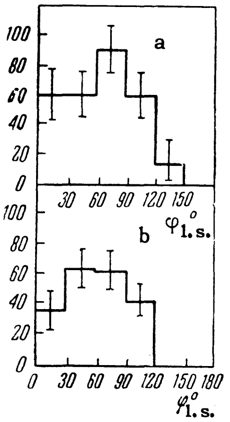

FIG. 7. Angular distribution for knock-on protons with energies $1 < E_p < 30$ Mev (a), and for α particles with $E_\alpha > 8$ Mev (b). The ordinate gives the number of protons and α particles per 30° angular interval.

and calculated distributions can be considered as characterizing the knock-on particles. Because of the small number of disintegrations, we have shown only the approximate angular distributions for knock-on particles (Fig 7). Figure 7 was obtained as the difference between $N(\varphi)$ and $N'(\varphi)$, with $N'(\varphi)$ normalized to the same number of particles as $N(\varphi)$ for the angular interval $150° < \varphi < 180°$ (it was assumed that practically no particles are knocked out at angles close to $\theta = 180°$ relative to the direction of the proton beam). From Fig. 7 we find that approximately 0.2 α particles are knocked out per disintegration, while about 0.28 protons are knocked out per disintegration with $E_p < 30$ Mev. In all about 0.28 + 0.75 = 1.03 protons are knocked out per disintegration (here 0.75 is the number of protons per disintegration with $E_p > 30$ Mev, all of which can be considered as knock-on with negligible error).

For knock-on α particles the overall ratio of the numbers of particles emitted forward and backward was found to be 3.8; for knock-on protons with $E_p < 30$ Mev it is 2.8. Thus, even for light nuclei, 20 - 25% of the knock-on particles are emitted at angles $\theta > 90°$ relative to the direction of the proton beam.

From Figs. 1a and 3a it can be seen that knock-on protons may also have energies up to 1.5 Mev, which is somewhat less than the Coulomb barrier for C, N, and O nuclei (~ 2 Mev). As can be seen from Figs. 4 and 5, the knock-on α particles are emitted effectively only with energies $E_\alpha > 8$ Mev, although the Coulomb barrier of the C nucleus for α particles is $U_{Coul} \approx 4$ Mev., and does not limit their emission for energies $E_\alpha > 4$ Mev. Nevertheless, knock-on α particles with $E_\alpha < 8$ Mev are practically unnoticed in the background of α particles originating in the decay of the residual nuclei.

3. Decay characteristics of the residual nucleus. The data on the knock-on particles permits one to estimate the mean charge $\overline{Z}$, mean mass $\overline{A}$, and mean excitation energy for the residual nucleus formed as a result of the cascade process.

Weighing equally all the gelatin nuclei, we obtain a mean charge $\overline{Z} = 6.63$ and mass $\overline{A} = 13.26$.[4] Assuming that the mean number of direct knock-on neutrons per disintegration n_n is equal to n_p, the number of direct knock-on protons, we obtain $n_n = n_p = 1.03$ and $n_\alpha = 0.2$. The mean values of $\overline{Z}$ and $\overline{A}$ for the residual nucleus are computed from the obvious relations

$$\overline{Z} = \overline{Z}_0 - (n_p + 2n_\alpha) = 5.2,$$
$$\overline{A} = \overline{A}_0 - (n_p + n_n + 4n_\alpha) = 10.4.$$

The residual nucleus in turn emits an average of $N_\alpha = 1.94 - 0.09 - n_\alpha = 1.65$ α particles per disintegration (1.94 being the total number of α particles emitted per disintegration of the C, N, and O nuclei, and 0.09 being the correction for Li emission) and an average number of protons equal to $N_p = 1.29 - n_p = 1.01$. The decay of the residual light nucleus is thus characterized by a high α-particle yield ($\alpha/p = 1.65$). The excitation energy of the residual nucleus can be determined if the number of emitted particles and their mean kinetic energies in the nuclear center of mass system are known. These kinetic energies were computed and found to be $E_{0p} = 4.98$ Mev for protons and $E_{0\alpha} = 7.28$ Mev for α particles. In the case of the neutrons emitted by the nucleus, their energy E_{0n} was assumed equal to $\overline{E}_{0p}$ less the Coulomb barrier height of the B^{10} nucleus, which for protons is about 2 Mev, i.e., $\overline{E}_{0n} \sim 2.98$ Mev. The binding energy of a nucleon in the residual nucleus can be assumed to be about 6 Mev and that of an α particle about 3.3 Mev.

If it is assumed that the excited residual nucleus emits only protons, neutrons, and α particles and that the number of neutrons emitted is equal to the number of protons, then the mean excitation energy of the residual nucleus is about 35 Mev.

4. Average α-particle lifetime τ_α inside the nucleus. After considering the reasons why knock-on α particles are effectively emitted only with energies $E_\alpha > 8$ Mev $> U_{Coul}$, we have assumed that this phenomenon is a consequence of α-particle instability inside the nucleus.[15]

A mathematical expression has already been proposed[15] to describe the energy spectrum of the ejected α particles, with allowance for their disintegration during the time they move through the nucleus. It is assumed that the probability of disintegration can be described by an exponential law of the form

$$N(E) = f(E)\,P(E)\exp\{-[m_\alpha/2(E+U)]^{1/2}\,l/\tau_\alpha\}, \qquad (2)$$

where f(E) is the recoil-energy distribution function of the α particle within the nucleus $(E > 0)$, P(E) is the Coulomb barrier penetration factor, l and τ_α are the shortest distance and average α-particle lifetime inside the nucleus, m_α is the mass, and U is the depth of the potential well for α particles.

With Eq. (2) and the data given in this article, one can estimate τ_α. For Eq. (2) to describe the fact that there are practically no α particles with energies $E_\alpha < 8$ Mev but that there is a rapid increase in their number when $E_\alpha > 8$ Mev, one can set the exponent in (2) equal to 3 for $E = E^* = 8$ Mev, i.e.,

$$[m_\alpha/2\ (E + U)]^{1/2} l/\tau_\alpha \approx 3. \tag{3}$$

Then, for $E_\alpha < 8$ Mev, the exponential term will be smaller than unity, while for $E_\alpha > 8$ Mev, it will rapidly increase and approach one.

To estimate τ_α from Eq. (3), l should represent the shortest possible distance over which the α-particle structures maintain contact with the nuclear nucleons. We shall assume that α particles are most effectively knocked out from the surface layer of the nucleus. Thus, l should equal $2R_\alpha$, where R_α is the radius of a α particle. According to data in reference (16), the mean value for R_α is 1.8×10^{-13} cm. The value of U for a C^{12} nucleus can be assumed to be ~ 11 Mev.[9,10] Inserting these values in Eq. (3) we obtain the value $\tau_\alpha \approx 4 \times 10^{-23}$ sec.

Because of the lack of sufficient statistical accuracy in our data we cannot state emphatically that there are practically no knock-on α particles when $E_\alpha < 8$ Mev. Therefore, the value $\tau_\alpha \approx 4 \times 10^{-23}$ sec should be considered as the minimum mean lifetime of α particles inside the nucleus. On the other hand, the effect of a drop in the number of knock-on α particles with a decrease in their energy could not occur for $\tau_\alpha \geq 5 \times 10^{-22}$ sec if Eq. (2) is valid. Consequently, all we can say is that the value for τ_α must lie between 4×10^{-23} and 5×10^{-22} sec.

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