Anomalous nuclear fragments

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CONTENTS

1. INTRODUCTION

In 1980 an experiment[7] performed at the Bevalac accelerator in Berkeley unexpectedly confirmed results[1–6] which have appeared from time to time in experiments with cosmic rays and which are interpreted as an indication that there exist anomalous nuclei with interaction cross sections almost ten times larger than geometrical. The data of Refs. 1–6 on anomalous nuclei from cosmic rays were not considered reliable as the result of poor statistics. In the accelerator experiment[7] (see also the detailed article in Ref. 33) a target of nuclear plates was irradiated parallel to the surface of the plates by oxygen and iron nuclei accelerated to energy ~ 2 GeV/nucleon. In the collisions the nuclei were broken into fragments. The mean free path to the next interaction with emulsion nuclei was measured for nuclear fragments with charges $3 \leqslant Z \leqslant 26$ emitted in a forward cone with opening angle 0.1 rad. It turned out that in the first few centimeters after formation of a fragment it has an appreciably smaller mean free path than the primary nuclei. At greater distances from the point of formation, the mean free path of the fragments becomes equal to the mean free path of the primary nuclei. This unusual behavior of the mean free path is explained if we assume that in 6% of the events exotic objects are formed (so-called anomalons[1)]) with anomalously large interaction cross sections (and accordingly with a small mean free path) which rapidly leave the secondary beam as the result of intensive interaction with the emulsion nuclei.

These results evoked special interest (and some skepticism). The point is that they refer to an area of physics in which no anomalies of any kind were foreseen, and they were obtained in comparatively simple and traditional experiments, reminding one of the discovery of buried treasure in a plowed field. Recently there have been a number of additional experimental studies[8–15] which have been devoted to the problem of anomalons, as well as more than ten different theoretical models[16–25] (see also the review of Ref. 26[2)]). In the present article we shall present experimental data and discuss the present-day status of the anomalon problem, and also touch on theoretical approaches to this problem.

[1)]This name appeared as the result of a misprint in the program of a meeting at Irvine: anomalons instead of anomalous.[26]

[2)]Since completion of the present article, several experimental studies[33,34,43–45] and theoretical articles[35–42] have been published on this subject.

2. EXPERIMENTAL DATA

Before proceeding to the experimental data we shall make clear what is meant by a mean free path $\lambda(L)$ which depends on the distance L from the star, and how it is measured at distances from a star significantly less than the mean free path itself and for such small intervals.

If λ does not depend on L, than the probability $w(L)$ for a particle in an emulsion to travel a distance L without interaction dies out exponentially is given by:

$$w(L) = e^{-L/\lambda}. \tag{1}$$

The data[7–10] indicate that the simple formula (1) is already not valid for a beam of fragments, but here is a deviation from an exponential law. The nonexponential dependence $\omega(L)$ is conveniently described by introducing a mean free path $\lambda(L)$ which depends on L, and which is related to $\omega(L)$ by the formula

$$w(L) = \exp\left(-\int_0^L \frac{dL}{\lambda(L)}\right). \tag{2}$$

The departure of $w(L)$ from an exponential corresponds precisely to departure of $\lambda(L)$ from a constant. However, extraction of $\lambda(L)$ from experimental data is usually accomplished not by analysis of data by means of Eq. (2), but by means of the following procedure. Let us consider in the emulsion layers an interval ΔL situated at a distance L from the point of formation of a fragment with charge Z in the direction of its emission. Let us calculate the sum S_Z of the track lengths of the secondary fragments in the interval ΔL. If the fragment has interacted in this interval, in calculation of S_Z the distance from the beginning of the interval to the point of interaction is taken, and if the fragment has traversed the interval without interaction—the interval length ΔL is taken. If the fragment has interacted at a distance from the point of formation less than L, it will not contribute to this interval. The mean free path $\lambda(L)$ is found from the relation $\lambda(L) = S_Z/N_Z$, where N_Z is the number of interactions of second-generation fragments with charge Z in a given interval (beam nuclei are considered to be first generation). Using Eq. (2), it is not difficult to verify that the ratio S_Z/N_Z actually gives $\lambda(L)$ (for a number of fragments produced $N \to \infty$ and for $\Delta L \to 0$).

The need of finding $\lambda(L)$ for a fixed charge Z is due to the fact that λ will depend substantially on the mass number

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TABLE I

References	Friedlander E. M. et al.[7]	Jain P. L., Das G.[8]	Aggarwal M. M. et al.[9]	Barber H. B. et al.[10]
Number of interactions of beam nuclei		5000	3500 (2 GeV) 2500 (1 GeV)	
Number of observed fragments	1460	2100		2072
Number of interactions of fragments		856		557

A of the fragment and this dependence must be separated from the dependence of λ on L (strictly speaking, it is necessary to fix just the mass number A, but in experiments only Z is measured). Such an analysis would be possible for the condition that the number of events with a given Z is large. The total numbers of nuclear fragments emitted forward with all charges $3 \leqslant Z \leqslant 26$ are given in Table I. We note that to obtain statistically well justified results on the dependence of λ on L, not only the number of primary interactions, but also the number of secondary interactions must be sufficiently large in each narrow interval ΔL, which was taken to have values from 1 to 2.6 cm (Refs. 7–11) for a mean free path $\lambda \gtrsim 10$ cm. The number of interactions of secondary fragments with a given Z, i.e., all events are divided into 24 groups with $Z = 3$–26 in this interval ΔL with the statistics given in Table I, amounts only to a few events on the average and only in the best cases exceeds 10. Therefore the statistical reliability of Refs. 7–10 has no margin of safety which would permit one to obtain the dependence of λ on L for fragments with fixed charge. Instead of this, those studies investigate a reduced mean free path Λ, from which the dependence on Z is removed acording to the empirical formula

$$\lambda(Z) = \Lambda Z^{-b}, \qquad (3)$$

which was obtained from an analysis of the mean free paths of the beam nuclei, with $b = 0.44 \pm 0.02$,[7] $b = 0.42 \pm 0.024$,[8,9] and $b = 0.34 \pm 0.03$.[10] We shall call the parameter Λ in Eq. (3) Λ_1 for beam nuclei and Λ_2 for fragments. Values of Λ_1 for beam nuclei are given below in column 3 of Table III. To avoid misunderstanding we emphasize that the charge Z in Eq. (3) determines the mean free path before the collision, due to the strong interaction, and therefore in a certain sense serves as a characteristic of the mass number A. The reduced mean free path Λ discussed below (in what follows, where this will not result in confusion, we shall omit the word "reduced") was determined from the expression

$$\Lambda(L) = \frac{\sum_Z \lambda_Z N_Z Z^b}{\sum_Z N_Z} = \frac{\sum_Z S_Z Z^b}{\sum_Z N_Z}. \qquad (4)$$

In Fig. 1 we have shown the data of Refs. 7–10 (the data of Refs. 7–9 were obtained in the Bevalac accelerator, and the data of Ref. 10 were obtained in cosmic rays). The dashed lines are the values of the mean free path Λ_1 of the primary nuclei. It can be seen that the mean free path of the fragments Λ_2 differs from Λ_1, and this difference exists mainly for small L. The values of Λ_2 for $L < 2.5$ cm are less than Λ_2 for $L > 2.5$ cm by 3.4 standard deviations.[7] The number of interactions of fragments near the point of production turns out to be greater than expected for an exponential law of beam attenuation.[7–10] It is just these mutually related effects which are interpreted[7–10] as the manifestation of formation of anomalons. The anomalon mean free path λ_a is extracted from these data in the following way.

If there is an admixture α_a of anomalons in the secondary beam, the probability for any beam particle with charge Z to traverse a distance L without interaction is given by the formula

$$w(L) = \alpha e^{-L/\lambda} + \alpha_a e^{-L/\lambda_a}, \qquad (5)$$

where $\alpha + \alpha_a = 1$. Equating the expressions (5) and (2), we find $\lambda(L)$:

$$\lambda(L) = \frac{\alpha \exp(-L/\lambda) + \alpha_a \exp(-L/\lambda_a)}{(\alpha/\lambda)\exp(-L/\lambda) + (\alpha_a/\lambda_a)\exp(-L/\lambda_a)}. \qquad (6)$$

Then N_Z is calculated (for $\Delta L \to 0$ N_Z is proportional to the denominator in Eq. (6)) and then after substitutioin of N_Z

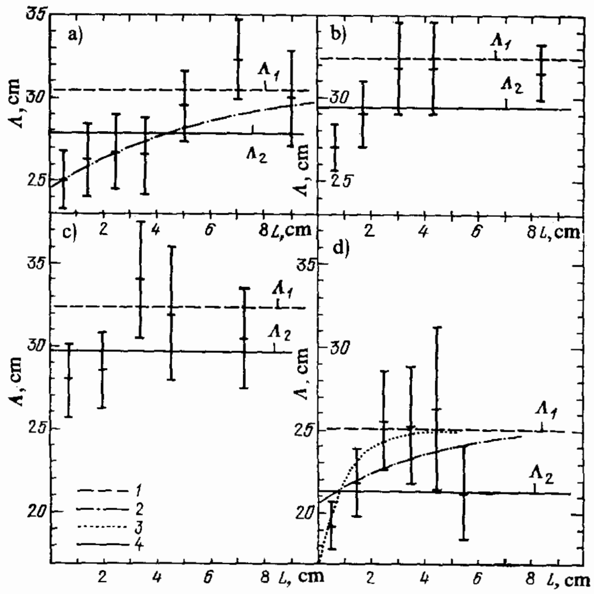

FIG. 1. Reduced mean free path of nuclear fragments as a function of the distance L from the point of production of the fragment. a) Data of Ref. 7 (the point $\Lambda = 29.5 \pm 2.1$ cm at $L = 20$ cm is not shown); b) data of Ref. 8; c) data of Ref. 9; d) data of Ref. 10. 1—Mean free path of beam nuclei; 2—model of Ref. 7 with 6% admixture of stable anomalons with $\lambda_a = 2.5$ cm; 3—model of Ref. 10 with decay anomalons; 4—best fit of the data according to χ^2 on the assumption of constant mean free path of fragments.

and λ_Z (determined from Eq. (6)) into (4) with inclusion of the formula (3) and the probability of formation of a fragment with charge Z the reduced mean free path $\Lambda(L)$ is found. The anomalon mean free path λ_a was assumed to be independent of Z.[3)] Comparison of the calculated curve $\Lambda(L)$ with the data, and minimization of χ^2, gives $\alpha_a = 0.06$ and $\lambda_a = 2.5$ cm.[7,10] The corresponding theoretical curves taken from Refs. 7 and 10 are shown by the dot-dash lines in Figs. 1a and d. We emphasize that in this phenomenological model no conversion of anomalons into normal nuclei is assumed, i.e., the anomalons are assumed to be stable on the time scale of their passage through the emulsion ($\sim 10^{-10}$ sec). In this model anomalons leave the beam only as the result of their intensive interaction with emulsion nuclei.

An alternative model was suggested in Ref. 10. There it is assumed that the entire 100% of the fragments have cross sections enhanced by 1.54 times in comparison with normal cross sections but are unstable and are converted into ordinary nuclei after a time corresponding to a characteristic distance 0.85 cm ($\sim 3\cdot 10^{-11}$ sec). The results of a fit of the data of Ref. 10 in this model are shown in Fig. 1d by the dotted line. In this model the effect should be accompanied by the emission of anomalon decay products and should depend on energy as the result of the relativistic slowing down of time.

To verify whether the effect observed in Fig. 1 is the result of systematic error, the behavior of the mean free path Λ_1 of the beam nuclei was checked as a function of the distance from the point of first detection. The data of Refs. 8 and 10 on Λ_1 are shown in Fig. 2. In both studies in the first centimeter there is a small excursion toward larger values of Λ_1 which hardly can be assigned any significance.

To confirm the existence of a dependence of λ on L, in Ref. 7 (and also in Ref. 8) the following analysis, which does not depend on the validity of Eq. (3), was made. All events[7] were broken down into 30 groups with fixed fragment charges (6 charges for the ^{16}O beam[4)] and 24 charges for the ^{56}Fe beam). For each group the procedure described was used to determine a pair of values of the mean free path λ_1 for $L < 2.5$ cm and λ_2 for $L > 2.5$ cm, and 30 values of the ratio λ_1/λ_2 were obtained. The purpose of the analysis of Ref. 7 was to compare the experimental distribution of λ_1/λ_2 with the theoretical distribution (calculated for the condition $\lambda = \text{const}$) and to find the quantitative characteristics of any possible deviation. The theoretical distribution of λ_1/λ_2 was calculated as follows. It was assumed[7,33] that the quantities $2N_1\lambda_1/\lambda$ and $2N_2\lambda_2/\lambda$ are distributed in the same way as χ^2 with $2N_1$ and $2N_2$ degrees of freedom (here N_1 and N_2 are the numbers of interactions of fragments in the intervals $L < 2.5$ cm and $L > 2.5$ cm, and λ_1 and λ_2 are random quantities). In particular, this assures equality of the average values: $\bar{\lambda}_1 = \bar{\lambda}_2 = \lambda$. With these distributions of λ_1 and λ_2 the probability $P(x)$ of observing a value of the ratio λ_1/λ_2 smaller than a given number x is given by the F distribution (the Fisher-Snedecor distribution):

$$P(x) = \int_0^x v(x)\,dx = F(x,\ 2N_1,\ 2N_2). \tag{7}$$

The explicit form of the distribution (7) can be found for example in Refs. 27 and 33. Then instead of x one introduces a new variable P ($0 \leqslant P \leqslant 1$) in terms of which the theoretical distribution of the probability density $v(x)$ in (7) is transformed to a constant. Obviously the relation between this new variable P and the old variable x is given just by Eq. (7). Then in terms of the variable P one constructs the probability density of the experimental distribution of the ratio λ_1/λ_2 and compares the locations of the centers of gravity of the theoretical distribution (its center of gravity occurs at $\bar{P} = 1/2$) and the experimental distribution.

In Ref. 7 the interval $0 \leqslant P \leqslant 1$ was broken down into five parts of 0.2 each, and for each ratio λ_1/λ_2 the value of P was found on the basis of Eq. (7). In this way the number of ratios λ_1/λ_2 falling in each interval ΔP was determined. This distribution of $\Delta N/\Delta P$ as a function of P is shown in Fig. 3a. It is evident that the distribution differs considerably from the constant distribution $dN/dP = \text{const}$ shown by the dashed

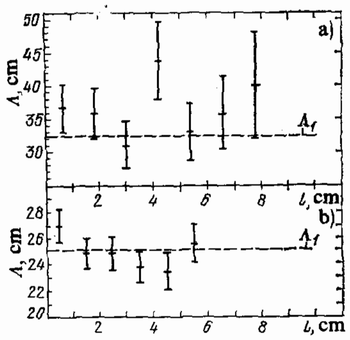

FIG. 2. Reduced mean free path of beam nuclei as a function of the distance L from the point of first detection. a) Data of Ref. 8 (beam of ^{56}Fe nuclei); b) data of Ref. 10 (cosmic rays).

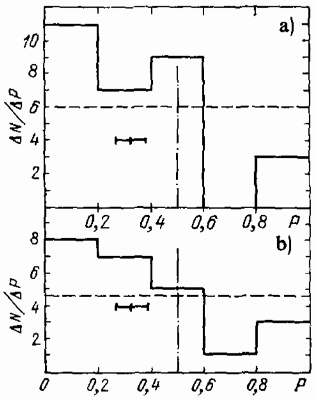

FIG. 3. Distribution of the ratios $\lambda_1(L < 2.5\text{ cm})/\lambda_2(L > 2.5\text{ cm})$ with respect to the values of the variable P given by Eq. (7). a) Data of Ref. 7 (the point with error bars is $\bar{P} = 0.323 \pm 0.053$); b) data of Ref. 8, $\bar{P} = 0.33 \pm 0.06$). The dashed line is the expected distribution for $\lambda(L) = \text{const}$. The dot-dash vertical line shows the expected value of $\bar{P}$, which is 0.5.

[3)]Analysis of the data of Refs. 7, 8, and 10 carried out in Ref. 25 indicates that the anomalon mean free path λ_a also depends on Z. With parametrization of λ_a in the form (3) it is found in Ref. 25 that $b > 0$ and $b' \equiv db/dZ < 0$. The data of Refs. 7, 8, and 10 do not permit more definite values of the parameters b and b' to be established.

[4)]The number 5 given for the charges in the ^{16}O beam in Ref. 7 is probably a misprint, since it is inconsistent with the histogram of Fig. 2 in Ref. 7 and with the total number of groups, which is equal to 30.

line, and is concentrated mainly at small P, which according to Eq. (7) corresponds to small x, i.e., $\lambda_1 < \lambda_2$. The point with error bars in Fig. 3a is the value $\bar{P} = 0.323 \pm 0.053$ obtained by averaging P over the experimental distribution of $\Delta N/\Delta P$ and differs from the value $\bar{P} = 1/2$ expected for a uniform distribution by 3.4 standard deviations, which corresponds to a probability $3 \cdot 10^{-4}$ of this being a statistical excursion. This result, regardless of the validity of Eq. (3), confirms that the mean free path of the fragments in the first few centimeters after the point of production is actually shorter than at greater distances. The results of the analysis of Ref. 8 based on 24 ratios λ_1/λ_2 are shown in Fig. 3b and lead to a value $\bar{P} = 0.33 \pm 0.06$ which differs from 1/2 by 2.8 standard deviations, which in turn corresponds to a confidence level better than 99%. A similar analysis shows that the mean free path of fragments of the third and higher generations is still shorter by 15%.[7] We emphasize that this analysis is based substantially on the distributions given above for the lengths λ_1 and λ_2. With poor statistics appreciable deviations from these distributions are possible (Ref. 42).[5)]

Another estimate of the level of reliability was obtained in Ref. 10. By modeling the process with a Monte Carlo procedure carried out by computer on the assumption that $\Lambda_2 = \Lambda_1$, the number of interactions of fragments in the first interval of length 1 cm was calculated. In the experiment[10] 179 fragments interacted in this interval, out of 1778 having a potential path greater than 1 cm. A Monte Carlo calculationn[10] gave a significantly smaller number of interactions, and the number 179 was reached only in one out of 2000 trials. This result does not depend on the values of the parameters in Eq. (3). Monte Carlo events in a model with unstable anomalons[10] gave a number of interactions close to that observed.

The characteristics of the primary (parent) interactions and the secondary (both normal and anomalous) interactions are on the whole similar.[8] The following properties of these interactions are also observed[8]:

1) Mean free paths of fragments produced in primary interactions of two types were studied. a) In collisions with light elements of the emulsion (C, N, O). These interactions are accompanied by a number N_h of nonrelativistic tracks (with $\beta < 0.7$) which is less than or equal to 7. b) In collisions with heavy elements (Ag, Br), i.e., with $N_h > 7$. It turns out that the greater part of the anomalous fragments are produced in events with $N_h \leqslant 7$, i.e., in light elements of the target. In fragments produced in events with $N_h \leqslant 7$, the mean free path λ_1 for $L < 2.5$ cm is 2.5 standard deviations shorter than λ_2 ($L > 2.5$ cm), and for $N_h > 7$ the mean free paths λ_1 ($L < 2.5$ cm) and λ_2 ($L > 2.5$ cm) are approximately equal.

2) The distributions of the multiplicity in secondary interactions for $L < 2.5$ cm and $L > 2.5$ cm are extremely close, but the peak of the distribution for $L < 2.5$ cm is shifted to the region of somewhat smaller multiplicity.

3) The distribution of the charges of fragments produced in light elements ($N_h \leqslant 7$) has a small enhancement in the region of small charges for events with $L < 2.5$ cm in comparison with events for $L > 2.5$ cm.

4) The fraction of "white stars" (i.e., events with $N_h = 0$) in secondary interactions is about 3.5% larger for fragments produced in collisions of beam nuclei with light elements ($N_h \leqslant 7$) than for fragments produced in collisions with heavy elements ($N_h > 7$).

5) The distribution of the multiplicity in all "white stars" for $L < 2.5$ cm has a peak at a smaller multiplicity than for $L > 2.5$ cm.

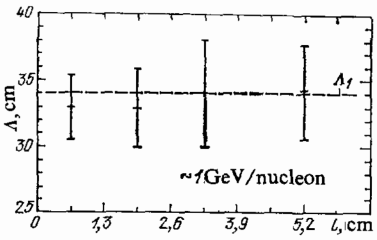

FIG. 4. Reduced mean free path of fragments at a beam energy of 1 GeV/nucleon.[9]

There is an indication of a threshold nature of the effect[9]: with a beam energy 1 GeV/nucleon the mean free path of the fragments does not depend on L and within experimental error coincides with the mean free path of the beam nuclei (Fig. 4). It should be noted that in Ref. 10 the spectrum of cosmic rays began at 400 MeV/nucleon, but a decrease of the mean free path of fragments for $L < 2.5$ cm is observed.

A negative result[11] was obtained for fragments with $Z = 2$: the mean free path of fragments with $Z = 2$ turned out to be equal to the mean free path of helium nuclei and has no tendency to decrease at small L (Fig. 5). This work was carried out at Berkeley in beams of ^{56}Fe and ^{40}Ar with energy 2 GeV/nucleon with a statistics of 3393 primary interactions giving tracks with $Z = 2$ in a cone of 0.1 rad. This number of events is 1.5–2 times greater than the statistics of each of Refs. 7–10. According to the statement of the auth-

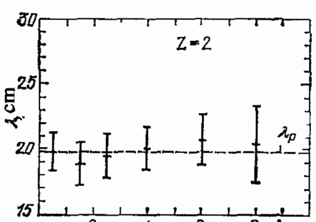

FIG. 5. Mean free path of fragments[11] with $Z = 2$. The dashed line is the mean free path of ^{4}He nuclei.

5)The distribution of the mean free paths λ expressed in terms of the distribution of χ^2 with $2N$ degrees of freedom is determined by a series of experiments with a given fixed number N of interactions of the nuclei. The numbers of beam nuclei are random and can be different in different experiments of this series. The mean free paths of the primary beam are determined under just such conditions. The conditions of the experiments of Refs. 7–10 appear closer to the opposite situation, in which the number of fragments produced, which comprise the secondary beam, is fixed (since this number now determines the statistical reliability of the data[7–10]; see Table I) and the numbers of fragment interactions are random (i.e., not fixed in a given series). A series of such experiments leads to some distribution of lengths λ which can influence the results of the statistical analysis of the data of Refs. 7–10, especially with breaking up of the entire statistics into small groups of events with fixed charges.[42]

ors of Ref. 11, the results obtained by them is inconsistent with the data of Ref. 28.

Up to this point we have been discussing data obtained in fragmentation of nuclei in nuclear emulsion. Recently the results have been published for an experiment carried out at Dubna,[14] in which the cross sections for interaction of fragments with $Z = 2$–6 produced in collision of carbon nuclei with momentum 4.2 GeV/c per nucleon with propane (C_3H_8) were studied in a propane bubble chamber. In comparison with the preliminary results,[12,13] the data of Ref. 14 were obtained with improved statistics. Interaction cross sections were determined for each group of fragments with a given charge. As the result of technical difficulties associated with superposition of tracks on each other near the primary star and of stars from different fragments produced in the same primary interaction, it was necessary for identification of fragments and determination of their interaction cross sections to move away from the primary star by 10 cm. The cross sections were determined on the basis of the mean free paths in the interval $10 \leqslant L \leqslant 30$ cm. The results of Ref. 12 (for $Z = 2$–4) and of Ref. 14 (for $Z = 5$ and 6) are given in Table II and in Fig. 6. The dashed line in Fig. 6 has been drawn through the known experimental points for beam nuclei. The mass numbers of fragments with $3 \leqslant Z \leqslant 5$ were taken equal to twice the charge. For fragments with $Z = 2$ the experimental point was placed between the mass numbers, $3 < A < 4$, and for fragments with $Z = 6$ it was placed in the interval $11 < A < 12$. The horizontal lines show the probable interval of variation of the mass numbers. From the data of Ref. 14 it follows that the cross sections for interaction of carbon fragments with charges $Z = 5$ and 6 are 10% larger than the expected value. For $Z = 2$, as in Ref. 11, there is no effect.

In Ref. 14 the characteristics of γ rays accompanying the production of fragments with charges $Z = 5$ and 6 were also studied. Emission of γ rays is expected in the transition of anomalous fragments to ordinary nuclei. These authors observed an excess of γ rays with energy $E_\gamma < 70$ MeV in the antilaboratory system above the background from decay of π^0 mesons. However, analysis of the existing experimental data on γ rays in events where multiply charged fragments are not produced showed that in the same kinematic region there is an appreciable contribution of γ rays arising as the result of hadronic bremsstrahlung. The data of Ref. 14 do not permit separation of the expected anomalon radiation from bremsstrahlung.

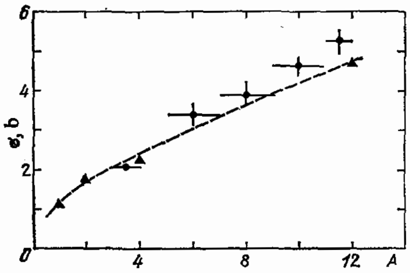

FIG. 6. Cross sections for interaction of fragments of carbon nuclei[12,14] as a function of their mass number A (circles). The triangles and the dashed line show the cross sections for interaction of beam nuclei.

An attempt to observe γ radiation from anomalons was made also in Ref. 15. The energy of the ^{56}Fe beam was set at 940 MeV/nucleon (in Ref. 15 doubt is raised as to the validity of the result of Ref. 9 regarding the absence of the effect at 1 GeV/nucleon). The fragments were produced in a steel target in which about $1.63 \cdot 10^8$ beam particles interacted. The collimator window was placed downstream from the target and directed to the secondary beam. Therefore the apparatus could record only γ rays from anomalons radiating in flight beyond the target at a distance from the target between 1.4 and 2.4 cm, and detection of bremsstrahlung from the target was excluded. The results of the experiment are negative: the expected γ radiation was not observed. The model with decaying anomalons[10] is excluded at the 95% confidence level if the γ-ray energy lies in the range $70 < E_\upsilon < 2000$ MeV and the anomalon lifetime is in the range $7 \cdot 10^{-12} < \tau < 3 \cdot 10^{-9}$ sec, which corresponds to a path $0.3 < L < 200$ cm. In a model[7] with a 6% admixture of anomalons, their electromagnetic decay is excluded if $140 < E_\upsilon < 2000$ MeV and $2 \cdot 10^{11} < \tau < 1.8 \cdot 10^{-10}$ sec $(0.9 < L < 9$ cm).

We note that normal excited states of nuclei are deexcited in a time less than about 10^{-12}–10^{-15} sec. For this reason it is impossible to explain the decrease in the fragment mean free path as the result of excitation of normal states and accordingly of an increase in their radius.

At the present time studies of the properties of nuclear fragments are being continued and new experiments are being planned.[26] In this connection we note that in spite of the arguments given in Refs. 7–10 and presented above in favor of the dependence of the fragment mean free path on the distance from the star, the data of Refs. 7–10 still do not provide complete confidence that this dependence actually

TABLE II

Fragment charge Z	2	3	4	5	6
Number of observed fragments	2892	645	517	1771	1272
Cross section for interaction of fragments, in barns	2,06 ±0,08	3,39 ±0,25	3,90 ±0,32	4,65 ±0,20	5,30 ±0,27
Cross section for interaction of beam nuclei with $A = 2Z$, in barns	2,260 ±0,050				4,780 ±0,060

TABLE III

References	1	2	3	4	5	6	7	8
	Number of points	b	Λ_1, cm	$\chi^2(\Lambda_1)$	$P(\chi^2(\Lambda_1))$	Λ_2, cm	$\chi^2(\Lambda_2)$	$\frac{\Lambda_1-\Lambda_2}{\Lambda_1}$
Friedlander E. M. et al.[7]	8	0,44±0.02	30,4±1,6	18,6	0,015	27,9	8,5	8%
Jain P. L., Das G.[8]	5	0,42±0.024	32,4±1,7	18,1	0,002	29,4	6	9%
Aggarwal M. M. et al.[9]	5	0,42±0.024	32,4±1,7	7.8	0,2	29,7	2,8	8%
Barber H. B. et al.[10]	6	0.34±0,03	25,1±1,7	26.0	0.0002	21.3	6.5	16%

exists. As has already been mentioned, the analysis presented in Fig. 3 depends on the probability distribution $P(x)$, which may differ from (7). To this we can add that the assumption that Λ_2 is independent of L is consistent, on the basis of the χ^2 criterion, with the data of Refs. 7–10 no more poorly than the model with an admixture of anomalons. We recall that the expected value of χ^2 in the case of N degrees of freedom is $\chi^2 = N \pm \sqrt{2N}$. The dot-dash lines in Figs. 1a and d describe the data[7,10] with $\chi^2 = 2.4$ and $\chi^2 = 4.4$ with 8 and 6 points, respectively. The results of a fit made by us to the data of Refs. 7–10 within the framework of the hypothesis $\Lambda_2 = \text{const}$ are shown in Fig. 1 by the solid lines. Values of Λ_2 and the corresponding χ^2 values are given in columns 6 and 7 of Table III. It can be seen that the hypothesis $\Lambda_2 = \text{const}$ gives optimal values of $\chi^2(\Lambda_2)$ and consequently, like the anomalon model, is in good agreement with the experimental data. From this point of view the smaller value of Λ_2 for $L < 1$ cm in Figs. 1a, b, and d, which differs from $\Lambda_2 = \text{const}$ by more than one standard deviation, is a statistical excursion. The probability of such an excursion in each individual case is not small, as follows from the values of $\chi^2(\Lambda_2)$ given in column 7 of Table III. However, the fact that in three studies[7,8,10] out of four[7–10] there is an excursion just in the direction of smaller values of Λ_2 seves as a serious objection to this interpretation. On the other hand, this objection can be offset by the data shown in Fig. 2 on the mean free paths Λ_1 of the primary nuclei.[8,10] In both cases for $L < 1$ cm there is a statistical excursion in the direction of larger values of Λ_1. We note that these data are in agreement with the hypothesis $\Lambda_1 = \text{const}$ with $\chi^2 = 7.4$ with 7 points and $\chi^2 = 5.1$ with 6 points, respectively, i.e., at the same level as the data[7–10] on Λ_2 agree with the hypothesis $\Lambda_2 = \text{const}$.

On breaking up the data of Refs. 7–10 on fragment mean free paths into groups with $L \lessgtr 4$ and fitting each group by means of the hypothesis $\Lambda_2 = \text{const}$, different values of Λ_2 are obtained for $L \lessgtr 4$, but with errors which overlap in the case of Refs. 9 and 10.

In column 4 of Table III we have given values of $\chi^2(\Lambda_1)$ for the mean free paths of the primary nuclei, calculated from experimental values of the fragment mean free paths. The corresponding probabilities of a statistical excursion are given in column 5 of Table III. It can be seen that there is a statistically reliable difference between the mean free paths of the fragments and those of the primary nuclei. This difference, as can be seen from column 8 of Table III, amounts to about 10%. For a final solution of the question of the dependence of Λ_2 on L, improved statistics and complete exclusion of possible systematic errors are required.

3. THEORETICAL APPROACHES

The theoretical models proposed for explanation of anomalously large interaction cross sections of nuclear fragments are very diverse and quite speculative. Therefore we shall confine ourselves to listing them and giving brief descriptions. The list of models given below is not exhaustive.

In Refs. 16–20 an increase of the cross sections is explained by excitation of color degrees of freedom. It is assumed that colored quarks interact with each other very strongly. Compensation of color in nucleons, which are colorless objects, leads to a weakening of this interaction, and the nuclear forces are similar to Van der Waals forces between neutral atoms. In collisions of nuclei, a rearrangement of their structure occurs, with formation of multiquark states with hidden and even explicit color, and around such objects there are significant fluctuations of the color gluon field, which leads to large interaction cross sections. The large lifetime is related to the necessity of a substantial rearrangement of the structure of a state for its conversion into an ordinary nucleus.

Reference 16 discusses such highly excited six-quark states with hidden color with mass greater than the sum of the masses of the two nucleons by approximately 1 GeV. Reference 17 also considers a six-quark state with $J^P = 0^-$, called by the authors a diquark deuteron or "demon", which is constructed of three pairs of quarks and has a mass less than the πNN threshold. It is assumed[17] that the demon is contained inside the nuclear fragments. In Ref. 18 in the bag model anomalons are related to heated quark matter. In Ref. 19 it is suggested that anomalons are colored nuclei. They are produced in pairs and are heavier than ordinary nuclei, which explains the threshold at 1 GeV/nucleon.[9] Reference 20 advances the hypothesis that anomalons have fractional electric charge.[6)] It is assumed[20] that the threshold for formation of fractional charges in nucleus-nucleus collisions is less than in pp or e^+e^- collisions.

Reference 21 considers a nonstatic but metastable state of nuclear matter (the σ-τ phase) which generates a coherent pion field with a large effective Compton wavelength.

[6)]This hypothesis is not confirmed by the experiments of Refs. 34 and 44. According to Ref. 34 the fraction of fractionally charged anomalons with $\Delta e = 0.3e$ in the first two centimeters after their formation does not exceed $3\cdot 10^{-3}$ (at the 95% confidence level).

In Refs. 22 and 23 the anomalously large interaction cross sections of fragments are a consequence of the increase of their geometrical size. Reference 22 considers the fact that nuclei with $Z = 3$–5 which are included among the fragments actually have a radius R and accordingly a parameter r_0 somewhat greater than the values which follow from the formula $R = r_0 A^{1/3}$ on extrapolation of this formula from the region of large A corresponding to beam nuclei. This leads to a reduction of 10–20% in the mean free path of the fragments and makes the mean free path independent of L, which is consistent with the experimental data. For $Z = 6$–10 a decrease of the fragment mean free path is not observed in Ref. 10, and for $Z \geqslant 12$ the observed decrease of the mean free path can be explained, according to Ref. 22, by formation of nuclear quasimolecules (highly deformed cluster states with low angular momentum). The radius of the nuclear quasimolecule ^{32}S is a factor of two greater than the radius of the ^{16}O nucleus. The hypothesis of Ref. 22 is criticized in Ref. 40. An answer to the criticism is given in Ref. 41.

In Ref. 23 it is shown that in nucleus-nucleus collisions it is possible to form nuclear isomers of low density and anomalously large size with a radius approximately three times that of ordinary nuclei. The excitation energy of such states is about 5–6 MeV/nucleon. There are no isomers with small values of Z (for example, with $Z = 2$, in agreement with the data of Refs. 11 and 14) and also with $A > 60$. Isomers with $Z \gtrsim 10$ are capable of splitting, and this process can be observed in emulsions. There should be an accumulation of isomers and a further decrease of the mean free path of fragments in the third and subsequent generations as observed in the experiment of Ref. 7. Nuclear isomers of low density are discussed also in Ref. 38.

Reference 24 considers nuclei which have an unusual shape. The cross sections for interaction of nuclei which have taken the shape of a pancake or doughnut[24] are several times larger than the cross sections for interaction of spherical nuclei, even at the normal nuclear density. A decrease of the density of such nuclei is possible, and this will lead to still larger interaction cross sections.

We emphasize that the theoretical models (except for Ref. 22) are directed toward explanation of the existence of nuclear fragments with tenfold enhanced cross sections. However, there is still no absolute confidence that the mean free path of the fragments depends on the distance to the point of production, and the explanation of the experimental data by a 10% increase of the cross sections of a large part of the fragments cannot be excluded. Such an increase of the cross sections will lead to a mean free path close to that shown by the solid line in Fig. 1. However, even a 10% effect represents a large value for traditional nuclear physics. To obtain a 10% effect it is sufficient that the mass number of *the fragments* be approximately 20% greater than 2*Z*. Isotopes with this or even higher neutron excess exist,[29–31] but the probability of their production at 2.1 GeV/nucleon[32] and at lower energies[31] is small and apparently is not sufficient to explain the magnitude of the effect.

An experiment which is critical to the choice of the model will consist of a reliable verification of the existence or absence of a dependence of λ on L.

4. CONCLUSIONS

The experimental data presented in Section 2 indicate that the mean free paths of nuclear fragments, with the exception of fragments with certain charges, are less than the mean free paths of the beam nuclei. The data also indicate a dependence of the fragment mean free path on the distance L from the point of formation of the fragments. However, the decrease of the fragment mean free path has been established more reliably than its dependence on L. The limited statistics do not firmly convince us that this dependence exists, whereas for theoretical interpretation of the data it is very important whether or not the mean free path depends on L. Therefore the question of whether or not anomalons exist cannot yet be considered finally solved. The observation of anomalons, if they really exist, would open new horizons in nuclear physics, hazy outlines of which may already be visible. The continually increasing activity of experimental investigations permits one to hope that the question will become definitively clear in the course of the next few years.

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