NUCLEAR DISINTEGRATIONS PRODUCED IN NUCLEAR EMULSIONS BY α-PARTICLES OF GREAT ENERGY

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Abstract

A study of nuclear disintegrations caused by α-particles of primary cosmic radiation with energies > 5 BeV per nucleon, has been carried out. In a systematic survey in nuclear emulsions using 'along the track' scanning method, 479 α-particles with a total track length of $40 \cdot 84$ metres and 242 interactions were obtained. From the angular distribution of shower particles associated with these interactions, a procedure has been found for distinguishing protons, which originally formed part of the incident α-particle and which have not taken part in the interaction, from other charged particles. The mean free path for nuclear interaction in G-5 emulsion is found to be $17 \cdot 5 \pm 1 \cdot 1$ cm. ($68 \cdot 9 \pm 4 \cdot 3$ gm./cm.^{2}). Assigning both to the incident α-particle and to the target nuclei a radius $R = r_0 A^{\frac{1}{3}}$, one obtains an effective nuclear radius $r_0 = 1 \cdot 13 \pm 0 \cdot 04 \times 10^{-13}$ cm. Using the number of protons emerging from disintegrations of heavy nuclei (Silver and Bromine) without having participated in the interaction (as can be deduced from the angular distribution) and assuming spherical nuclei of uniform density, the mean free path of nucleons in nuclear matter is calculated to be less than $3 \cdot 2 \times 10^{-13}$ cm.

1. Introduction

For the study of nuclear reactions above 6 BeV, only cosmic ray particles are available at present. Such interactions can be observed in emulsions exposed in the stratosphere. The great majority of such interactions is produced by singly charged particles, but in general it is not possible to say in those interactions, whether the incident particle is of primary or secondary origin. Therefore, even if the exposure is made at low latitudes, one cannot easily separate interactions of particles of energy above several BeV from those of lower energy. This separation is, however, possible if one confines oneself to primary α-particles. In this case at a given latitude, one deals with known particles with a known energy spectrum and fairly well-defined minimum energy. On the other hand, one has to accept the disadvantage of dealing with collisions whose interpretation is more complex than those initiated by singly charged particles. Still, in the interest of obtaining an uncontaminated sample of high energy interactions we have thought it worth while to study the nuclear processes in emulsions due to α-particles whose energy exceeds 5 BeV/nucleon.

Apart from obtaining a mean free path for various types of interactions, it turns out that one can separate in these interactions, the protons which originally formed part of the incident α-particle and which have not collided with any part of the target nucleus, from the remaining shower particles, namely, protons which have interacted, and charged mesons which have been produced in the collision. This separation which is based on the angular distribution of shower particles may, in the future, be of use in the study of high energy interactions, because it permits the identification in the shower core of tracks of singly charged particles whose energy is known to be close to the energy per nucleon of the primary.

Nuclear interactions caused by artificially produced α-particles with energies upto about 100 MeV per nucleon have been studied by various worker.[1, 2] A few investigations have also been carried out using α-particles from the cosmic radiation.[3–5] In the latter experiments, the emulsions were exposed to the cosmic radiation at latitudes where the geomagnetic cut off for α-particles was less than 500 MeV/nucleon. Our work differs from that of other investigators using α-particles of cosmic radiation, in that we obtained an appreciably larger number of interactions and worked with α-particles whose lower energy limit was 5 BeV/nucleon. In order to compare the characteristics of interactions produced by these α-particles directly with those produced by protons of comparable energy we also obtained stars produced by 6·2 BeV protons of the Berkeley Bevatron.*

2. EXPERIMENTAL PROCEDURE AND RESULTS

In order to obtain an unbiased selection of interactions produced by high energy α-particles as well as by 6·2 BeV protons of the Berkeley Bevatron, we adopted the 'along the track' method where the track of the primary particle is first observed and then followed until it makes an interaction or leaves the emulsion stack.

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* We are grateful to Professor Leprince-Ringuet of the Ecole Polytechnique, Paris, for kindly lending us two of their emulsions exposed to the direct beam of the Berkeley Bevatron.

2.1. EMULSION BLOCKS USED FOR OBTAINING THE α-PARTICLE INTERACTIONS

The experiment was carried out almost exclusively with one emulsion block consisting of 200 G-5 emulsions, 600 μ thick and of size 15 × 15 cm. This stack was flown from Delhi and it floated above an altitude of 70,000 ft., for about 3 hours. The geomagnetic cut off for α-particles at Delhi (19° N.) is 5·3 BeV/nucleon. About 10% of the interactions came from a second stack flown from Ahmedabad (13° N. and 5·8 BeV/nucleon geomagnetic cut off) at a mean altitude of 60,000 ft. for 3½ hours.

In both these exposures, the geomagnetic cut off is so high that all primary α-particles have four times the ionization of relativistic singly charged particles. In our emulsions this corresponds to about 3·5 times the grain density at the plateau of ionization for singly charged particles.

2.2. SELECTION OF TRACKS

We scanned the plates under a total magnification of × 375 and selected tracks which fulfilled the following criteria :

(*a*) The grain density by visual judgment was in the neighbourhood of 3·5 times the plateau value for singly charged particles ;

(*b*) The track length per emulsion was $\geqslant$ 5 mm. ;

(*c*) The potential range in the stack was $\geqslant$ 5 cm.

These tracks should have been produced either by relativistic α-particles or by slow singly charged particles—protons, deuterons or tritons. In order to differentiate between relativistic α-particles and slow protons, deuterons and tritons a rough estimate of the coulomb scattering of these particles was made in the following manner :

The hairline in the microscope eye-piece was set exactly along the track and it was followed from its point of entrance to that of exit in the emulsion. It can easily be seen that if by error of visual judgment we included even a triton of grain density as low as 3·0 times the plateau value, its deviation due to coulomb scattering in a distance of 5 mm. is quite appreciable ($\sim 5\mu$) and can be detected visually under the maginification of × 375 that we employed. In some cases where it was not possible to decide with certainty in the first emulsion, a similar test in the succeeding one was sufficient to separate relativistic α-particles from slow protons, deuterons and tritons. We would like to point out here that these emulsions after processing had small distortions ($\leqslant$ 20 covans).

That the above test was sufficient to identify relativistic α-particles can also be seen in the following way. Every track must have a minimum

TABLE I

Size frequency distribution of α-induced interactions

N_h / N_s	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	⩾25	Total
0																											0
1			1																								1
2	16	6	1	2	1	1	1																				28
3	5	2	2		1																						10
4	2	3		2	1					1						1											10
5	5	2	2	5	1		2	1	1		1		1											1			22
6	4		2	2	2	2										1											13
7	2					1	1			1	1		1				1				1					1	10
8		1	1	1	1		3	1			2	1				1		1								1	14
9	1	1			3			1						1													7
10				2	4	3	1			1				1		1								1		1	15
11	2	1		4	1	5			1		2	2	1		1		1					1				1	23
12											1			1	1			1								3	7
13			1			1											2		1		1			1	3	1	8
14			1		1	1	1		2			1										1					8
15						1							1	1						1				3	1		8
16									2				1			1			1								5
17																	1	1								1	3
18			1	1												1					1						4
19																								1	1	1	3
⩾20		1	1			1						1		3	1			1		2	1	1		3		3	19
Total	37	17	13	19	16	16	9	3	6	3	7	5	5	7	3	6	5	4	2	3	4	3	0	10	2	13	218

α in–α out interactions

0		7		1	2																						10
1			1		2						1																4
2						1																					1
3																											0
4																											0
5	1																										1
10				1																							1
Total	1	7	1	2	4	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	17

GRAND TOTAL .. 235

potential range of 5 cm. in order to satisfy our selection criteria; a triton of grain density as low as 3·0 times the plateau value should show a significant and easily recognizable increase in grain density in this distance, yet none of the tracks selected showed an observable change of grain density along the entire track length. If the selected track terminated in a star, it was always a high energy star with relativistic prongs, a type of star which cannot be produced by a slow proton, deuteron or triton. Thus, from all these considerations we feel that we have obtained a selection of primary α-particle tracks without contamination from slow singly charged particles. A further argument in favour of this conclusion will be given in 4.1.

2.3. THE RESULTS

We have selected a total of 479 α-particle tracks with a total track length of 40·84 metres and obtained 242 interactions. For the 6·2 BeV protons we obtained a total track length of 35·69 metres and 103 interactions. We would like to point out here that the median energy of the α-particles is about 10 BeV/nucleon, whereas the proton energy is only 6·2 BeV, this being the highest energy available at present from accelerators.

The interactions produced by α-particles could be classified in the first instance into two types:

(*a*) Events in which a relativistic doubly charged particle continues almost along the same direction as the primary α-particle (α in-α out events);

(*b*) Interactions in which only singly charged relativistic particles and other non-relativistic particles are emitted (α-destructive collisions).

Various types of interactions produced by α-particles are illustrated in Fig. 1.

The distribution of the 242 interactions according to the number of shower particles n_s and the number of heavily ionizing particles N_h is shown in Table I.

3. CLASSIFICATION OF THE INTERACTIONS ACCORDING TO THE NUMBER OF PROTONS TAKING PART IN THE COLLISION PROCESS

A visual examination of all the $(0+2)\ \alpha$ events† strongly indicated that the relativistic singly charged particles emerging from these collisions either

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† In accordance with the nomenclature introduced by Brown *et al.*,[6] the first number designates the number of grey or black tracks (N_h), the second number designates the number of charged shower particles, *i.e.*, tracks whose ionization is less than 1·5 times that produced by singly charged relativistic particles. The symbol outside the brackets indicates the nature of the primary particle initiating the collision.

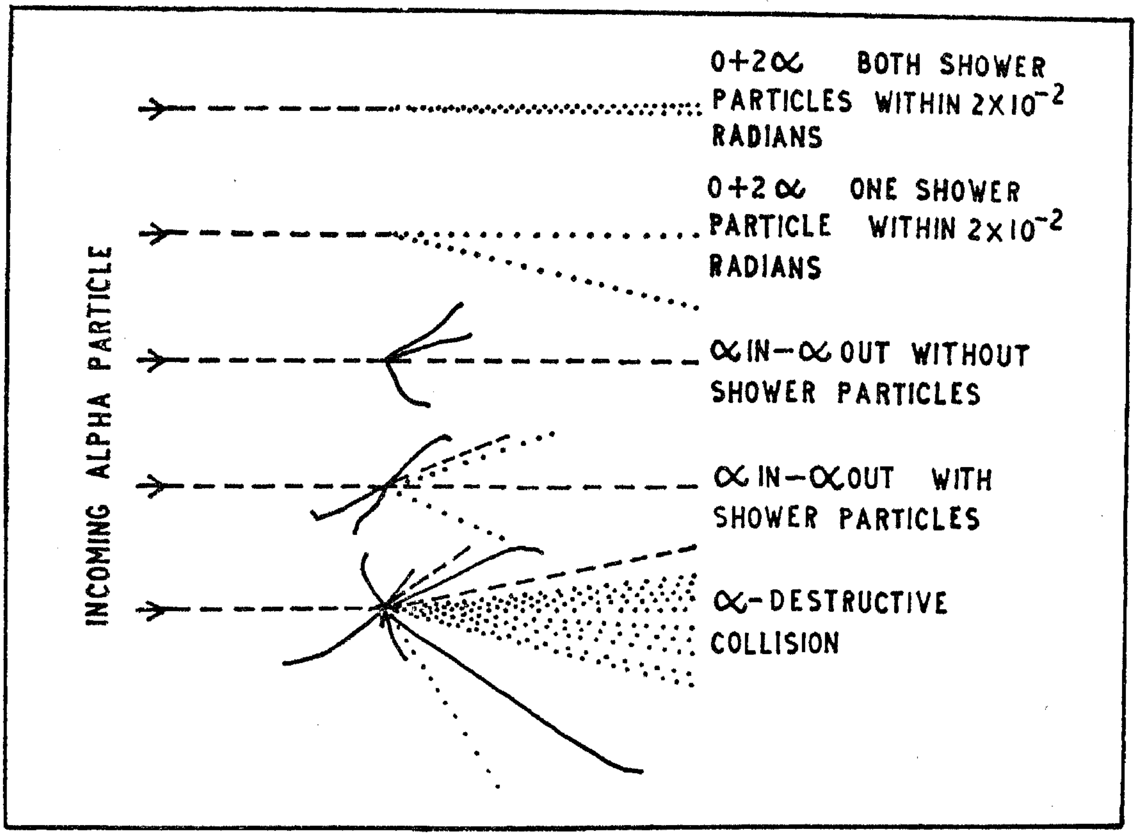

FIG. 1. Figure showing typical examples of interactions caused by α-particles of energy $\geqslant 5$ BeV/nucleon in nuclear emulsions.

continue almost in the same direction as the primary or make fairly large angles with it. This observation suggests that if accurate angular measurements are made on the shower particles of all the disintegrations it might be possible to separate in individual interactions the protons that have not taken part in the collisions from those which have.

3.1. THE ANGULAR DISTRIBUTION OF THE SHOWER PARTICLES

Angular measurements were made on those events where:

(*a*) The primary α-particle and also the shower particles in the forward direction had at least 1 mm. track length in the same emulsion;

(*b*) The event was situated in a region of the emulsion far away from the processed edge ($\geqslant 1$ cm.) and free from bubbles;

(*c*) The energy involved in the disintegration estimated from the opening angle of the shower (for $n_s \geqslant 10$) was $\leqslant 50$ BeV/nucleon.

A total of 176 interactions which satisfied the above conditions was obtained. Tracks which made angles greater than 10^{-1} radian were measured by determining the projected angles and the dip angles under a total magnification of ×675 (using ×45 oil immersion). Only 150 μ track length was used in these measurements. Tracks making angles less than 10^{-1} radians were measured in the following manner:

The α-particle track was aligned along the x-axis on a scattering microscope and the y-coordinate of the track was measured every 200 μ for a distance of $\geqslant$ 1 mm. This was done in the same setting for each secondary particle which made a projected angle of $\leqslant 10^{-1}$ radians. Depth measurements were also made every 200 μ using at least 1 mm. length of the primary track and the same length for each secondary. By this method the projected angles could be measured accurately to 5×10^{-4} radians, while the depth measurements were accurate to 5×10^{-3} radians. Therefore, the errors in our measurements of angles $\leqslant 10^{-1}$ radians will be of order 5×10^{-3} radians.

In Fig. 2 (a) we give the angular distribution of shower particles below 10^{-1} radians. We have also included in this figure the doubly charged par-

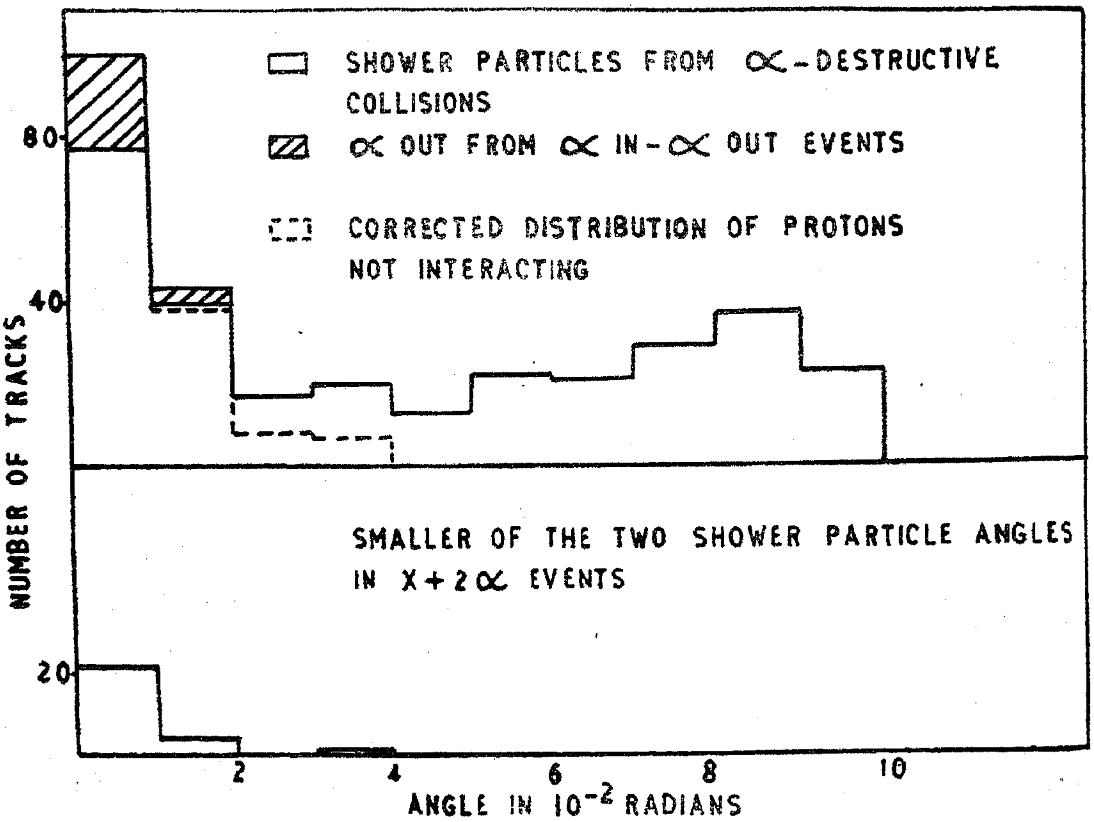

FIG. 2. (a) Angular distribution of shower particles ejected at angles less than 10^{-1} radians from α-particle induced interactions.

(b) Angular distribution of shower particles which make the smaller of the two angles with the primary in events of the type ($x + 2$) α.

ticles (counting each as equivalent to 2 shower particles) emerging from α in–α out events; the corresponding part of the histogram has been shaded.

It is seen from Fig. 2 (*a*) that there is a narrow peak at $0\text{–}2\times10^{-2}$ radians and an apparently significant trough in the distribution at an angle of about 4×10^{-2} radians.

3.2. SEPARATION OF PROTONS THAT HAVE NOT TAKEN PART IN INTER-ACTIONS FROM THE REST OF THE SHOWER PARTICLES

The shower particles associated with the α-disintegrations are due either to:

(*a*) Protons which formed part of the incident α-particle and have not taken part in nuclear interaction with the target nucleus;

(*b*) 'Secondary shower particles' defined as protons that have made nuclear interactions, fast recoil protons and mesons produced in the collision.

We will now present evidence that the trough in the angular distribution [Fig. 2 (*a*)] arises from the fact that almost all particles (*a*) are emitted at angles smaller than 2×10^{-2} radians, while particles (*b*) are very rarely emitted within this angle.

(*i*) In Fig. 3 we give the track density per unit solid angle for the interval of $0\text{–}10^{-1}$ radians.

It is seen that in the interval of 5×10^{-2} to 10^{-1} radians the track density is constant within experimental errors. The mean track density in this angular interval is found to be $5{\cdot}60 \pm 0{\cdot}50 \times 10^3$ particles per steradian. This distribution strongly indicates that the narrow peak between $0\text{–}2\times10^{-2}$ radians is due to a process which differs from that which gives rise to the majority of shower particles. Presumably it is due to protons which have not themselves collided with nucleons in the target. If we make the reasonable assumption that the secondary shower particle density has the same value from $0\text{–}5\times10^{-2}$ radians as it has from 5×10^{-2} to 10^{-1} radians, we can separate the protons that have not interacted from other particles. The density distribution of protons which passed through the target without interacting is shown by a dotted line in Fig. 3. We now define a cut off angle which contains 90% of the protons that have not participated in collision processes. This angle is found to be 2×10^{-2} radians. A cut off angle of 2×10^{-2} radians is chosen because the contribution of 'secondary shower particles' within this angle is very small (about 5% of the particles within the cut off angle are 'secondary shower particles') and, therefore, allows

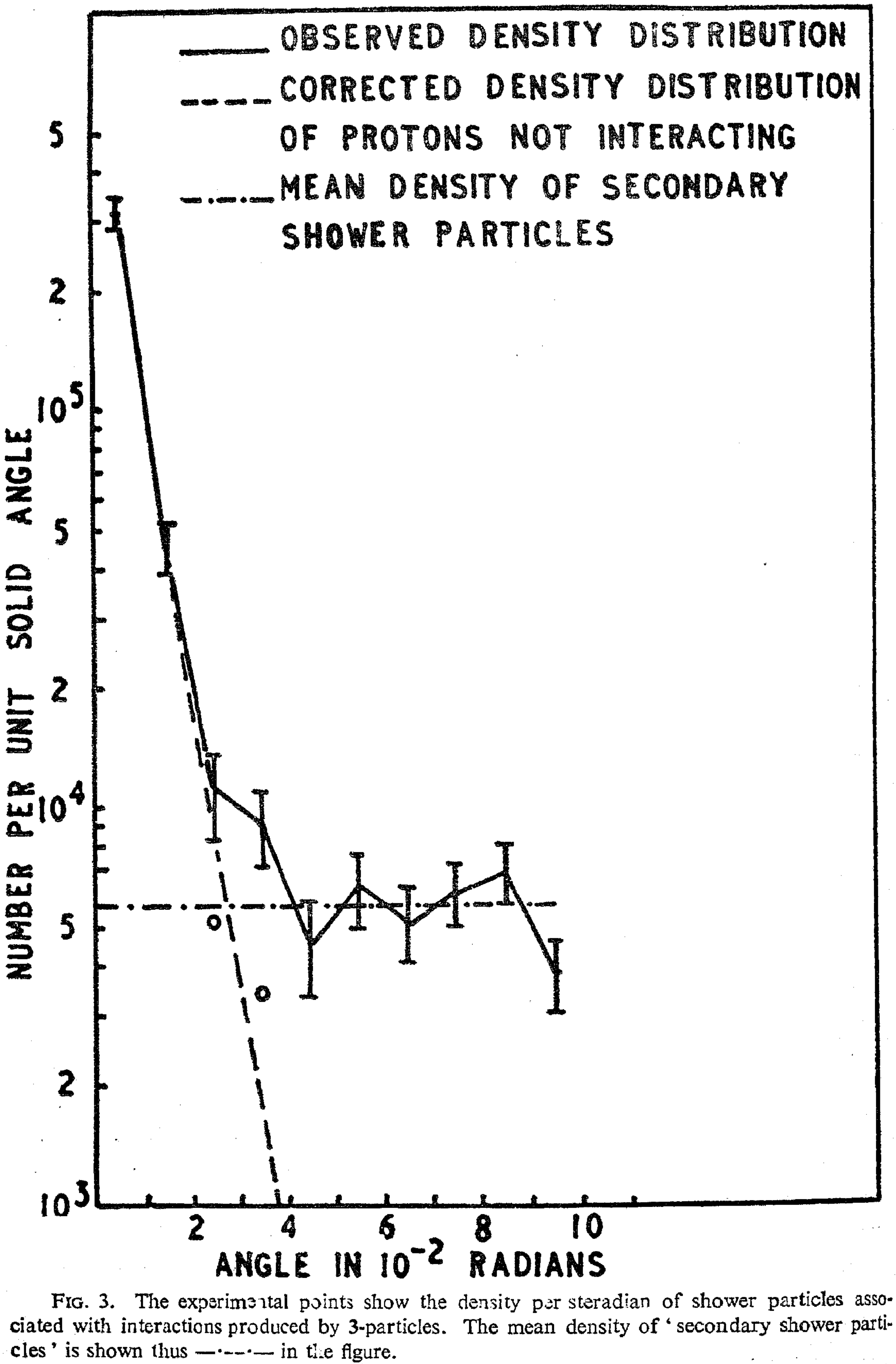

FIG. 3. The experimental points show the density per steradian of shower particles associated with interactions produced by 3-particles. The mean density of 'secondary shower particles' is shown thus —·—·— in the figure.

The dashed line represents the corrected density distribution for protons that have not made any collisions in the target nucleus.

identification *in individual events* of protons that have not participated in collisions, without much ambiguity. The remaining evidence (*ii–vi*) is in good agreement with this conclusion.

(*ii*) In events of the type $(x+2)\ \alpha$ the two shower particles are presumably in almost all cases the same two protons which originally were bound in the incident α-particle. Except for a few events which result from coulomb interaction (see 3.3), it is reasonable to assume that only one nucleon takes part in this type of interaction, because the chance of two interacting and still not producing any charged meson should be very small at energies above 5 BeV/nucleon. If this is so, then in all 26 events of this type there should be at least one proton which has not interacted, and at least one of the two shower particles should then make an angle less than 2×10^{-2} radians with the primary. In Fig. 2 (*b*) we have plotted for all $(x+2)\ \alpha$ events the angular distribution of those shower particles which make the smaller of the two angles with the primary. The histogram shows that in 25 of the 26 events at least one track makes an angle of less than 2×10^{-2} radians with the primary. In the 26th case the smaller of the two angles is $3{\cdot}5\times10^{-2}$ radians. It is found that 75% of the shower particles in the $(x+2)\ \alpha$ events fall within the angular interval 0–2×10^{-2} radians (only 11% of the shower particles from all measured events fall into the same angular interval).

(*iii*) If, now we consider only events of high multiplicity (irrespective of other considerations), then in most cases both protons belonging to the primary α-particle should have made collisions and, therefore, should emerge outside the cut off angle. Therefore, we selected stars with $n_s \geqslant 20$ and found that out of 205 shower particles associated with nine interactions, only two are ejected at angles less than 2×10^{-2} radians. Less than 1% of the shower particles in this type of events fall within the cut off angle 2×10^{-2} radians.

The relatively small proportion of shower particles emitted within the cut off angle in interactions of high multiplicity and the very large proportion of such particles associated with interactions of the type $(x+2)\ \alpha$ (stars where no charged meson is produced) strongly favour our hypothesis.

(*iv*) It will be shown in 3.3 that in each α in–α out event only one neutron should have participated in the collision, therefore, all shower particles associated with them should necessarily be secondary in nature and fall outside the cut off angle. There are 15 shower particles in this type of events and none of them falls within the interval 0–2×10^{-2} radians.

(*v*) We have also studied the angular distribution of shower particles from stars produced by 6·2 BeV protons. Here we know that all shower particles should be ' secondary ' in nature (type *b*). We find that out of a total of 258 shower particles associated with 99 of these stars, only one is emitted at an angle less than 2×10^{-2} radians.

(*vi*) Another indirect evidence for the validity of choosing a cut off angle of 2×10^{-2} radians is offered from the size distribution of events when classified according to the number of interacting protons (obtained by using this cut off angle to separate protons that have not interacted, from the rest). It is found (Table II) that the mean number of shower particles $< n_s >$ and the mean number of heavy prongs $< N_h >$ increase as the number of interacting protons increases.

The evidence given above proves the correctness in our procedure of separating protons that have not interacted from the rest of the shower particles. It is seen from Fig. 3 that the corrected total number of protons that have not participated in collisions should be 151. From Fig. 2 (*a*), we see that there are 143 particles observed within the cut off angle. From the angular distribution given in Fig. 3, and the definition of the cut off angle given earlier in this section, it follows that the 143 particles observed within 2×10^{-2} radians should contain 136 protons that have not interacted as well as 7 ' secondary shower particles '. Thus, it becomes possible to separate without much ambiguity in individual interactions, protons that have not participated in collisions from those which have.

Singly charged relativistic particles emitted within the cut off angle are almost always fragments of the incident α-particle and we have so far simply designated them as protons. Actually they may emerge as protons, deuterons or tritons. In the experiment carried out by Quareni and Zorn,[1] with 90 MeV/nucleon α-particles, events were observed where an incident particle just split into two singly charged particles of the same velocity as the α-particle. Among these secondary particles they were able to identify protons, deuterons and tritons. It is, therefore, likely that in our events also, there are protons, deuterons and tritons emitted at angles less than 2×10^{-2} radians. This observation will not affect our subsequent analysis since we will consider complete symmetry in behaviour between protons and neutrons as far as the nuclear interactions are concerned.

3.3. $(0 + 2)\ \alpha$ AND α IN–α OUT EVENTS

Among the events on which accurate angular measurements were possible there are 11 examples of $(0 + 2)\ \alpha$ type in which both outgoing particles are contained within an angle of 2×10^{-2} radians and 9 examples of α in–α out $[(x + 0 + \alpha)\ \alpha]$ without any associated shower particle. These events could arise from either:

(*a*) Interactions in which only neutrons are involved and no charged mesons are produced; or

(*b*) The disintegration of the α-particles in the coulomb field of the target nucleus $(0 + 2)\ \alpha$; or

(*c*) The break up of the target nucleus in the coulomb field of the α-particle (α in–α out).

In order to estimate the proportion of $(0 + 2)\ \alpha$ and α in–α out events arising from coulomb interactions, we made use of the treatment employed by Weizsacker to calculate the frequency spectrum of virtual photons associated with a charged particle in motion. Using the virtual photon spectrum from 10 to 200 MeV, and assuming for the photo-disintegration of Helium a mean cross-section of $1{\cdot}8 \times 10^{-27}$ cm.^{2},[7] and for the γ, p cross-section in emulsion nuclei a mean value of 2×10^{-26} cm.^{2},[8], we estimate the mean free path for the break up of the α-particle and the target nucleus to be about 5 metres and 100 metres, respectively. From this it can be seen that among all the 176 interactions included for the angular measurement there should be six events of $(0 + 2)\ \alpha$ type (where both shower particles should be within the cut off angle) due to coulomb interaction. The rest as well as the α in–α out events should be due to nuclear rather than coulomb interaction.

3.4. CHARACTERISTICS OF INTERACTIONS IN WHICH 0, 1 OR 2 PROTONS INTERACT

From the arguments given in 3.2, it is clear that we can separate the α-stars into groups defined by the number of protons which have taken part in the interactions. Classified in this manner, we have:

A Group—34 examples with at least two shower particles at angles less than 2×10^{-2} radians (including 14 cases of " α in–α out ");

B Group—63 examples with one shower particle at less than 2×10^{-2} radians; and

C Group—73 examples with no shower particle within the cut off angle.

Total—170.

We have excluded from this and from all the ensuing analysis on *nuclear interactions*, 6 events of the type $(0 + 2)\ \alpha$ (with both shower particles inside the cut off angle) which we attribute to coulomb interactions.

The multiplicity and the heavy prong distributions of stars classified in (A), (B) and (C) are represented in Figs. 4 and 5.

Separate histograms are included for the " α in–α out" events where the emerging α-particle is considered equivalent to two singly charged particles.

In this we have also included two other examples of "α in–α out" observed in a less systematic survey. The mean values of the multiplicity $< n_s >$ and the heavy prong number $< N_h >$ as well as the mean number of 'secondary shower particles' (type *b*) $< n'_s >$ per star for the various groups are summarised in Table II.

TABLE II

	6·2 BeV Proton Stars	All α-stars	A No Proton Interacting		B	C
			α in–α out (one neutron interacting) (*a*)	The rest (one or two neutrons interacting) (*b*)	One Proton + 0, 1 or 2 neutrons interacting	At least two protons interacting
No. of events	99	170	13	21	63	73
Mean No. of shower particles per star $<n_s>$	2·6	8·0	3·1	5·6	7·0	11·0
Mean No. of secondary shower particles per star $<n'_s>$	2·6	7·5	1·1	3·6	6·0	11·0
Mean No. of heavy prongs per star $<N_h>$	6·4	7·7	2·5	2·1	5·6	12·7

In Group A (*a*) stars we know that only one neutron has interacted and the emerging doubly charged particle should be a He^3. Therefore, almost all these events should represent edge collisions. This argument is further strengthened by the fact that the mean number of heavy prongs associated with these stars is only 2·5. We may conclude that subject to an appreciable statistical uncertainty, in a single neutron-nucleon collision at the energies we are dealing with, the mean number of secondary charged shower particles produced is 1·1. This may be compared with the value of 2·6 averaged for all types of collisions produced by 6·2 BeV protons.

It has been shown in 3·2 that the corrected total number of protons that have not interacted is 151. We remove from this the six (0 + 2) α events of coulomb interaction; there remain 139. If we now assume symmetry in

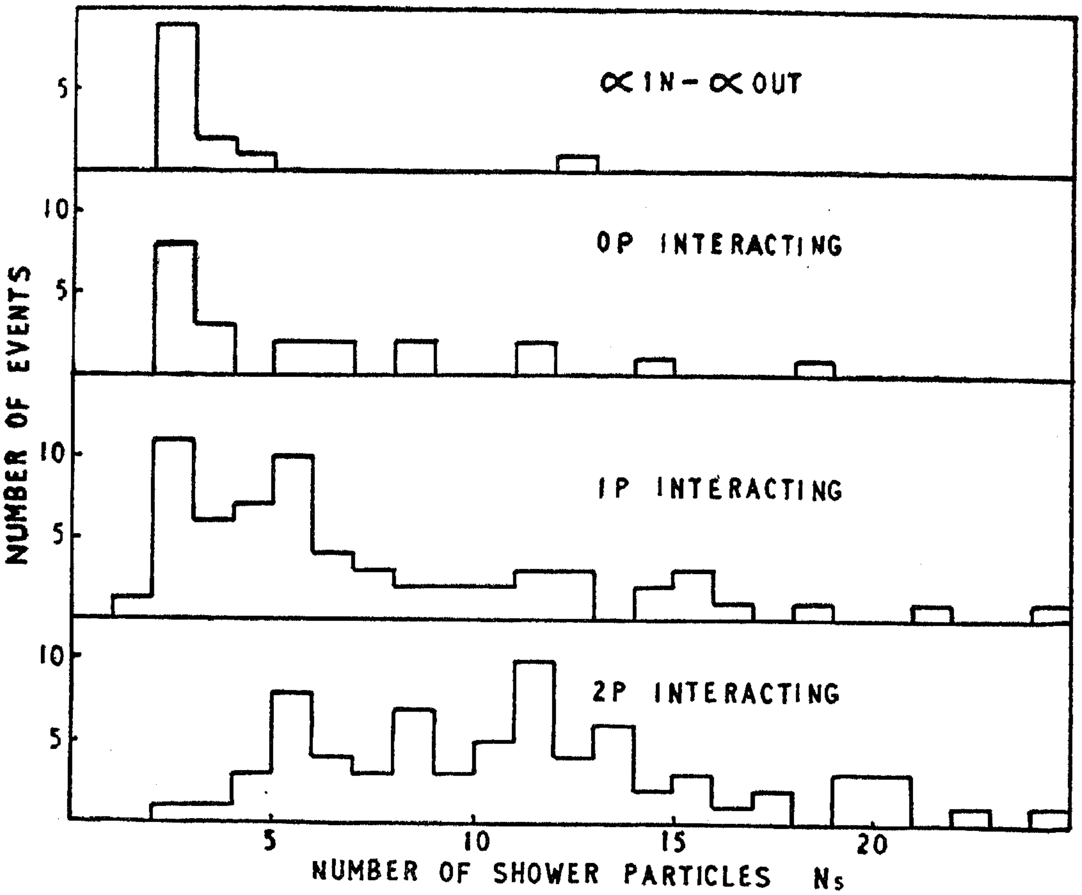

FIG. 4. The shower particle distribution of α-induced interactions classified as to whether 0, 1 or 2 protons have taken part in collisions. The shower particle distribution of α in–α out events is also given.

behaviour between neutrons and protons taking part in nuclear interactions, then the mean number of nucleons taking part in collisions per α-star is:

$$\frac{170 \times 4 - 139 \times 2}{170} = 2{\cdot}4.$$

From this we find that the mean number of secondary shower particles per nucleon averaged for all α-stars is 7·5/2·4 = 3·1 for a median energy of 10 BeV/nucleon. This should be compared with the value of 2·6 for 6·2 BeV proton stars.

We would like to point out here that from a knowledge of the number of disintegrations where 0, 1 or 2 protons have taken part in interactions, it is possible to estimate the number of events in which 1, 2, 3 or 4 nucleons should have participated. This information together with a nuclear density distribution obtained from other experiments may permit one to calculate the nucleon-nucleon cross-section at very high energies. Such an attempt has

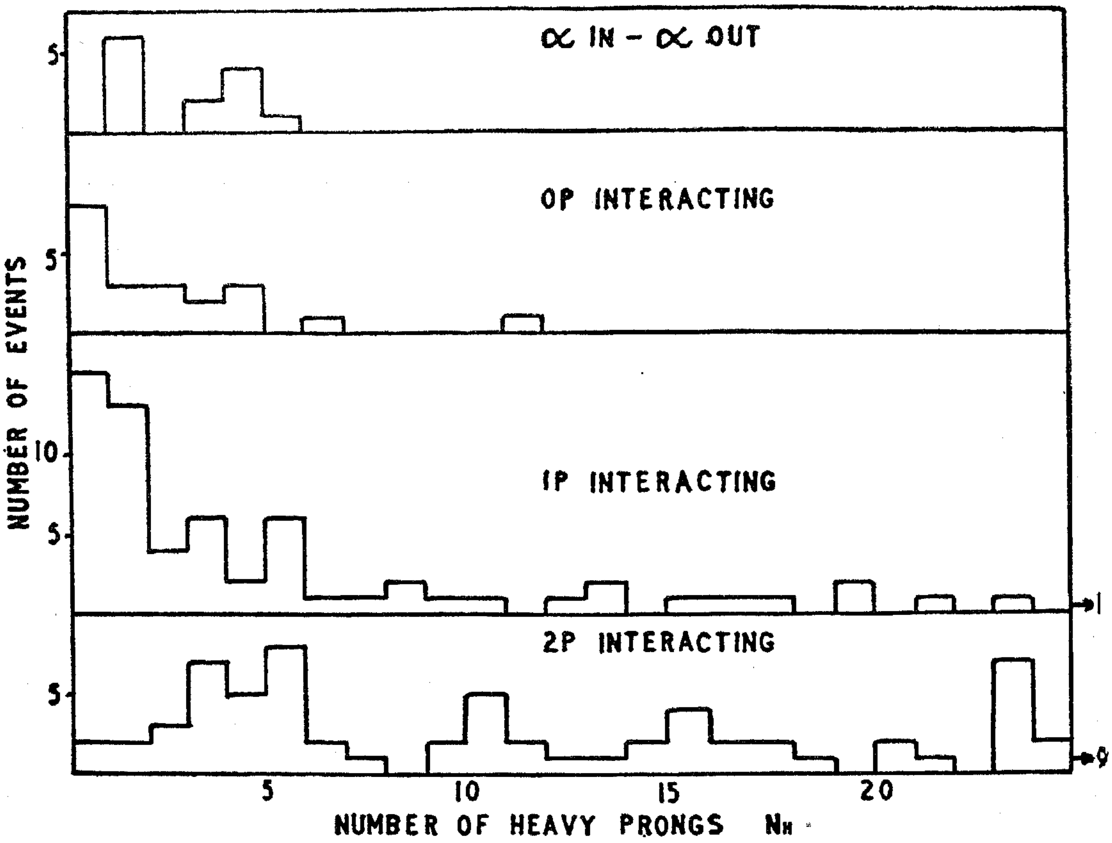

FIG. 5. The heavy prong distribution is given for α-induced interactions when classified as to whether 0, 1 or 2 protons have interacted. A similar distribution for α in–α out events is also included.

not been made because there is as yet no precise knowledge of the nuclear density distribution.

4. MEAN FREE PATH OF HIGH ENERGY α-PARTICLES AND PROTONS

4.1. MEAN FREE PATH FOR NUCLEAR INTERACTION OF α-PARTICLES IN EMULSION

As stated previously we obtained a total of 242 interactions from a total path length of 40·84 metres. We have shown in 3.3 that the mean free path for coulomb interaction is 5 metres. Therefore, corresponding to the 234 interactions of nuclear origin, we obtain a mean free path $\lambda = 17 \cdot 5 \pm 1 \cdot 1$ cm. ($68 \cdot 9 \pm 4 \cdot 3$ gm./cm.^{2}). (The density of our emulsions estimated from the range of μ-mesons arising from the decay at rest of π-mesons is 3·94 gm./cm.^{2})

There could be two possible sources of error in determining the total track length of the α-particles:

(*a*) Contamination due to slow protons, deuterons and tritons;

(*b*) While testing tracks for their straightness by the use of the eye-piece hair line in the first plate, it is possible that some genuine relativisitic α-particle may be rejected because of local distortion, while if it interacted in the same emulsion, it would have been included. Thus, there could be a bias in favour of α-particles which produce a nuclear disintegration in the first or second emulsions.

It has been shown in 2.2 that the contribution from slow protons, deuterons and tritons is negligible. This can further be tested as follows: We calculate the mean free path taking only tracks with a potential range greater than 10 cm. in the stack. Any appreciable contamination due to P, D, T should now be greatly reduced, for at 10 cm. traversal they will either be brought to rest or show considerable change in grain density. The value $\lambda = 17 \cdot 0 \pm 1 \cdot 7$ cm. which we obtain, does not differ from that obtained by including tracks of shorter potential range. We may state, therefore, that there is no significant contamination by singly charged particles in our selection of primary α-particles.

In order to test whether there could be any systematic bias as suggested in (*b*), we removed the first 2 cm. of track length of every α-particle track as well as the interactions observed in that distance. The mean free path obtained from the rest of the track length should be independent of this bias in selection of tracks and is found to be $16 \cdot 7 \pm 1 \cdot 2$ cm., as compared to $17 \cdot 5 \pm 1 \cdot 1$ cm., obtained without this correction. Thus, the values agree within experimental errors, and indicate no bias in favour of α-particles interacting in the first 2 cm. of track length.

In Table III, we have summarised the mean free path for nuclear interactions of α-particles observed in nuclear emulsions by various authors.

TABLE III

Authors	Method of Scanning	Energy per Nucleon	M.F.P. λ
D. F. Sherman ..	Area scanning	95 MeV	$18 \cdot 1 \pm 1$ cm.
Ceccerelli and Zorn ..	Along the track	90 MeV	$20 \cdot 5 \pm 2 \cdot 5$ cm.
Waddington ..	do.	>500 MeV	$20 \cdot 6 \pm 2 \cdot 2$ cm.
Present experiment ..	do.	>5 BeV	$17 \cdot 5 \pm 1 \cdot 1$ cm.

Using the mean free path for interaction we have obtained, and the composition of the emulsion as supplied by the manufacturers, we calculate an effective nuclear raidus. We assume a radius $R = r_0 \times A^{1/3}$ for all target nuclei as well as the α-particle (here A denotes the mass number). In this way one obtains the value:

$$r_0 = 1 \cdot 13 \pm 0 \cdot 04 \times 10^{-13} \text{ cm.}$$

This value is very close to that obtained from recent work on high energy electron scattering,[10] and mesic X-rays.[11]

4.2. MEAN FREE PATH OF 6·2 BeV PROTONS IN EMULSION

When scanning for nuclear interactions produced by 6·2 BeV protons of the Berkeley Bevatron, using the 'along the track' method, we obtained 35·69 metres of track length and 103 interactions. From this we get for the mean free path a value of 34·7 ± 3·4 cm. in emulsion. We now used the value of $0 \cdot 78 \pm 0 \cdot 24 \times 10^{-13}$ cm. for the size of the proton obtained by Hofstadter *et al.*[9] from electron scattering experiments and calculated the value of r_0 as described in 4.1. We get $r_0 = 1 \cdot 01 \pm 0 \cdot 11 \times 10^{-13}$ cm., in agreement with the value of $1 \cdot 13 \pm 0 \cdot 04 \times 10^{-13}$ cm. obtained from the mean free path of nuclear interaction of α-particles (4.1).

4.3. MEAN FREE PATH OF NUCLEONS IN NUCLEAR MATTER

Though at present we do not have any precise knowledge of the nuclear density distribution, it is still possible with our experimental data to infer an upper limit to the mean free path of nucleons in nuclear matter. This is done in the following manner:

Stars associated with 9 or more heavy prongs represent collisions of α-particles with the heavy nuclei of silver and bromine in the emulsion. Because of the large number of slow particles associated with the disintegrations it is reasonable to assume that:

(*a*) The majority of these events should have resulted from central or near central collisions with the target nucleus; and

(*b*) As we go to events with greater number of N_h the area involved becomes smaller and will refer more and more to the central portion of the target nucleus.

An estimate of the size of the central area involved can be made from the total α-particle track length, the number of collision events of the required type and the proportion of Ag and Br in emulsions. Here one must take into account the finite size of the α-particle and must choose a value of N_h such that, when the centre of the α-particle lies just within the corresponding central area, the α-particle lies wholly within the nuclear boundary of the target nucleus (Fig. 6). This value of N_h was found to be $\geqslant 15$. We have assumed in

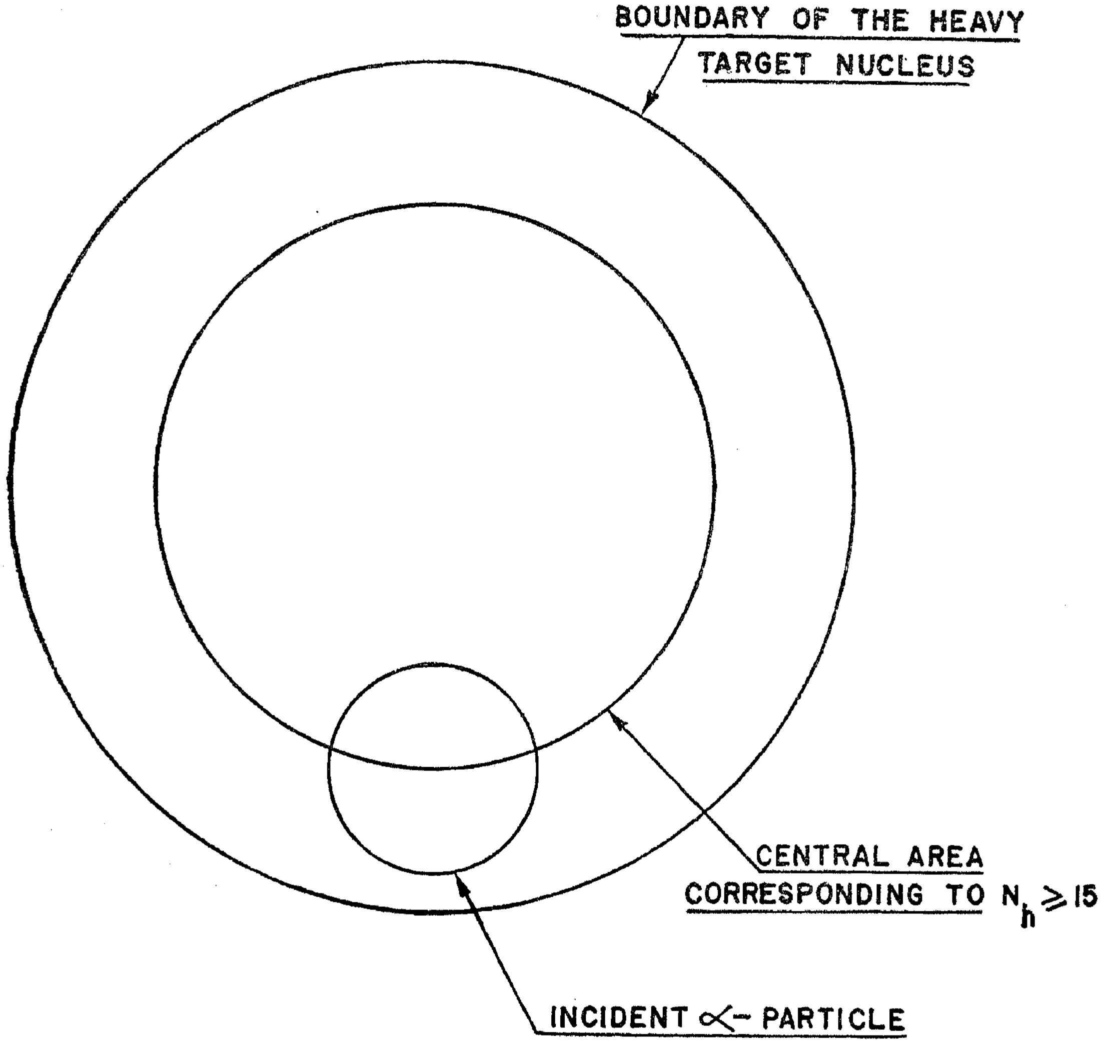

FIG. 6. Diagram illustrating the relative positions of the incident α-particle and the target nucleus in central collisions (corresponding to events with $N_h \geqslant 15$).

these calculations that the nuclei (both the target as well as the α-particle) are spherical and their radii given by the relation $R = r_0 A^{1/3}$, where $r_0 = 1 \cdot 13 \times 10^{-13}$ cm. We then calculated the mean distance in nuclear matter traversed by the α-particle after taking into consideration the different sizes and numbers of silver and bromine nuclei and this is found to be $6 \cdot 86 \times 10^{-13}$ cm. We observed among 39 stars with $N_h \geqslant 15$ included for angular measurements, 9 protons emerging without taking part in collisions. Using this information and the mean distance of nuclear matter traversed by the α-particle the mean free path for nucleon-nucleon collisions in nuclear matter λ_N is found to be $3 \cdot 2 \times 10^{-13}$ cm. Though it may be true that on the average stars with $N_h \geqslant 15$ result from central collisions with the heavy target nuclei, this will not be the case in individual events. It is certain that our selection of stars will contain some edge collisions where a portion of the incident α-particle may not traverse any nuclear matter and still result in $N_h \geqslant 15$. Therefore, the value of $3 \cdot 2 \times 10^{-13}$ cm. we obtain here for the mean free path for nucleon-nucleon collisions in nuclear matter will be an upper limit only.

5. CONCLUSIONS

The main conclusions deduced from the above investigation may be summarised as follows :

(*i*) From the angular distribution of shower particles associated with interactions produced by α-particles of energy greater than 5 BeV/nucleon, it is shown that singly charged relativistic particles ejected at angles less than 2×10^{-2} radians consist of :

(*a*) 95% of protons which originally formed part of the incident α-particle and did not participate in any collision processes; and

(*b*) 5% of secondary shower particles.

This permits separation of protons that have not collided with any part of the traget nucleus from the remaining shower particles without much ambiguity.

(*ii*) The mean free path for nuclear interaction of α-particles with energies > 5 BeV/nucleon in emulsion is found to be $17 \cdot 5 \pm 1 \cdot 1$ cm. ($68 \cdot 9 \pm 4 \cdot 3$ gm./cm.^{2}). Assigning both to the incident α-particle and the target nuclei a radius $R = r_0 A^{1/3}$, an effective nuclear radius $r_0 = 1 \cdot 13 \pm 0 \cdot 04 \times 10^{-13}$ cm. is obtained.

(*iii*) The mean free path for nuclear interaction of protons of 6·2 BeV energy in emulsions is $34 \cdot 7 \pm 3 \cdot 4$ cm.

(*iv*) Assuming that events with $N_h \geqslant 15$ result from central collisions of α-particles with silver and bromine of the emulsions, an upper limit to the mean free path of nucleons in nuclear matter λ_N has been calculated. We find $\lambda_N < 3 \cdot 2 \times 10^{-13}$ cm.

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