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Heavy Nuclei and α Particles between 7 and 100 Bev/Nucleon. I. Interaction Mean Free Paths and Fragmentation Probabilities*

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In a stack of nuclear emulsion exposed to the cosmic radiation near the geomagnetic equator, 540 tracks of heavy nuclei were located in a systematic scan and followed along the track. Twenty-two interactions of light ($3\leqslant Z\leqslant 5$), 218 of medium ($6\leqslant Z\leqslant 9$), and 99 of heavy ($Z\geqslant 10$) nuclei have been found. The average energy of the nuclei in this experiment was about 20 Bev per nucleon. The interaction mean free paths for all charge groups are in reasonably good agreement with results obtained at lower energies, indicating that the mean free path is independent of energy within the limits of error. In addition, all the α particles originating in fragmentations of heavy nuclei have been followed. The mean free path of α particles resulting from fragmentations is again in agreement with results obtained at lower energies. The same is true for the fragmentation probabilities.

Fragmentation probabilities in hydrogen are given and their significance is discussed.

INTRODUCTION

THERE are many investigations of the heavy-nuclei component of the primary cosmic radiation at northern latitudes, mainly near $\lambda\approx 41°$ (Texas), $\lambda\approx 56°$ (Minnesota) and $\lambda\approx 46°$ (northern Italy) using nuclear emulsion techniques.[1-19]

During the Office of Naval Research expedition EQUEX to the Marianas Islands in 1957, we obtained a satisfactory exposure close to the geomagnetic equator of a fairly large stack of nuclear emulsion. In such a stack all primary heavy nuclei entering from the outside have relativistic velocities making identification possible by δ-ray counting only. Due to the magnetic cutoff which allows only particles with kinetic energies greater than 7 Bev per nucleon to enter the stack from the vertical direction, the average energy of our heavy nuclei is much higher than those at northern latitudes where most of the other measurements were carried out. In addition, we used a rather large stack in which each particle could be followed through for secondary interactions. In such collisions very frequently the primary heavy nucleus does not suffer a "destructive collision," but undergoes a fragmentation in which α particles or heavier nuclear splinters emerge without any noticeable energy loss. Treating a "multiple fragment collision" (two or more fragments) as an evaporation process in the center-of-mass system of the primary heavy nucleus, one can easily estimate the primary energy by the angular distribution of the fragments. Furthermore, in the energy range above 7 Bev/nucleon the fragments are sufficiently well collimated in the direction of the primary heavy nucleus to make relative scattering measurements feasible and, in fact, more reliable than other known energy determinations. Due to the high energy of the colliding particles, meson production will occur in most of the nuclear collisions. The same is true for the subsequent interactions of the fragments and α particles. The angular distribution of the mesons produced in such collisions can frequently be used for an independent estimate of the energy of the colliding particles.

Therefore, this stack should yield more information regarding the flux of heavy nuclei near the geomagnetic equator, and regarding the energy spectrum beyond the geomagnetic cutoff up to energies of about 100 Bev/nucleon. However, one can attack this problem only after the energy independence of various quantities has been established. First it is necessary to establish this for all the interaction mean free paths and the fragmentation probabilities. Furthermore, one has to check this method of determining the energy by the angular distribution of the fragments and of the mesons, and then either prove that the results do not depend on energy, or establish the energy dependence on primary energy and on the mass of the interacting heavy nucleus.

No special effort was made to study the Li, Be, and B problem. This paper will deal mainly with the general characteristics of the heavy-nuclei interactions, mean

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[1] Freier, Lofgren, Ney, Oppenheimer, Bradt, and Peters, Phys. Rev. **74**, 213 (1948).

[2] Freier, Lofgren, Ney, and Oppenheimer, Phys. Rev. **74**, 1818 (1948).

[3] H. L. Bradt and B. Peters, Phys. Rev. **74**, 1828 (1948); **75**, 1779 (1949); **77**, 54 (1950); **80**, 943 (1950).

[4] Dainton, Fowler, and Kent, Phil. Mag. 42, 317 (1951); 43, 729 (1952).

[5] Kaplon, Peters, Reynolds, and Ritson, Phys. Rev. **85**, 295 (1952).

[6] K. Gottstein, Phil. Mag. **45**, 347 (1954).

[7] Kaplon, Noon, and Racette, Phys. Rev. **96**, 1408 (1954).

[8] B. Peters, Proc. Indian Acad. Sci. **A40**, 230 (1954).

[9] J. H. Noon and M. F. Kaplon, Phys. Rev. **97**, 769 (1955).

[10] H. Fay, Z. Naturforsch **10a**, 572 (1955).

[11] F. Hänni, Helv. Phys. Acta **29**, 281 (1956).

[12] Noon, Herz, and O'Brien, Nuovo cimento **5**, 854 (1957).

[13] Fowler, Hillier, and Waddington, Phil. Mag. **2**, 239 (1957).

[14] Engler, Kaplon, and Klarmann, Phys. Rev. **112**, 597 (1958).

[15] V. Y. Rajopadhye and C. J. Waddington, Phil. Mag. **3**, 19 (1958).

[16] Koshiba, Schultz, and Schein, Nuovo cimento **9**, 1 (1958).

[17] W. Püschel, Z. Naturforsch. **13a**, 801 (1958).

[18] Cester, Debenedetti, Garelli, Quassiati, Tallone, and Vigone, Nuovo cimento **7**, 371 (1958).

[19] Bisi, Cester, Garelli, and Tallone (to be published).

free paths, and fragmentation probabilities. In a second paper investigations of meson production by heavy nuclei and α particles will be described. Flux values and the energy spectrum will be described in a third paper.

EXPERIMENTAL PROCEDURE

A stack consisting of 100 emulsions, Ilford G5, 20×40 cm, each 600 μ thick, was flown in February, 1957, for 7 hours at a mean altitude of 102 000 feet near Guam (Marianas Islands). The stack was exposed to the cosmic radiation with the 40-cm side pointing to the vertical direction. Each emulsion was scanned along a line parallel to the top edge and on both sides, about 8 mm from the edge. All heavy nuclei crossing the scanning line, having more than 15 δ rays per 1 mm, and a projected length of more than 2 mm per plate were accepted and followed through until they left the stack or interacted. The interactions were then classified with respect to n_f, the number of heavy fragments $(Z \geqslant 3)$; n_α, the number of helium nuclei; N_s, the number of shower particles (ionization $\leqslant 1.4$ minimum ionization); and N_h, the number of heavily ionizing tracks. The angular distribution of the shower particles was measured for a statistically significant sample of collisions. In all cases where the primary heavy nucleus did not undergo a destructive collision the remaining heavy fragments and α particles were followed again in the same way. By this method we could eliminate, among the fragments, all tracks of low-energy nuclear particles due to evaporation of the target nuclei because their ionization would have changed with range. Furthermore, in the cases of "multiple fragment collisions" in which two or more fragments or α particles continued on after the collision, their relative scattering was measured. These measurements will be discussed in detail in the following paper as well as measurements of the angles between emitted fragments and α particles. By this method we efficiently eliminated all low-energy particles among the assumed fragments.

The charge of the heavy nuclei was measured by counting δ rays with four and more grains. Furthermore, we assumed that after subtracting the electron background the δ-ray density for nuclei of charge Z_1 and Z_2 could be represented by

$$N_\delta(Z_2) = (Z_2/Z_1)^2 N_\delta(Z_1).$$

The calibration was carried out by using unambiguous cases of fragmentations.

This simple procedure for charge determination is well justified for an equatorial stack flown at very high altitudes. Due to the magnetic cutoff of 7 Bev/nucleon, all entering heavy nuclei must have relativistic velocities and the ionization loss in the air above the stack and in the stack is negligible. We divided all heavy nuclei into one of the following charge groups: L $(3 \leqslant Z \leqslant 5)$, M $(6 \leqslant Z \leqslant 9)$, H $(Z \geqslant 10)$, and VH $(Z \geqslant 20)$.

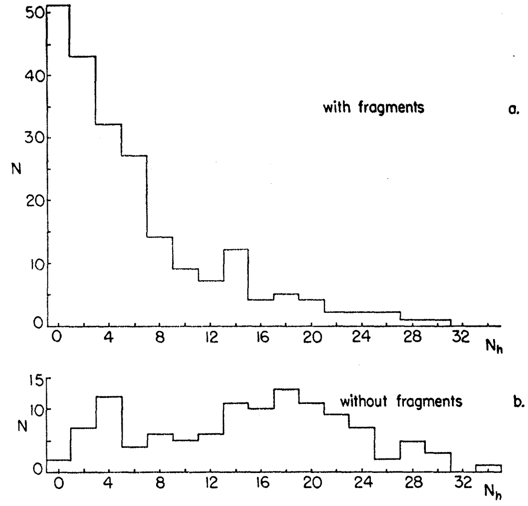

FIG. 1. Distribution of number of black tracks N_h originating from heavy-nuclei interactions with and without fragments. N: number of events with N_h heavy prongs.

EXPERIMENTAL RESULTS

Prong Distribution in Interactions

(*a*) *Heavy nuclei.*—In Table I the details of the observed interactions of the heavy nuclei followed through the stack are given. The primary nuclei are grouped into "light" (L), "medium" (M), and "heavy" (H) nuclei. According to conventions followed by other authors,[13,15,18] interactions with only one heavy prong were omitted. As expected, the fraction of "destructive collisions" in which no fragments $(Z \geqslant 2)$ continue on is much smaller among the H nuclei than among the M and L nuclei. In collisions of the H nuclei the interactions are predominantly of the "fragmentation" type. In such cases one or more fragments of the original nucleus continue on. In Fig. 1 the distribution of heavy tracks (N_h) is given for destructive collisions and fragmentations separately. For the first type of interactions the distribution shows two distinct maxima near $N_h = 4$ and $N_h = 18$. Therefore, a separation of these events according to the target nucleus seems meaningful. The first peak is due to collisions of the primary heavy nuclei with light or medium nuclei in the photographic emulsion (H, C, N, O); whereas the second peak is caused by interactions with heavy target nuclei (Ag, Br). The N_h distribution for the fragmentations does not show two distinct maxima. Therefore, the only reasonable procedure is to assume that in collisions with $N_h > 7$ the target nucleus belongs to the Ag, Br group. For $N_h \leqslant 7$ we have a mixture of interactions with all possible target nuclei; however, for geometrical considerations most of these collisions should occur with light nuclei.

(*b*) *α particles.*—In Table II all observed collisions of α particles are listed according to N_s and N_h. These interactions were collected as an unbiased sample because they all originated in fragmentations of heavy

TABLE I. Statistics of heavy-nuclei interactions in emulsion.

Li, Be, B				C, N, O, F				C, N, O, F				C, N, O, F				C, N, O, F				C, N, O, F				$Z\geqslant 10$				$Z\geqslant 10$			
n_f	n_α	N_s	N_h	n_f	n_α	N_s	N_h	n_f	n_α	N_s	N_h	n_f	n_α	N_s	N_h	n_f	n_α	N_s	N_h	n_f	n_α	N_s	N_h	n_f	n_α	N_s	N_h	n_f	n_α	N_s	N_h
1	1	0	2	1	2	2	1	1	0	1	0		1	31	25			29	23			25	5	2	2	21	0	1	0	41	10
1	0	3	6	1	2	1	1	1	0	7	0		1	16	5			35	24			11	11	2	2	15	7	1	0	42	14
1	0	3	0	1	2	3	2	1	0	5	0		1	10	4			23	36			26	2	2	1	23	3	1	0	8	2
0	2	1	0	1	1	4	0	1	0	7	2		1	14	0			28	32			34	15	1	4	17	5	1	0	20	3
0	2	3	0	1	1	4	5		3	6	0		1	28	14			37	17			56	16	1	4	17	2	1	0	12	5
0	2	0	0	1	1	13	10		3	23	13		1	8	5			53	14			27	8	1	3	13	1	1	0	12	10
0	1	4	0	1	1	…	…		3	0	1		1	13	4			42	4			12	18	1	3	8	5	1	0	20	18
0	1	4	5	1	1	4	1		3	14	5		1	3	1			65	22			13	6	1	3	10	6	1	0	4	1
0	1	4	2	1	1	0	0		3	1	0		1	6	0			26	9			14	2	1	0	…	3	1	0	2	2
0	1	13	13	1	1	1	3		3	14	2		1	32	10			33	15			26	21	1	2	7	4	0	8	39	2
		5	0	1	1	4	7		3	11	4		1	17	16			33	3			9	8	1	2	21	1		5	23	12
		5	8	1	1	6	9		3	4	2		1	3	0			46	21			40	20	1	2	19	0		4	8	0
		7	12	1	1	…	0		3	6	1		1	5	0			27	13			25	18	1	2	3	1		4	40	30
		22	17	1	1	8	0		2	8	0		1	18	2			47	20			36	13	1	2	0	0		3	6	2
		10	4	1	1	20	4		2	…	5		1	8	5			23	13			20	8	1	2	25	17		3	26	16
		6	2	1	0	5	1		2	6	3		1	18	6			55	17					1	2	0	14		3	11	4
		42	20	1	0	2	5		2	3	0		1	36	10			48	23					1	2	16	1		3	23	10
		39	22	1	0	3	4		2	2	0	1	0	6	4			46	20					1	1	…	…		3	43	14
		26	17	1	0	16	7		2	5	11		1	22	7			27	3					1	1	10	0		2	16	12
		15	3	1	0	2	3		2	7	3		1	8	0			36	13					1	1	3	0		2	47	20
		12	11	1	0	5	1		2	…	…		1	26	5			13	4					1	1	40	17		2	29	13
		39	14	1	0	5	8		2	27	3		1	38	23			29	24					1	1	15	7		2	30	2
				1	0	4	13		2	…	1		1	18	28			13	18					1	1	54	14		2	24	2
				1	0	1	1		2	2	0		1	8	2			29	30					1	1	5	2		2	11	0
				1	0	12	2		2	6	5		1	53	24			31	10					1	1	1	0		2	24	5
				1	0	3	1		2	7	7			33	16			18	10					1	1	2	0		2	13	5
				1	0	6	0		2	2	6			27	11			19	13					1	1	22	18		2	12	7
				1	0	4	13		2	19	5			9	10			9	3					1	1	25	12		1	39	20
				1	0	17	7		2	…	8			23	17			35	11					1	1	4	0		1	19	4
				1	0	5	6		2	8	0			50	19			24	29					1	1	8	0		1	44	25
				1	0	6	4		2	7	3			16	15			35	29					1	1	17	12		1	89	12
				1	0	3	2		2	8	0			22	2			20	7					1	1	0	0		1	30	21
				1	0	3	4		2	6	3			91	16			8	0					1	1	5	0		1	24	6
				1	0	…	2		2	2	0			54	32			45	21					1	1	0	0		1	16	4
				1	0	3	4		2	4	3			18	14			34	24					1	0	2	2		1	25	7
				1	0	7	1		2	79	21			42	15			36	25					1	0	9	14		1	52	17
				1	0	2	0		2	6	3			24	24			19	2					1	0	12	0			34	20
				1	0	2	1		2	2	0			13	4			30	13					1	0	0	5			117	16
				1	0	8	0		2	18	2			23	4			50	16					1	0	18	4			23	16
				1	0	0	3		2	3	2			32	18			66	26					1	0	5	6			25	3
				1	0	12	10		1	10	20			49	31			147	29					1	0	9	4			50	30
				1	0	0	2		1	53	4			60	22			20	5					1	0	6	7			73	26
				1	0	13	10		1	21	8			18	21			27	22					1	0	48	4			44	22
				1	0	1	0		1	27	20			14	19			34	23					1	0	1	7			52	27
				1	0	3	0		1	6	0			49	10			32	2					1	0	5	15			42	19
				1	0	1	4		1	…	…			73	17			46	18					1	0	2	1			50	4
				1	0	8	5		1	2	3			41	2			37	17					1	0	5	5			11	20
				1	0	4	4		1	2	0			56	27			26	8					1	0	22	1			142	14
				1	0	17	3		1	31	16			23	5			39	11					1	0	32	11			137	14
				1	0	7	4		1	6	8			12	3			81	19											94	18
				1	0	…	0		1	8	0			32	19																

nuclei which were found in a systematic way by track following. The events in Table II(a) and II(b), furthermore, are all of known energy and all are above the magnetic cutoff of 7 Bev/nucleon. The methods of energy determination of the α particles will be discussed in detail later. Table II(a) gives the distribution for low-energy α-particle interactions ($\langle E\rangle = 10$ Bev per nucleon) and Table II(b) for high-energy α particles ($\langle E\rangle = 40$ Bev per nucleon). In Table II(c) all α-particle collisions are listed in which the α particle continues on. Precisely speaking, this means collisions in which the incoming particle as well as the outgoing particle has four times minimum ionization. Therefore, these collisions could consist of interactions of the type $He^6 \rightarrow He^4$, $He^4 \rightarrow He^3$, $He^4 \rightarrow He^4$, etc. From Table II it is evident that in these events the average number of black prongs is smaller than in the others. They are mainly due to stripping interactions in which the primary nucleus loses only one neutron. The contribution of He^6 events may be not negligible because its mean life of about 0.8 sec is long enough for it to be detected as a fragment. The He^6 contribution to the primary helium flux at the top of the atmosphere, however, will be practically zero.

Mean Free Paths

(*a*) *Heavy nuclei.*—In quoting accurate interaction mean free paths one has to keep in mind that there are

TABLE II. Statistics of α-particle interactions.

(a) "High" energy

N_h N_s	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	$\geqslant 17$	Total
0				1															1
1			1																1
2	4	5			1														10
3		2	2																4
4	2	1	1	1							1								6
5	2			1															3
6				1		1													2
7			1	2															3
8		1		1					1		1	1							5
9						1												1	2
10			1																1
11																		1	1
12																			0
13	1								1							1			3
14				1	1				1										3
15	1										1					1			3
16														1	1			1	3
17	1																		1
$\geqslant 18$			1	1				1					1			1		10	15
Total	11	9	7	9	2	2	0	1	3	0	3	1	1	1	1	3	0	13	67

(b) "Low" energy

N_h N_s	0	1	2	3	4	5	6	7	8	9	10	11	$\geqslant 12$	Total
0					1									1
1	1	2		1								1		5
2	4	1			1								1	7
3		2	1					1						4
4	2	3	1	1	1		1			1			1	11
5	1	1	1		1		1					1	1	7
6						1								1
7	1		1											2
8	2		2		1		2			1				8
9			1	1	1								1	4
10				1										1
11	1								1					2
12								1			1	1	4	7
13													2	2
14													1	1
15				1									3	4
16													1	1
17	1													1
$\geqslant 18$													5	5
Total	13	9	7	5	6	1	4	2	1	2	1	3	20	74

(c) α-α interactions

N_h N_s	0	1	2	3	4	5	6	7	8	9	10	11	$\geqslant 12$	Total
0		2		1		1			1					5
1			1			1								2
2			1											1
3		1	1										1	3
$\geqslant 4$			1	1	1					1			1	5
Total		3	4	2	1	2			1	1			2	16

two main difficulties. One arises from interactions where a heavy fragment continues and only one dark track is seen, the other comes from cases in which only one or very few minimum-ionization tracks are emitted. In both cases the charge of the colliding nucleus may change not at all or only by one or two units. First of all, both types of collisions are easy to miss by the scanners; secondly, the first type of interaction could be due to elastic scattering with hydrogen. Therefore, we followed the procedure of certain authors who did not count events with only one heavy prong.[13,15,18] The uncertainty in the interaction mean free paths introduced by this procedure is rather small because we observed only 4 cases against 339 accepted interactions. The scanning loss of events of the second type is a more serious problem because it could have a significant

TABLE III. Interaction mean free paths for heavy nuclei (in g/cm² in nuclear emulsion).

	Cutoff energy Bev/nucleon	L $3\leqslant Z\leqslant 5$	M $6\leqslant Z\leqslant 9$	H $Z\geqslant 10$	VH $Z\geqslant 20$
This work	7	51.4±7.2	49.8±3.6	44.2±4.5	35.5±8
Bristol[a, b]	1.5	51.6±6.1	51.9±3.8	37.0±3.1	31.2±4.4
Turin[c]	1.5	60 ±6.9	51.6±3.8	42.5±4.9	

[a] See reference 13. [b] See reference 15. [c] See reference 18.

influence on the fragmentation probabilities too. Therefore, we followed a representative sample of tracks of heavy primaries a second time very carefully under high magnification to determine the correction factor. In doing this one has to keep in mind that high-energy heavy nuclei are capable of emitting energetic knock-on electrons at small angles. In addition, the direct production of electron-positron pairs is not negligible for high-energy heavy nuclei. Therefore, in all events where only one or two minimum tracks can be seen and no change of charge can be established, the minimum tracks had to be followed for some distance in order to exclude electrons. For the same purpose, relative scattering measurements were carried out in all favorable cases. The correction obtained by this method turned out to be significant for "hydrogen" only and will be explicitly given later. In order to increase our statistics, the interactions of heavy fragments ($Z>2$) are included in our values of the interaction mean free paths which are given in Table III for four groups of heavy nuclei. The values for L, M, H, and VH nuclei are compared with recent results obtained by the Bristol and Turin groups. These results are of comparable statistical weight and were obtained in a similar way. In calculating our results in g/cm² we assumed our emulsion to have a density of 3.81 g/cm³.

One sees that the values of different authors agree well within the limits of statistical errors. The results of the Bristol[13,15] and Turin[18,19] groups were obtained in northern Italy where the magnetic cutoff is about 1.5 Bev per nucleon (kinetic energy). Assuming an energy spectrum of the form $N(>E)\propto E^{-\gamma}$, one can calculate the average energy of their heavy nuclei. For $\gamma=1.5$ one obtains 6.5 Bev. Our value of γ will be discussed in a separate paper. In our investigation near the equator, the average energy was 20 Bev/nucleon. Comparing the results of Table III, it is seen that the mean free paths do not change with energy within the limits of error in the indicated energy range.

(*b*) *α particles.*—All α particles used in this work originated from fragmentations of heavy nuclei. First we determined the mean free paths for α particles, the energy of which could be measured as mentioned above. In addition we include the mean free paths for those α particles for which an estimate of the energy was not possible by scattering measurements. Their average energy, of course, is also 20 Bev/nucleon. The rather high value for the third group of α particles in Table IV is most probably due to some statistical fluctuation since the number of events was small. There is no reason to assume that these particles could be different from the particles considered in the first two groups. Our results do not indicate any energy dependence of the interaction mean free path between 10 and 40 Bev per nucleon. In Table V the results of other investigators at different energies using different methods are

TABLE IV. Interaction mean free paths for α particles (in nuclear emulsion).

Individual energy measurement possible	$\langle E\rangle=10$ Bev/nucleon	19.7±2.4 cm	75.0±9.1 g/cm²
	$\langle E\rangle=40$ Bev/nucleon	18.1±2.3 cm	68.9±8.8 g/cm²
Individual energy estimate impossible	$\langle E\rangle=20$ Bev/nucleon	34±9 cm	130±34 g/cm²
All interactions of α particles	$\langle E\rangle=20$ Bev/nucleon	20.2±1.7 cm	76.8±6.5 g/cm²

TABLE V. Energy dependence of α-particle interaction mean free path.

Authors	Source of particles	Interaction mean free path (cm in emulsion)	Average kinetic energy (Bev per nucleon)
Quareni and Zorn[a]	Artificially accelerated α particles	20 ±1.7	0.09[g]
Willoughby[b]		18.4±0.9	
Bristol[c]	Primary α particles in cosmic radiation	20.5±2.2	6[h]
NRL[d]		19.7±2.2	20[h]
Bombay[e]		17.5±1.1	12[g]
Hänni[f]	α particles from fragmentations of heavy nuclei in cosmic radiation	18.4±4	8[h]
This work		20.2±1.7	20[h]

[a] G. Quareni and G. T. Zorn, Nuovo cimento **1**, 1282 (1955).
[b] D. Willoughby, Phys. Rev. **101**, 324 (1956).
[c] C. J. Waddington, Phil. Mag. **45**, 1312 (1956).
[d] Shapiro, Stiller, and O'Dell, Bull. Am. Phys. Soc. **1**, 319 (1956).
[e] Appa Rao, Daniel, and Neelakantan, Proc. Indian Acad. Sci. **A43**, 181 (1956).
[f] See reference 11.
[g] Quoted by the authors.
[h] Calculated by us.

TABLE VI. Fragmentation rates of heavy nuclei.

Primary heavy-nucleus charge group	Laboratory	Primary cut-off energy Bev/nucleon	Total number of events	n_f+n_α $=0$	$\geqslant 1$	$\geqslant 2$	$\geqslant 3$
	This work	7	218	(41±4.5)%	(59±5.2)%	(24±3.5)%	(5.6±1.7)%
M	Bristol[a]	1.55	163	(37±5)%	(63±6.3)%	(26.5±4)%	(7.5±2.2)%
	Turin[b]	1.55	180	(30±4)%	(70±6.2)%	(27±4)%	(5±1.7)%
	This work	7	99	(14±4)%	(86±9.5)%	(52±7.5)%	(26±5)%
H	Bristol[a]	1.55	84	(18±5)%	(82±10)%	(49±7.5)%	(26±5.5)%
	Turin[b]	1.55	76	(24±6)%	(76±10)%	(47.5±8)%	(25±6)%

[a] See reference 13. [b] See reference 18.

TABLE VII. Fragmentation probabilities in emulsion.

	$P_{M\alpha}$	P_{ML}	P_{MM}	$P_{H\alpha}$	P_{HL}	P_{HM}	P_{HH}
This work	0.61±0.05	0.19±0.03	0.11±0.03	1.19±0.12	0.17±0.05	0.25±0.05	0.23±0.06
Bristol[a]	0.77±0.06	0.14±0.02	0.08±0.02	1.27±0.12	0.17±0.03	0.27±0.04	0.20±0.03
Turin[b]	0.75±0.06	0.18±0.03	0.16±0.03	1.04±0.12	0.13±0.04	0.18±0.05	0.25±0.06
Koshiba and Schein[c]	0.97±0.10	0.17±0.04	0.08±0.03	1.21±0.16	0.40±0.09	0.17±0.06	0.09±0.04
Püschel[d]		0.11±0.03	0.11±0.03		0.16±0.09	0.25±0.07	0.20±0.05

[a] See reference 15. [b] See reference 18. [c] See reference 16. [d] See reference 17.

listed for comparison. All these results are consistent with the assumption that the interaction mean free path is independent of energy within 5–10% over a wide range between about 0.10 Bev per nucleon and approximately 50 Bev per nucleon.

Fragmentation Probabilities

In Table VI we give our observed numbers of heavy nuclei interactions according to their fragmentation type. In addition similar figures are given for investigations carried out in northern Italy (cutoff energy about 1.5 Bev/nucleon) by the Bristol[13] and Turin[18] groups in order to check the independence of energy of the fragmentation rates. Within the limits of the quoted statistical errors the fraction of multiple fragmentations ($n_f+n_\alpha \geqslant 2$) among all interactions remains constant.

The fragmentation probabilities, P_{ik}, in emulsion have been investigated by various groups during the last years. Our values are given in Table VII. In addition we include in this table the results of the Bristol[15] and Turin[18] groups; Koshiba *et al.*[16]; also Püschel,[17] for comparison. All P_{ik} agree well within the statistical errors indicating that the change of these quantities over an energy range of roughly a factor of 3 is less than 10%.

For the extrapolation of measured flux values to the top of the atmosphere, one needs the fragmentation probabilities in air which cannot be measured directly. As an approximation one can use the fragmentation probabilities in emulsion obtained in interactions with "light" target nuclei $Z \leqslant 8$ (l-events) because these nuclei should behave very much like air nuclei. There is, of course, only an approximate way of selecting such events in emulsion. Following other authors we included all interactions with $N_h \leqslant 7$ in Table VIII where the fragmentation probabilities for l-events are listed. In addition we included results obtained by other groups in a similar manner.[13,16-18] In the last line we quote recent data by Rajopadhye and Waddington[15] in which they used a somewhat different method to calculate the fragmentation probabilities for l events. They used statistical arguments and the model introduced by Bradt and Peters to eliminate all events among the interactions with $N_h \leqslant 7$ which did not occur at a C, N, O target nucleus. Their results obviously do not differ very much from the data obtained by using the ($N_h \leqslant 7$) criterion.

For some cosmological aspects the fragmentation

TABLE VIII. Fragmentation probabilities in emulsion (for "light" target nuclei).

	$P_{M\alpha}$	P_{ML}	P_{MM}	$P_{H\alpha}$	P_{HL}	P_{HM}	P_{HH}
This work	0.91±0.10	0.30±0.06	0.18±0.05	1.33±0.17	0.15±0.05	0.33±0.07	0.33±0.09
Bristol[a]	0.98±0.11	0.18±0.04	0.16±0.04	1.55±0.19	0.12±0.06	0.45±0.08	0.29±0.07
Turin[b]	0.88±0.08	0.23±0.04	0.19±0.04	1.23±0.17	0.14±0.06	0.27±0.08	0.34±0.09
Koshiba and Schein[c]	1.3 ±0.16	0.22±0.07	0.10±0.04	1.41±0.25	0.32±0.12	0.27±0.11	0.09±0.06
Püschel[d]		0.13±0.04	0.19±0.04		0.11±0.05	0.35±0.07	0.30±0.07
Bristol[e]	1.27±0.28	0.23±0.07	0.17±0.06	1.23±0.40	0.21±0.09	0.46±0.15	0.29±0.11

[a] See reference 13. [b] See reference 18. [c] See reference 16. [d] See reference 17. [e] See reference 15.

TABLE IX. "Hydrogen" target interactions in emulsion.

	Number of fragments							Total number of interactions	
Charge group of primary heavy nucleus	M			H				M	H
Charge group of fragments	α	L	M	α	L	M	H		
This work	46	21(15)	8(4)	26	1	12	9(5)	51(41)	23(19)
Bristol[a]	32	6	2	22	0	8	5	24	15
Turin[b]	53	10	8	32	2	7	5	37	19
Koshiba and Schein[c]	45	7	2	9	3	3	2	27	8
	Fragmentation probabilities								
	α	L	M	α	L	M	H		
Average from above data	1.27±0.11	0.32±0.05	0.14±0.04	1.37±0.17	0.09±0.04	0.46±0.09	0.32±0.08		
Bristol[d]	1.57±0.25	0.38±0.11	0.06±0.06	1.90±0.38	0.11±0.09	0.35±0.15	0.30±0.12		

[a] See reference 13. [b] See reference 18. [c] See reference 16. [d] See reference 15.

probabilities in hydrogen are of interest. We choose to use the following criteria for selecting proper events:

(1) $N_h=0$,
(2) $N_h=1$, only if the charge of fragments plus N_s equaled the charge of the incoming heavy nucleus.

This method, of course, is again an approximation only and the selected events include a small fraction of collisions with bound nucleons also. In Table IX we give the number of α particles, L, M, and H fragments for interactions of M and H heavy nuclei. The figures in parentheses are our results before following the heavy-nuclei tracks for a second time. One sees quite clearly that there is a serious scanning bias against "hydrogen" events if one does not take extraordinary care in following heavy-nuclei tracks.

In order to increase the statistical significance of the fragmentation probabilities we applied the same procedure to the figures from the papers by the Bristol[13] and Turin[18] groups and by Koshiba and Schein,[16] and added their events to ours. From these figures we calculated fragmentation probabilities in hydrogen. They are again in good agreement with results recently published by the Bristol group,[15] which used somewhat different selection criteria.

CONCLUSIONS

We have compared our results obtained at the geomagnetic equator with those of other investigators at lower energies. It is shown that the interaction mean free paths of heavy nuclei do not depend on energy within the limits of error between about 6 Bev/nucleon and 20 Bev/nucleon. The same is true for α particles between 0.1 and 40 Bev/nucleon. Within the accuracy of present measurements we could find no indication that the fragmentation probabilities of heavy nuclei depend on energy. Furthermore, we could also show that the fraction of multiple-fragment interactions is independent of energy within small limits of error. This result is of particular significance for the derivation of an energy spectrum of the heavy nuclei which will be given in a forthcoming paper.

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