Some Characteristics of the Interactions of 1.9 GeV n^{-1} Iron Nuclei with Photographic Emulsion

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Abstract

We have scanned 18.06 m of track of 1.9 GeV n^{-1} iron nuclei accelerated at the Bevalac and passing through Ilford G5 nuclear research emulsion. From the 233 interactions found, details are given here of mean free paths and fragmentation parameters for various types of event.

Introduction

A considerable fraction of cosmic ray particles of total energy 100 GeV are iron nuclei. There is some evidence that this fraction is increasing in the range 10^{11} eV ($\equiv 100$ GeV) to 10^{15} eV (Hillas 1975) and also evidence (McCusker 1975*a*, 1975*b*) that between 10^{15} and 10^{17} eV the iron component begins to predominate. In this high energy range, the particles interact to produce air showers that reach sea level, and an important method of studying these is to simulate them, using Monte Carlo techniques, and to compare the results of the simulations with experiment (McCusker *et al.* 1969; Gaisser 1974; Grieder 1977). For simulations of showers produced by iron primaries, we need as accurate a knowledge as possible of the interaction mean free path and fragmentation probabilities.

The interactions of energetic heavy nuclei are also interesting in themselves; for instance, the possibility of studying shock waves in nuclear matter exists. There is also nowadays considerable interest in the use of heavy ion beams for the compression and heating of small pellets with the object of producing controlled thermonuclear reactions.

In the experiment reported here I have used the most energetic beam of the heaviest ions (iron nuclei at 1.9 GeV per nucleon) so far obtained to produce nuclear interactions in nuclear research emulsions, that is, interactions with hydrogen, carbon, nitrogen, oxygen, silver and bromine nuclei.

Experimental Details

The stack (7 cm by 12 cm by 11 by 600 μ m) of Ilford G5 nuclear research emulsion was exposed to the 1.9 GeV n⁻¹ beam from the Bevalac. The experimental procedure was similar to that used for lighter ions by Heckmann *et al.* (1978). The plates have a grain density of ~20 grains per 100 μ m for fast singly charged particles.

In scanning, tracks were picked up at the leading edge of the stack and followed until they interacted or left the stack. Following an iron track is, of course, very easy and most interactions are extremely obvious. However, some types of events may be expected to give some difficulty. One such type are the events

$$Fe + X \rightarrow Mn + p + X$$
,

in which the target emits *no* charged fragments and the iron projectile loses a single proton. Another type which could be missed are events in which the iron projectile makes a glancing collision with hydrogen (usually) to continue itself without loss of charge and to knock on a single slow proton at almost 90° to the beam direction. Normally, these events are easy to detect but if the slow proton moves either vertically upwards or downwards they can be missed.

Because of the above and other possibilities the following scanning procedure was adopted. Firstly, the author carried out a rapid scan using semi-automated equipment: 3.05 m of track yielded 41 interactions, giving a total interaction mean free path of $7.44^{+1.37}_{-1.01}$ cm. Next, two very experienced scanners scanned 18.06 m of track, mostly under $\times 20$, but occasional under $\times 100$. The scanners then exchanged plates and each scanned 1 m of the other's track, mostly under $\times 100$. In the scan of the original 18.06 m, 233 interactions were found. In the rescan, under $\times 100$, of 2.051 m of track an extra 4 events were found. In three of these cases, the iron projectile carried on unaltered; two of these had a single slow proton at almost 90° to the beam track while the other had a single grey track. The fourth interaction had a single fast proton going forward at 1.5° to the beam track.

Results

Interaction Mean Free Paths

In the first scan, of 18.06 m of track, we found 233 interactions. This gives an uncorrected interaction mean free path λ'_{tot} in Ilford G5 emulsion for any interaction of

$$\lambda'_{\text{tot}} = 7 \cdot 75^{+0.54}_{-0.48} \text{ cm} \equiv 29 \cdot 6^{+2.1}_{-1.8} \text{ gcm}^{-2}$$

for the emulsion density of $3 \cdot 815 \text{ g cm}^{-3}$.

However, the second scan revealed an extra 4 events in 2.051 m of track. Assuming a similar loss in the remaining 16.01 m of the first scan, we find the corrected number of interactions to be

$$233 + (4/2 \cdot 051) \times 18 \cdot 06 = 268$$
.

So the corrected total interaction mean free path λ_{tot} for iron nuclei of 1.9 GeV per nucleon in G5 emulsion is

$$\lambda_{\text{tot}} = 6 \cdot 74^{+0.44}_{-0.39} \text{ cm} \equiv 25 \cdot 7^{+1.7}_{-1.5} \text{ g cm}^{-2}.$$

For collisions in which the main fragment of the projectile has Z < 20 (158 events), there is no correction and we get

$$\lambda(Z_{\rm frag} < 20) = 43.6 \ {\rm g \, cm^{-2}}$$
.

For collisions in which the main fragment has $Z \ge 20$, the corrected value is

$$\lambda(Z_{\rm frag} \ge 20) = 62 \cdot 2 \, {\rm g \, cm^{-2}}$$
.

Fragmentation Parameters

Table 1 gives the numbers of events in which the heaviest surviving nucleon had a charge of Z. This is done for events with $N_h > 7$ and for events with $N_h \leq 7$, where N_h is the number of 'black' evaporation prongs, i.e. tracks whose ionization is ≥ 10 times the minimum value for fast singly charged particles. The first set of events must be collisions with silver or bromine. The second set are mostly collisions with carbon, nitrogen or oxygen, with a small admixture of collisions with hydrogen and some distant collisions with silver or bromine. This second set is, of course, the closer approximation to the collisions that iron nuclei make in the atmosphere.

Charge 7	No. of events		Charge Z	No. of events	
of max. fragment	$N_{\rm h} > 7$	$N_{\rm h} \leqslant 7$	of max. fragment	$N_{\rm h} > 7$	$N_{\rm h} \leqslant 7$
1	10	5	14	2	7
2	20	18	15	2	3
3	1	0	16	0	5
4	3	0	17	3	7
5	5	5	18	0	.8
6	0	5	19	1	9
7	3	3	20	3	10
8	4	5	21	0	10
9	2	3	22	1	9
10	3	2	23	1	6
10	3	4	24	2	6
12	1	2	25	0	3(11) ^A
12	2	2	26	0	24(51) ^A

Table 1. Number of events in which charge of heaviest surviving fragment is ZEvents are classified according to the number $N_{\rm h}$ of 'black' evaporation prongs from the target nucleus

^A Values in parentheses are those corrected for the initial scanning inefficiency.

Table 2. Fragmentation parameters of 1.9 GeV iron nuclei in emulsion

The number $N_{\rm f}$ of fragments of a given class and the corresponding fragmentation parameter F are shown both for the total sample of events and for events with $N_{\rm h} \leq 7$. The results have been corrected for scanning inefficiency

 Fragment	Charge	All events		Events with $N_{\rm h} \leq 7$	
class	Z	$N_{ m f}$	F	$N_{ m f}$	F
VH	$ \begin{cases} 26 \\ 20-25 \end{cases} $	$51 \\ 59 $ 110	0.41 ± 0.04	$51 \\ 52 $ 103	0.53 ± 0.05
н	10-19	67	0.25	47	0.24
M	6–9	31	0.12	20	0.10
L	3–5	32	0.12	15	0.08
α	2	377	$1 \cdot 41 \pm 0 \cdot 08$	250	$1 \cdot 28 \pm 0 \cdot 10$

It has been the practice in cosmic ray work to use 'fragmentation parameters' (Waddington 1960). Fragments are classified as VH ($20 \le Z \le 26$), H ($10 \le Z \le 19$), M ($6 \le Z \le 9$), L ($3 \le Z \le 5$) and α (Z = 2), and the fragmentation parameter is the number of fragments of a given class per event. Table 2 gives the fragmentation parameters for the various classes. The parameters are given for both the total sample of events and also events with $N_h \le 7$. The data have been corrected for the initial scanning inefficiency.

Comparison with Other Work

Heckmann *et al.* (1978) have analysed the collisions of $2 \cdot 1$ GeV n⁻¹ helium, carbon, nitrogen and oxygen nuclei with emulsion. Fig. 1 is a plot of λ_{tot}^{-1} against $A^{2/3}$ for their results and for mine. The value derived in this paper is within one standard deviation of the extrapolated value from their experiments. Since the extrapolation is considerable, the agreement is excellent.



Fig. 1. Inverse of the total interaction mean free path λ_{tot}^{-1} (in units of cm⁻¹) plotted against $A^{2/3}$, where A is the atomic weight of the projectile. The points for helium, carbon, nitrogen and oxygen are from Heckmann *et al.* (1978).

Table 3. Classification of types of event

The event types are classified in the manner of Heckmann *et al.* (1978), as described in the text. In addition, type 2 has been subdivided into two categories: (2a) $24 > \Delta Z_{proj} \ge 1$ and (2b) $\Delta Z_{proj} = 24$

Event type:	1	$2 \begin{cases} 2a \\ 2b \end{cases}$	3	4
Number of events	22(30) ^A	$172 \begin{cases} 134 \\ 38 \end{cases}$	15	24(51) ^A

^A Values in parentheses are those corrected for the initial scanning inefficiency.

Heckmann et al. (1978) classified interactions as of four types:

- (1) $n_{\rm H} = N_{\rm b} + N_{\rm g} = 0$, that is, events having, as far as we know, no target breakup, but with projectile fragmentation;
- (2) events with projectile fragmentation and with target breakup, that is, $n_{\rm H} \neq 0$, $24 \ge \Delta Z_{\rm proj} \ge 1$;
- (3) events with catastrophic breakup of the projectile;
- (4) $\Delta Z_{\text{proj}} = 0$, that is, events in which the projectile continues apparently undamaged.

Iron Nuclei in Emulsion

Table 3 shows the present results analysed in this way. For further information (possibly useful in some cosmic ray work), I have subdivided type 2 into two categories. Events of types 1 and 4 need correction for the initial scanning inefficiency; the corrected values are given in parentheses. By comparison with the lighter nuclei (cf. Table 1 of Heckmann *et al.* 1978) we see that the iron nucleus has a much higher probability of surviving unchanged and a much lower probability of catastrophic breakup—a result to be expected.

Waddington (1960) gives fragmentation parameters for cosmic ray 'projectiles' in the VH class. The mean A of these is 51, i.e. the beam is mostly iron but with an admixture of lighter nuclei. Both for events with $N_h > 7$ and $N_h \leq 7$, I find a higher rate of surviving VH fragments. For instance, for VH production in $N_h \leq 7$ events, I obtained a fragmentation parameter of 0.53 ± 0.05 , as against the previous value of 0.26 ± 0.05 , which is a statistically significant difference. Moreover, the result is in the direction to be expected from the greater ease of scanning the long flat tracks in the accelerator exposure as compared with the more difficult cosmic ray work.

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