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Search for anomalons produced in nuclear emulsion by 1.88*A* GeV ^{40}Ar ions

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Abstract. The interaction mean free paths of relativistic projectile fragments produced from a ^{40}Ar beam at 1.88*A* GeV in nuclear emulsion are measured. No statistically significant anomalously short mean free path is observed for projectile fragments of charges ranging from $Z=2$ up to $Z\geqslant 10$ at such energy.

1. Introduction

Observations in nuclear emulsion of short reaction mean free paths of relativistic projectile fragments of high-energy heavy ions were first observed in cosmic radiations by Milone (1954), Yagoda (1956, 1957), Tokunga *et al* (1957), Friedlander and Spirchez (1959), Judek (1968, 1972) and Cleghorn *et al* (1968). In her systematic measurements of the mean free path (MFP) of relativistic cosmic ray primary and secondary nuclei, Judek concluded that a few per cent of the secondary nuclei with charges $1\leqslant Z\leqslant 4$ interact with an anomalously short MFP of the order of 3 cm. With the availability of relativistic heavy-ion beams from accelerators at CERN, LBL and JINR, further studies could be carried out in a more systematic way (Friedlander *et al* 1980, Jain and Das 1982, Jain *et al* 1984, Barber *et al* 1982). There is, however, a disagreement as to whether or not anomalons occur. A recent experiment (Ismail *et al* 1984) shows no anomalons for particles with $Z=$ 2, 3 or 4, but others (El-Nadi *et al* 1984) report the existence of anomalons with $Z=2$. The experimental results give rather a confusing picture regarding the existence of anomalons (Bayman and Tang 1987). It is likely that both the energy and the structure of the projectile fragments as well as the mechanism of the primary interaction play an important role in the existence of this anomalous behaviour.

2. Experimental results and discussion

2.1. Mean free path

A stack of low-sensitivity Ilford G 5 nuclear research emulsion pellicles, 7 grains/100 μm for singly charged relativistic particles, 600 μm thick, of size 10×10 cm^2 was exposed to a ^{40}Ar beam parallel to the emulsion surface at 1.88 GeV/nucleon at Lawrence Berkeley Laboratory (LBL). Each beam trajectory was scanned along the track under high magnification (100 ×). A total scanned length of about 232 m of the primary ^{40}Ar beam tracks gave 2303 inelastic interactions. The corresponding value of the average mean free path of argon is found to be 8.99 ± 0.18 cm after applying a correction factor due to scanning losses of $N_h = 0$ (N_h refers to the number of highly ionising particles emitted by the target nucleus). The high value of the correction factor (~12%) is due to the low sensitivity of the emulsions used. This value of the average MFP is in agreement with the value 8.97 ± 0.16 cm determined by Bhanja *et al* (1985) in the same experimental conditions.

The first part of the present work dealt with the determination of the MFP of helium nuclei produced by the interaction of ^{40}Ar, accelerated to $\sim 1.88A$ GeV, with emulsion nuclei. The MFP of fragments of charges $Z > 2$ is considered in the second part. These fragments of $Z \geqslant 2$ are identified by measuring their ionisation and by their δ-ray densities. They are divided into three categories, namely L ($3 \leqslant Z \leqslant 5$), M ($6 \leqslant Z \leqslant 9$) and H ($Z \geqslant 10$) where L, M and H refer to light, medium and heavy fragments.

2.2. *Analysis of the data for* $Z = 2$

We followed about 2000 relativistic tracks of projectile fragments produced within a forward cone of angle 7° until they either interacted or left the plate. About 400 secondary interactions were collected. Each fragment is identified and classified into one of four groups: alpha ($Z = 2$), L ($Z = 3$–5), M ($Z = 6$–9) or H ($Z \geqslant 10$) according to its charge determined by their gap density measurements.

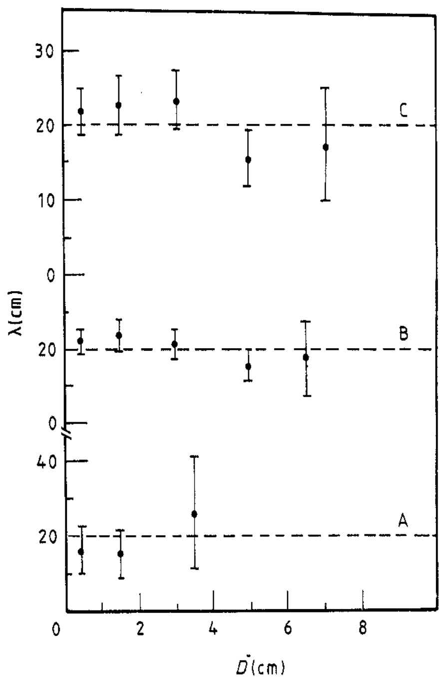

Figure 1. Experimental distribution of mean free path of the fragments at different path length D from the origin of the projectile fragments of ^{40}Ar for different values of N_h: A, $N_h = 0$; B, $N_h > 0$; and C for all types of Ar interactions.

Table 1. Mean free paths of α particles produced from ^{40}Ar interaction with emulsion for different α multiplicities.

N_α	$\langle\lambda\rangle$ (cm)	Number of events	Number of scanned tracks	$P(<\chi^2)$
1	23.09 ± 4.92	22	248	0.778
2	21.49 ± 3.20	45	445	0.707
3	18.21 ± 2.74	44	366	0.289
4	23.53 ± 4.16	32	327	0.844
all	21.18 ± 1.77	143	1386	0.768

In figure 1, the MFP's (λ) are shown as a function of the distance D from the interaction vertex for ^{40}Ar $Z=2$ fragments produced in:

(i) peripheral collision ($N_h = 0$) events;

(ii) non-peripheral collision ($N_h \neq 0$) events; and

(iii) all types of Ar interactions.

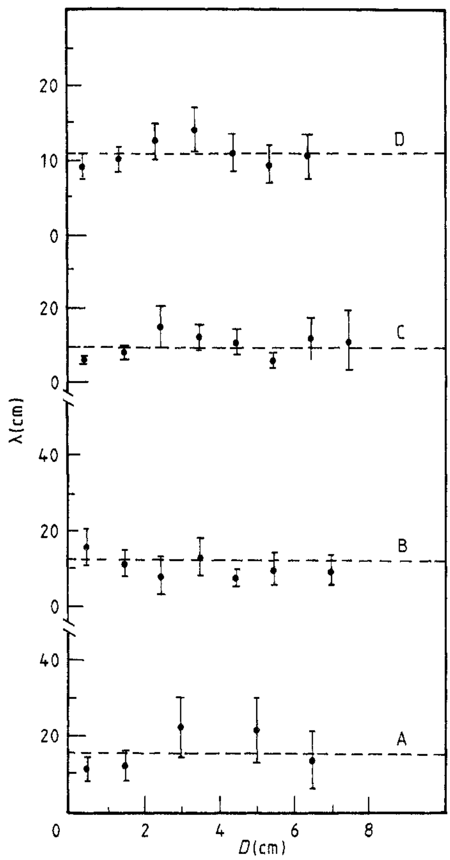

Figure 2. Experimental distribution of mean free path λ at different path lengths D for different grouped charge emitted from ^{40}Ar beam interaction: A, L; B, M; C, H; D, for all types of fragments ($Z \geqslant 3$).

The mean free path is computed by dividing the total track length in a certain path length interval by the number of interactions observed in that length. The result does not show any statistically significant deviations from the primary MFP value (19.98 cm) calculated by Beri *et al* (1983) and shown by the broken line in figure 1. Also, our data show no deviations from the primary He mean free path data (20.19 ± 0.7 cm) from the Bevatron (Barber *et al* 1982, Jain and Das 1982).

Table 1 shows the mean free path values for events with different N_α multiplicities. They lead to no detectable anomalous behaviour. The chi-square tests, χ^2, were carried out and the probabilities $P(<\chi^2)$ are given in table 1. According to these results, it may be stated that the present data on He fragments do not show any anomalous effects in the following cases:

(i) $Z=2$ single or multiple fragments produced in $N_h=0$ (peripheral) collisions of ^{40}Ar with emulsion nuclei; and

(ii) $Z=2$ single or multiple fragments produced in $N_h \neq 0$ (non-peripheral) collisions of ^{40}Ar.

2.3. *Analysis of the data for $Z \geqslant 3$*

In figure 2 and table 2 one finds the mean free path distribution of secondary fragments with $Z \geqslant 3$ as a function of the distance D from the point of the primary interaction of ^{40}Ar projectile ions according to the following different charge categories:

(i) light fragments L ($3 \leqslant Z \leqslant 5$);
(ii) values of the probabilities $P(<\chi^2)$; and
(iii) values of the probabilities $P(<F)$.
(iv) all fragments emitted from ^{40}Ar projectile with charge $Z > 2$.

These values of the mean free path of the $Z \geqslant 3$ fragments indicate no statistically significant deviations from the values of the corresponding beam-like ions (calculated by Beri *et al* 1983). In table 2 the following results of the standard statistical χ^2 and F tests (F is the ratio between the value of the MFP λ at $D \leqslant 2.5$ cm and λ at $D > 2.5$ cm) are given:

(i) values of the standard deviations SD;
(ii) values of the probabilities $P(<\chi^2)$; and
(iii) values of the probabilities $P(<F)$.

From these results, we notice that there is only a small difference between the MFP values of the two segments ($D \leqslant 2.5$ cm and $D > 2.5$ cm), but the difference never exceeds 2 SD. The difference between MFP values in the first segment ($D \leqslant 2.5$ cm) and the values of beam-like ions predicted according to Beri *et al* (1983) also gives SD values less than 1.5.

So we can say that neither figure 2 nor table 2 gives any deviation from normal MFPs calculated for every charge category using the relation, suggested and tested by Friedlander *et al* (1980, 1983) and used by Beri *et al* (1983),

$$\lambda_Z = \Lambda Z^{-b}$$

where $\Lambda = \Lambda_{\text{beam}} = 30.4 \pm 1.6$ cm†, $b = 0.44 \pm 0.02$ and Z is the average charge for every charge category.

Similar results were obtained by many authors (Heinrich *et al* 1983, Tincknell 1983). The anomalon was not observed for charges less than nine (Ismail *et al* 1984, Alma-Ata 1983). Stevenson *et al* (1984) detected no anomalon effect for heavy projectile fragments ($Z = 13-17$).

† Heckman *et al* (1978): to account for possible differences in scanning efficiencies in keeping with the independence of the experiments, they actually use two fits to primary beams. For National Research Council of Canada, $\Lambda_{\text{beam}} = 28.9 \pm 2.5$ cm, $b = 0.43 \pm 0.04$; for LBL, $\Lambda_{\text{beam}} = 32.2 \pm 2.5$ cm, $b = 0.44 \pm 0.03$.

Table 2. Detailed information of the mean free paths at $D \leqslant 2.5$ cm, $D > 2.5$ cm and $D \leqslant 1$ cm and all distances (indicated as average) from the origin of the projectile fragments for grouped charges (L, M, H and $Z \geqslant 3$) of the interaction of ^{40}Ar with the emulsion nuclei. The table also lists the cumulative probability for the measured values to occur at a fluctuation assuming the null hypothesis as well as the expected values, calculated according to Beri *et al* (1983) given in the last column. The tables also gives the values of the ratio of the two estimates as well as the calculated probability of F lying below the observed value (without any assumption about the expected value of λ).

Collision	N	$D \leqslant 2.5$ cm			$D > 2.5$ cm			F test	
type	Prongs	λ† (cm)	SD	$P(<\chi^2)$	λ† (cm)	SD	$P(<\chi^2)$	F	$P(<F)$
L	135	12.72 ± 2.71 (21)	−0.937	0.175	21.94 ± 5.67 (15)	1.403	0.920	0.580	0.049
M	144	12.90 ± 2.57 (25)	0.371	0.644	9.03 ± 1.50 (35)	−1.638	0.051	1.429	0.918
H	202	7.60 ± 1.03 (54)	−1.480	0.069	10.05 ± 1.55 (43)	0.473	0.682	0.756	0.086
$Z \geqslant 3$	481	10.12 ± 1.01 (100)	−0.568	0.255	11.57 ± 1.20 (93)	0.658	0.745	0.875	0.176

Collision	N	Average			$D \leqslant 1$ cm			$\lambda_{calc.}$
type	Prongs	λ† (cm)	SD	$P(<\chi^2)$	λ† (cm)	SD	$P(<\chi^2)$	(cm)
L	135	16.46 ± 2.71 (36)	0.268	0.606	11.20 ± 3.38 (10)	−0.996	0.160	15.90
M	144	10.60 ± 1.36 (60)	−0.997	0.159	15.50 ± 5.17 (9)	0.873	0.808	12.15
H	202	8.70 ± 0.89 (97)	−0.739	0.230	6.10 ± 1.12 (30)	−2.157	0.015	9.42
$Z \geqslant 3$	481	10.82 ± 0.78 (193)	−0.018	0.493	9.13 ± 1.30 (49)	−1.132	0.129	10.85

† Number of interactions observed is given in parenthesis.

3. Conclusions

The present work shows the following features.

(i) No anomalous effect is detected for ^{40}Ar PFs with $Z \geqslant 2$ at 1.88 GeV/nucleon. This may be due to, among other factors, the relatively low energy of the ^{40}Ar beam (type of projectile) used in the present experiment.

(ii) The doubly charged fragments (He fragments) produced in peripheral collisions ($N_h = 0$ events) of ^{40}Ar projectiles show no anomalous effect, although there seems to be strong evidence for their presence in carbon projectiles (El-Nadi 1984, Badawy 1983). Also, no effect is seen for different multiplicities of the $Z = 2$ fragments.

The weak signals detected before in experiments using mixed data of light and heavy projectiles, such as ^{16}O and ^{56}Fe ions in the case of LBL and the NRC experiment at Berkeley (Friedlander *et al* 1983), may be due to the ^{16}O projectile.

So it is useful to look for $Z = 2$ anomalons in peripheral collisions of light projectiles such as ^{12}C and ^{16}O.

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