COSMIC AND SUBATOMIC PHYSICS REPORT
LUIP 8314
AUGUST 1983
LUNFD6/(NFFK-7037)1-11(1983)
ISSN 0348-9329

THE MEAN FREE PATH OF RELATIVISTIC FRAGMENTS FROM HEAVY ION REACTIONS BY 1.8 A GEV ^{40}AR IN LOW SENSITIVE NUCLEAR EMULSIONS*

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* PRESENTED AT THE 2:ND WORKSHOP ON ANOMALONS, LAWRENCE BERKELEY LAB., JUNE 28 - JULY 1, 1983.

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THE MEAN FREE PATH OF RELATIVISTIC FRAGMENTS FROM HEAVY ION REACTIONS INDUCED BY 1.8A GeV ^{40}Ar IN LOW SENSITIVE NUCLEAR EMULSIONS*

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Preliminary data is given for the mean free path of projectile-like fragments, $2 \leq Z \leq 18$, emitted in ^{40}Ar induced heavy ion reactions in nuclear emulsions at 1.8A GeV as well as in later generations of fragmentation chains.
Only within a distance of one cm or less from the interaction point do we observe an enhanced collision frequency. If this observation is a signal of an anomalous fragmentation component this must have a very short mean free path or a lifetime less than 10^{-11}s. Some suggestions are given for systematic or statistical effects which could also possibly explain our results.

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*Presented at the 2:nd Workshop on Anomalons, Lawrence Berkeley Lab., June 28 - July 1, 1983, by B.Jakobsson, Univ. of Lund, Lund, Sweden.

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INTRODUCTION

Cosmic ray based-[1] and recent accelerator based heavy ion fragmentation experiments[2-4] have given some indications of an anomalous component which has an extremely large reaction probability and a long enough lifetime to produce collisions separated in space from the primary interaction. Speculations about the origin of this component range from quark-gluon effects[5-6] via normal nuclear physics effects[7-8] to quasi-molecular effects[9].

In this paper we give a status report from a proceeding nuclear emulsion experiment where particular attention is paid to;

i) The charge identification of the fragments from all generations of collisions.

ii) Estimations of statistical fluctuations by means of Monte-Carlo simulations of the experiment.

iii) A test of possible sources of background which may simulate the observed "anomalous" effect.

EXPERIMENTAL DETAILS

Three stacks, containing 1.1 litre of Ilford G5 emulsions have been exposed horisontally to the 1.8A GeV ^{40}Ar beam of the Bevalac with a flux of $2 \cdot 10^3$ ions/cm^2. The sensitivity of the emulsions is low (7 grains per 100μm for minimum-ionizing particles) which means that only projectile fragments with a charge $Z \geq 2$ can be observed normally. This has the advantage of giving a relatively clean registration of the projectile-like fragments close to the interaction point. Almost 5300 primary ^{40}Ar tracks have so far been followed (along-the-track) under 250^x magnifi-

1) B.Judek, Can.J.Phys. 46 (1968)343, 50 (1974)2082 and references therein.

2) E.M.Friedlander et al., Phys.Rev.Lett. 45 (1980)1084

3) P.L.Jain and G.Das, Phys.Rev.Lett. 48 (1982)305.

cation and the mean free path is found to be 9.21±0.16 cm. This value is surprisingly close to the expected mean free path (9.08 cm) determined from the overlap reaction cross-section expression,

$$\sigma_P = \pi r_o^2 (A_1^{1/3} + A_2^{1/3} - b)^2 , \qquad (1)$$

fitted to all available data (r_o = 1.5 fm , b = 1.3 fm) as we know it. This indicates that we lose only a few interactions in spite of the low sensitivity. Normal scanning efficiency tests by double-scanning agree well with this statement since the efficiency was found to be ≥ 95%.

The mean free paths of ^{40}Ar reported from the five different laboratories which contributed to the data collection have only normal statistical fluctuations as shown in table 1. The natural guess that those collisions which are lost in the scanning, have a small charge difference between primary and secondary fragment is confirmed in the next section.

About 700m of ^{40}Ar and $2 \leq Z \leq 18$ fragment tracks has been followed so far, resulting in the number of collisions in the different generations given in table 2. Up to five generations of fragments have been observed and in one single case a fifth generation fragment collided within the stack. The notations which are used subsequently in this paper for various fragments and collisions are given in table 2.

CHARGE DETERMINATION

The preliminary classification of the fragments into the charge groups α (Z=2), L ($3 \leq Z \leq 5$), M ($6 \leq Z \leq 9$) and H ($Z \geq 10$), based mainly on the scanners visual inspection of the track, is followed

4) W.Heinrich et al., Univ. of Siegen Preprint SI-82-15 (1982).

5) Y.Karant, Lawrence Berkeley Lab. Preprint LBL-9179 (1979).

6) S.Fredriksson and M.Jandel, Phys.Rev.Lett. 48 (1982) 14.

up by accurate charge measurements. Two methods were followed independently. One group (Lund) measured the gap densities of light fragments ($Z \leq 4$) and the track width from light absorption with a photometer for higher charges. The charge spectrum based on fragments from 1350 primary nuclei (only F_1) is given in fig.1. Here the proper gap density-charge and width-charge relations, based mainly on calibration tracks of He,Li,C (calibration exposure) and Ar, have been introduced. The charge resolution (σ_Z) is 0.2 units for light fragments, 0.3 units for ^{12}C and 0.5 units for ^{40}Ar (see fig.1). Because of this resolution and the low statistics of medium- and heavy fragments we can of course not expect to see separated charge peaks for $Z \geq 7$.

The other experimental groups measured the gap density and gap-length distribution with eyepiece micrometers for each fragment track. The correlation between the gap density and the (inverse) mean gap length (the gap length coefficient) gives the charge determination within 0.5, 1.0 and 1.5 units for the L, M and H groups respectively. The mutual normalization between the different pellicles and the different scanners was checked continously by measurements on tracks with known charges (i.e. Z = 2,3,6 and 18).

The two methods give charge distributions in good qualitative agreement. Therefore the charge distribution of the entire sample of F_1 fragments is shown in fig.2 (histogram) compared to a distribution which is obtained from existing spectrometer data[10-11] and the assumption of factorization of fragmentation cross-sections[10]. This comparison indicates that we are underestimating the number of fragments with $Z \geq 13$. Because of the poor information on the He-production cross-sections one may leave out this dominating contribution and renormalize the distributions in the interval $3 \leq Z \leq 18$ in order to make a reaso-

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7) J.Boguta, Lawrence Berkeley Lab. Preprint LBL-13885 (1982).

8) W.C.Harris and J.O.Rasmussen, Lawrence Berkeley Lab. Preprint LBL-14075 (1982).

nable efficiency estimation. When doing so, we find that only about 20% of the events producing a fragment with Z≥13 is left out. This corresponds well to a total scanning loss of ~5% as observed in the efficiency tests.

EXPERIMENTAL RESULTS

It has been suggested[2] that the charge dependence of the mean free path can be represented by the formula,

$$\lambda_Z = \lambda_0 Z^{-\beta} \qquad (2)$$

The overlap formula (1) together with information about isotope production cross-sections[10] (or a parabolic mass distribution centered around the most stable isotope) leads to λ_Z values giving the best fit to (2) for λ_0=26.0cm and β = 0.38. Since we have not yet completed our charge determination we use the α, L, M, H classification and assume from the preliminary charge distribution (fig.2) that the average charge within each group ($\bar{Z}$) is 2, 3.65, 7.41 and 14.45 respectively. The experimental mean free path within each group ($\lambda_i = L_i/N_i$ where L_i is the followed track length and N_i the number of collisions) is now multiplied by $\bar{Z}^{\beta}$ and a weighted Z-independent mean free path,

$$\lambda_0^* = \Sigma L_i \bar{Z}^{\beta} / \Sigma N_i \qquad (3)$$

can be obtained. The α-group should contain a negligible amount of Z ≠ 2 fragments and we have therefore first separated the fragment sample into this group and the 3≤Z≤18 group. All generations are included since we did not observe any significant differences between them with respect to λ_0^*.

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9) B.F.Bayman, J.S.Ellis and Y.C.Tang, Phys.Rev.Lett. 49 (1982) 532

10) P.J.Lindstrom et al., Lawrence Berkeley Lab. Preprint LBL-3650 (1975).

In fig.3 where λ_o^* is presented as a function of the distance from the interaction point we observe that neither the α distribution nor the $3 \leq Z \leq 18$ distribution is significantly different from a hypothesis of a normal constant λ_o^* . Possibly there is in both cases a deviation in the first cm. When the two distributions are combined (fig.4) the fluctuations become small enough to draw significant conclusions. We see now, that the point representing the first cm is about three s.d. below the normal λ_o^*, while the other points are statistically distributed around this value. It should be noticed that λ_o was not obtained from our data which (excluding the first cm) give a slightly higher value (λ_o=26.7 cm).

A separation into smaller d-bins (fig.4) shows that it is mainly in the first few mm from the interaction point where a substantially enhanced reaction probability is observed.

From the detailed information about the generation number, the charge of the fragments, the number of "target associated" particles (N_h) etc., we have observed the following tendencies;

i) The tendency of a short mean free path in the first cm is more clearly observable for light fragments (i.e. α and L) than for heavy.

ii) No differences are observed between the primary fragments and those coming from later generations of collisions (no memory).

iii) A tendency towards a more clear short mean free path effect after N_h=0 - than after $N_h \geq 1$ events is observed. The main contribution to the N_h=0 sample comes from reactions induced in the H-target component (can also contain decays).

The generation distribution is given in table 2. From this we can obtain the probability that N collisions in a chain from an F_1 fragment will appear (P(N)). For P(3), P(4) and P(5) we

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11) G.D.Westfall et al., Phys.Rev. C19 (1979)1309.

get $(1.6\pm0.2)\cdot10^{-2}$, $(2.0\pm0.7)\cdot10^{-3}$ and $(2.4\pm2.4)\cdot10^{-4}$ respectively. A complete simulation of the experiment (in progress) is in our opinion the only way to make a good comparison to the null hypothesis (normal fragmentation). However we can meanwhile compare the experimental distribution to those obtained from a) an assumption of independent reaction probabilities (except for an increasing λ with increasing generation number) along the track and b) a Poisson distribution with the average N ($\bar{N}$) taken from the experimental P(N) distribution (for justification see ref.[12]). Hypothesis a) gives,

$$P(N) = f_p \prod_1^N (1-e^{-x_i/\lambda_i}) \quad . \qquad (4)$$

The frequency of potential F_5 collision candidates at the end of the stack (f_p;decreases due to escaping fragments and collisions without a $Z\geq2$ fragment and increases due to multi-fragmentation) was found to be 0.5 in preliminary Monte Carlo simulations. x_i can be taken as the potential path length (15cm) divided by N and λ_i as λ_H, λ_M, λ_L, and λ_α for i= 1, 2, 3 and ≥4 respectively. Hypothesis b) gives,

$$P(N) = (\bar{N}^N/N!)e^{-\bar{N}} \quad , \qquad (5)$$

where $\bar{N}$ is 0.46136. The values for P(3), P(4) and P(5) obtained from these assumptions are (hypothesis b) within brackets); $1.9\cdot10^{-2}$ $(1.0\cdot10^{-2})$, $1.6\cdot10^{-3}$ $(1.2\cdot10^{-3})$ and $9.9\cdot10^{-5}$ $(1.1\cdot10^{-4})$ respectively. Since none of the experimental frequencies for 3, 4 or 5 collisions is significantly above the estimated null hypothesis, we can not claim to see any anomalous fragmentation component with memory from the generation distribution. More elaborated tests are discussed in [12].

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12) E.M.Friedlander et al., Phys.Rev. C27 (1983)1489.

INTERPRETATION OF THE RESULTS

If we take the viewpoint that the short mean free path we observe in the first few mm after an interaction is a signal of an anomalous fragmentation component, then we can make the following statements;

i) A pure stable anomalon contribution is of the order of 1% and its characteristic mean free path is about 0.5cm. These values are obtained from a least squares fit of the inverse observed mean free path, $1/\lambda(x) = (1/N_c(x))\Delta N_c(x)/\Delta x$, ($N_c$ is the number of collisions) to the function,

$$1/\lambda(x) = \frac{(f_N/\lambda_N)e^{-x/\lambda_N} + ([1-f_N]/\lambda_A)e^{-x/\lambda_A}}{f_N e^{-x/\lambda_N} + (1-f_N)e^{-x/\lambda_A}} \qquad (6)$$

where f_N is the frequency of normal fragments and $\lambda_{N(A)}$ is the mean free path of the normal(anomalous) component. The contribution we find is smaller and the mean free path shorter than previous reported values[2-4].

ii) A pure decaying anomalous component must have a decay length ($D = \beta c\gamma\tau$) shorter than 1cm and thus a lifetime $\tau<10^{-11}$s. The unstable component may of course also have an enhanced reaction probability but this situation will hardly increase the upper limit of the lifetime.

Since we have found an enhanced reaction probability only within a short distance from the collision point it is very important to study whether statistical fluctuations or systematic ambiguities in the detection technique can introduce a simulation of this effect. The Monte Carlo simulation procedure, which we develop, includes an initial generation of the Ar entrance coordinates (from the beam profile) and the depth (from the differential reaction probability distribution) as well as the kind of target nucleus for an eventual first collision. Once a collision is appearing we generate the charge(s) of the produced fragment(s) (from topological cross-section weights) as well as its(their) angular distribution (Fermi gas breakup). Generation for generation these fragments are followed until they leave the stack or produce a collision without any Z≥2 fragment.

In fig.5 we present a preliminary normal fragmentation simulation of the first cm λ_o^* distribution in 66 events with 3500 primaries in each. This distribution should be asymmetric but for simplicity we have here fitted a Gaussian (not normal) distribution. The experimental points of fig.4(lower) are indicated. A normal distribution of random errors (σ=1.24cm) places the 0-1cm point 2.7σ (0.7%) from the average λ_o^*. In view of the fact that several other experiments[2-4] have reported a short mean free path in this interval we find it unlikely that this point is created by statistical fluctuations alone.

Let us now turn to the possible systematic ambiguities.

In fact most of the possible systematic errors have been discussed and ruled out as explanations for the anomalous effect in ref.[12]. The discussion about possible errors in measurements of distances,inhomogeneities in the emulsion, spread in the fragment energy and variable scanning efficiency is valid also for our experiment.

Because of the short distance of enhanced reaction frequency in our experiment, both systematic and statistical errors in the final charge determination should be carefully considered. However, as long as the visual inspection of a few hundreds of μm is the base for our α, L, M, H classification, there should be no differences in the systematic errors between the first cm and the rest of the track. Naturally, a decrease of $\bar{Z}$ with increasing distance from the interaction point is to be expected.

Very few He-nuclei are misidentified and for the other groups the estimated maximum systematic error is 0.5 charge units which for the L group means that λ_0^* has an error of < 5%. This is too small an effect to account for the point of short mean free path. The strongest candidate for a simulating systematic error is in our opinion the possible background of n, p, d, t and π induced reactions within a cylinder around the fragment track where confusion is possible. We have tried to estimate the possible number of confusing interactions within a cylinder of 1μm radius, under the assumption that all nucleons which are not bound in $Z \geq 2$ fragments come out as free protons and neutrons with an angular distribution of,

$$dN/d\cos\theta = C_0 + C_1 p_{beam}^2 \cos\theta \cdot e^{-p_{beam}^2(1-\cos^2\theta)/2\sigma^2} \quad .(7)$$

p_{beam} is here the momentum per nucleon of the projectile. The distribution is a consequence of a Fermi-gas breakup + an isotropic (direct) scattering process. The constants C_0, C_1 and σ are taken (after renormalization) from ref.[13]. The $Z \geq 2$ fragments are in a first approximation all given an emission angle of $\theta = 0^\circ$ - all except the He-nuclei which have a correction due to their rather wide angular distribution. A correct angular distribution of the heavy fragments, inclusion of nucleons bound in d and t fragments and track divergence due to multiple Coulomb scattering are all effects which may decrease the frequency of confusing collisions substantially. However, the radius of the cylinder may well be 2μm and that would compensate the decrease.

Because of all uncertainties, the graph shown in fig.6, which presents the number of confusing interactions per true fragment interaction as a function of the distance from the collision point, has an error of ~50%. Anyhow, it is obvious that if only

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13) G.M.Chernov et al., to be published in Nucl.Phys A.

the first 2.5mm after a collision gives a significant lower λ_o^* (see fig.4) then the introduced false anomalous behaviour due to the disturbing background cannot be ruled out (without further investigations) as a source of this effect.

CONCLUDING REMARKS

From our present data we cannot decide if the observed anomalous component (frequency 1%, mean free path 0.5cm) is a reality which must be given a physical interpretation or if it is introduced due to a confusing background of interactions (possibly combined with other effects of systematic and/or statistical nature). Increased statistics of collisions within the first two cm from the interaction point, careful vertex measurements and complete charge determinations are ingredients in the final state of our experiment. We hope thereby to be able to make a final conclusion about the observed short mean free path very soon.

One of us (B.J.), who presented the status report, wishes to thank V.Kopljar and S.Persson for valuable contributions to the presentation and to the experimental work.

TABLES

LABORATORY	λ_{Ar} (cm)
Banaras	9.67±0.38
Chandigarh	8.95±0.45
Jaipur	8.76±0.38
Jammu	9.01±0.37
Lund	9.34±0.26
Totally	9.21±0.16

Table 1. The primary ^{40}Ar mean free path in emulsion reported from the different laboratories.

KIND OF PARTICLE OR COLLISION	NOTATION	NUMBER OF EVENTS total	α(2)	L(3-5)	M(6-9)	H(≥10)
Primary	P	5293				
Primary collision	P_*	3494				
1:st gen.fragment	F_1	5603⁺	3442⁺	539	551	1071
1:st gen.coll.	F_{1*}	2141⁺				
2:nd gen.fragment	F_2	1395	851	191	194	159
2:nd gen.coll.	F_{2*}	[illegible]71				
3:rd gen.fragment	F_3	29	159	28	25	17
3:rd gen.coll.	F_{3*}	64				
4:th gen.fragment	F_4	30	22	3	2	3
4:th gen.coll.	F_{4*}	8				
5:th gen.fragment	F_5	4	3	1	0	0
5:th gen.coll.	F_{5*}	1				

Table 2. The total number of fragments and colliding fragments(*) in all generations of the followed Ar projectiles. It should be noticed that two stacks with different length (15 and 20 cm) have been scanned. ⁺means that the number has been corrected for some F_1-He nuclei which were left out in a part (25%) of the scanning.

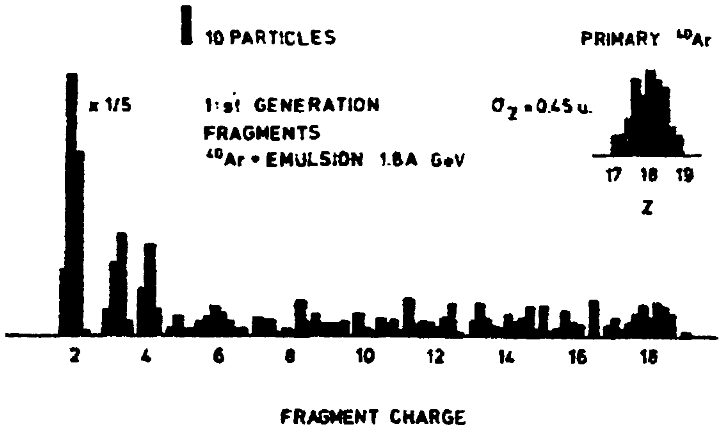

Fig.1. The charge spectrum from gap density($Z \leq 4$) and photometric($Z \geq 5$) measurements on F_1 fragments.

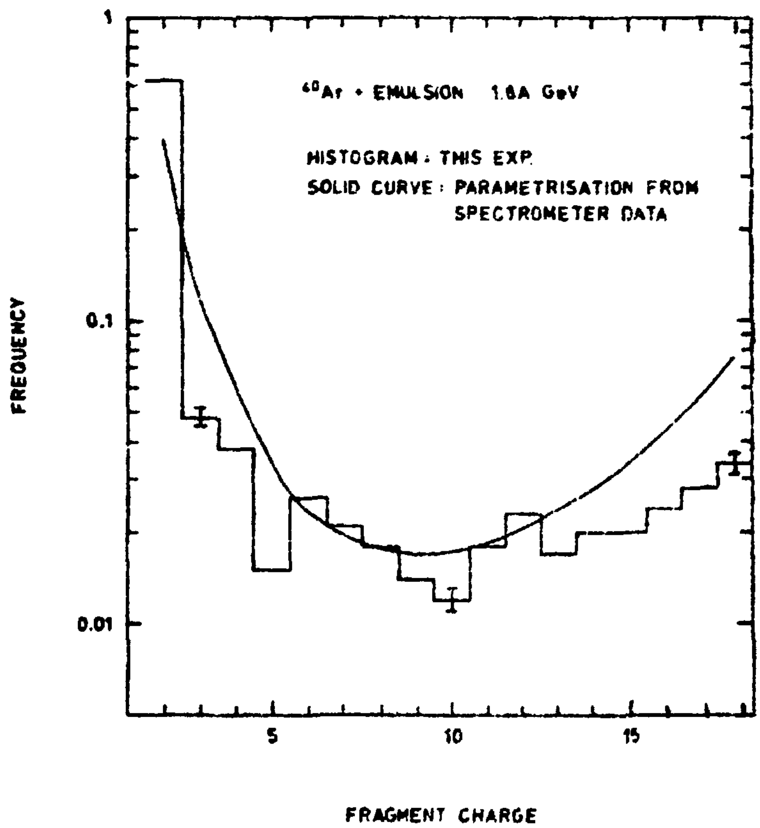

Fig.2. The charge distribution of all F_1 fragments in ^{40}Ar+emulsion collisions at 1.8A GeV. The solid curve is obtained from data in ref[10-11]

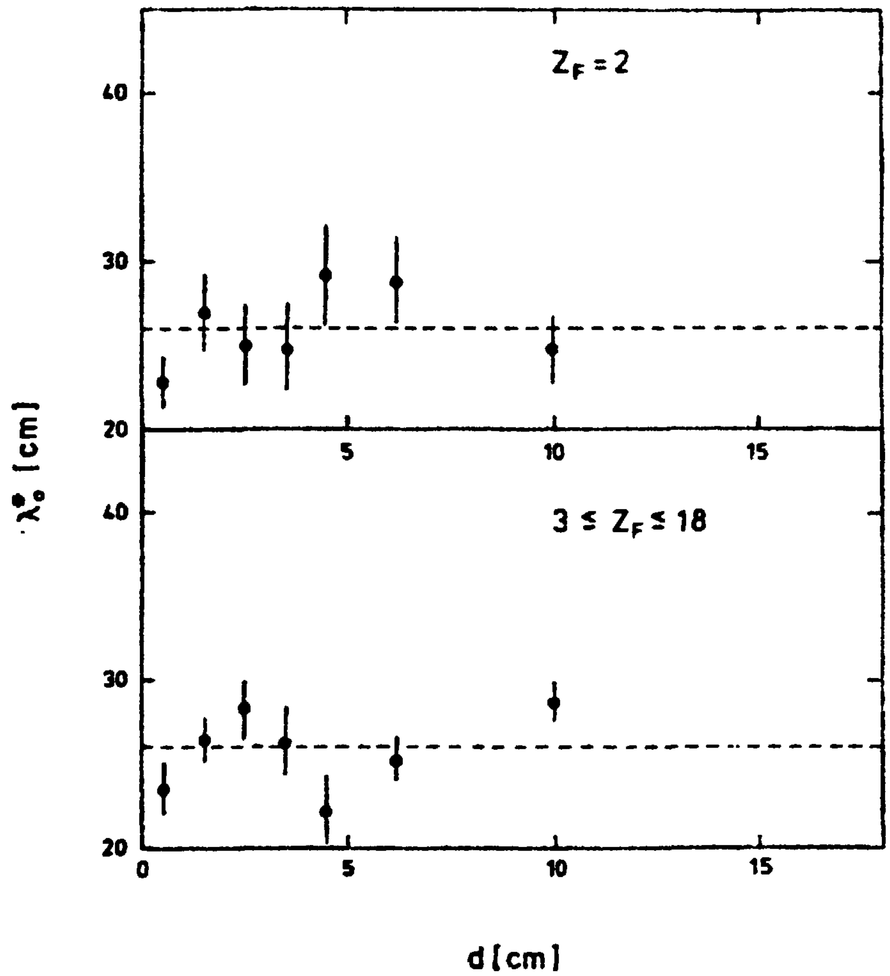

Fig.3. The charge independent mean free path (λ_o^*) as a function of the distance from the interaction point. Upper figure: He fragments from generations 1-5. Lower figure: $3 \le Z \le 18$ fragments from generations 1-5. The dashed line represents λ_o (see (2))

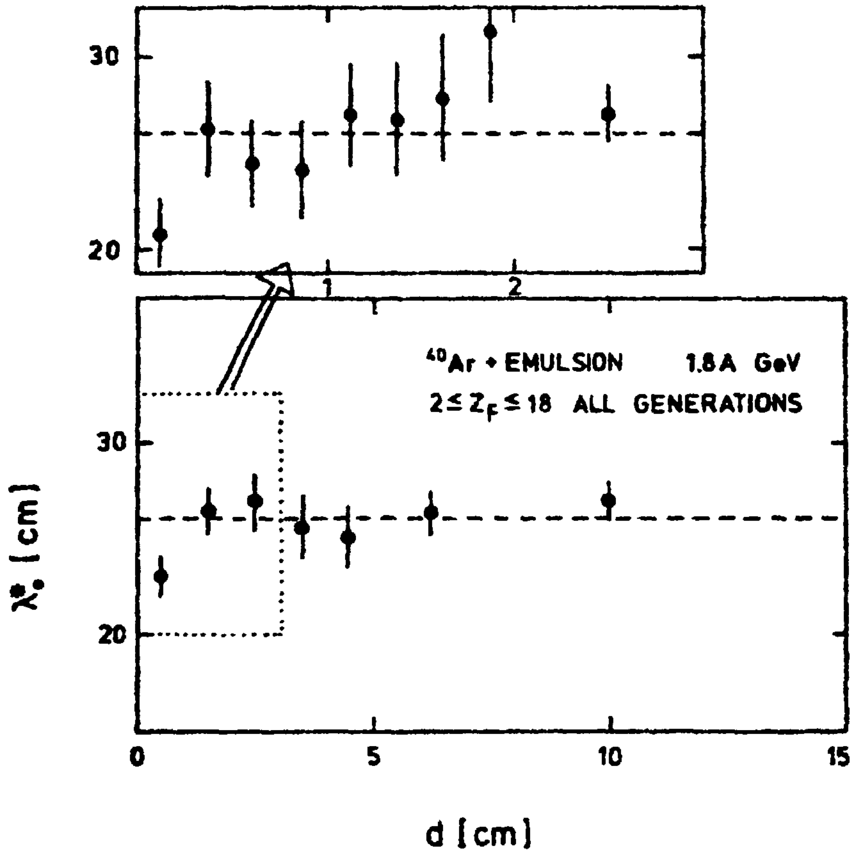

Fig.4. The charge independent mean free path (λ_o^*) as a function of the distance from the interaction point. All fragments with $2 \leq Z \leq 18$ from generation 1-5 are included. The upper figure gives the $0 \leq d \leq 2$cm interval in 2.5mm bins.

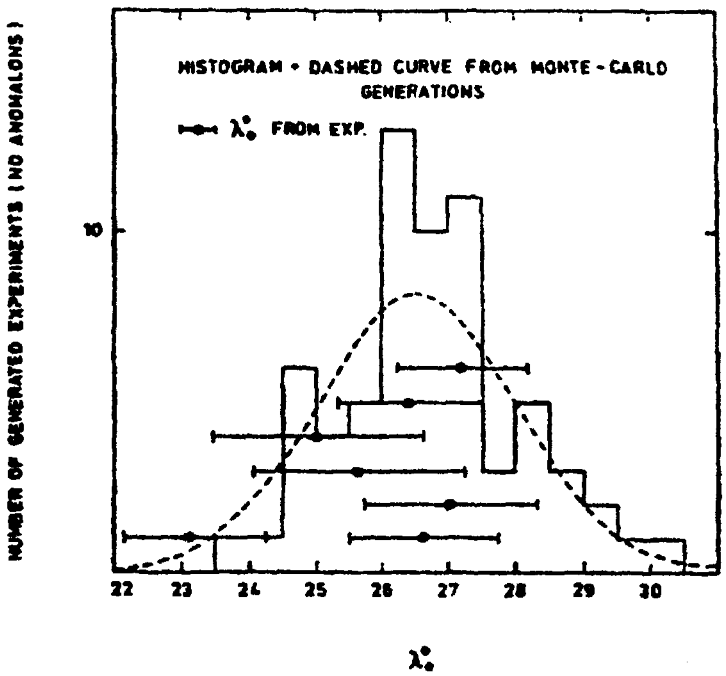

Fig.5. The λ_o^* value in the first cm from the interaction point obtained in 66 Monte Carlo generations of our experiment (normal fragmentation). The points represent the measured λ_o values from fig.4. The curve is a Gaussian fit.

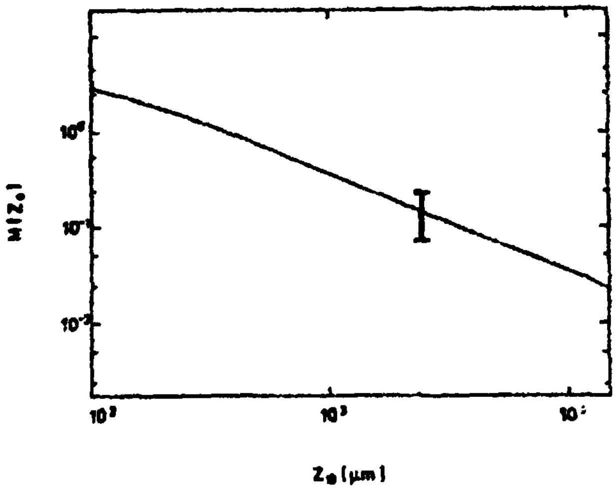

Fig.6. The number of confusing p- and n induced collisions per Z≥2 fragment collision ($M(z_*)$) as a function of the distance from the interaction point (z_*). The error bar is placed at a distance of 2.5mm from the int. point. For details see text.

Dokumentutgivare

UNIVERSITY OF LUND
Department of Physics

Handläggare

Dokumentnamn

Internal report

Utgivningsdatum

August 1983.

Dokumentbeteckning

LUNFD6/(NFFK-7037)

Ärendebeteckning

Författare

S.B.Beri, K.B.Bhalla, R.Bhanja, A.Bharti, V.S.Bhntia, G.Claesson, S.Garpman, S.K.Gupta, N-Y.Herrström, B.Jakobsson, R.Joseph, G.L.Kaul, G.Kaur, M.Kaur, S.Kumar, V.Kumar, S.Lokanathan, I.Lund, L.K.Mangotra, I.S.Mittra, B.Norén, A.Oskarsson, I.Otterlund, Y.Prakash, N.K.Rao, S.Sankhyadhar, S.Satti, M.M.Sherif, K.Söderström, S.K.Tulli

Dokumenttitel och undertitel

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Referat (sammandrag)

Preliminary data is given for the mean free path of projectile-like fragments, $2 \leq Z \leq 18$, emitted in ^{40}Ar induced heavy ion reactions in nuclear emulsions at 1.8 A GeV as well as in later generations of fragmentation chains.

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Referat skrivet av

The authors.

Förslag till ytterligare nyckelord

Klassifikationssystem och -klass(er)

Indextermer (ange källa)

Omfång 11 pages;
2 tables; 9 figures,

Övriga bibliografiska uppgifter

Språk

English

Sekretessuppgifter

ISSN

0348-9329

ISBN

Dokumentet kan erhållas från

Department of Cosmic and Subatomic Physics
University of Lund
Sölvegatan 14, S-223 62 LUND, Sweden.

Mottagarens uppgifter

Pris