FRAGMENTATION STUDIES OF 158 A GeV Pb IONS USING CR39 NUCLEAR TRACK DETECTORS

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ABSTRACT

Six stacks of CR39[1] nuclear track detectors with different targets were exposed to a lead beam of 158 A GeV at the CERN-SPS, in order to study the fragmentation properties of ultra-relativistic lead nuclei. The exposures were performed at normal incidence with a mean density of about 2000 lead ions/cm^2 in the beam central area. The typical number of events in a stack was about 5.8×10^4 distributed in 8 spots. We present experimental results on lead fragmentation and charge pick-up cross sections.

1. Introduction

The study of the fragmentation properties of high energy atomic nuclei is of relevance for nuclear physics, cosmic ray physics and astrophysics. For instance, fragmentation cross sections are needed to evaluate the changes in composition undergone by cosmic ray particles in the collisions with the interstellar medium.

In this paper we present results on the fragmentation cross sections of 158 A GeV lead ions (charge $Z = 82$); in particular the total charge changing

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[1]CR39, $(C_{12}H_{18}O_7)_n$, is a Registered Trade Mark of PPG Industries Inc.

cross sections, the partial fragmentation cross sections for $\Delta Z = -1, -2, -3$, and the $\Delta Z = +1$ pick-up cross sections were measured. The measurements were performed on different targets: CR39, Pb, Cu, Al, C and $(CH_2)_n$ and composite targets. We have also evaluated the cross sections in Hydrogen and Oxygen.

The CR39 detectors were manufactured by the Intercast Europe Co. of Parma (Italy) and are similar to those used in a large area experimental search for magnetic monopoles at the Gran Sasso Laboratory (the MACRO experiment) [1].

Previous results concerning the fragmentation of 158 A GeV lead ions, relative to a different exposure and with lower statistics were published in ref. [2].

2. Experimental procedure

Six stacks made of CR39 nuclear track detectors and different targets were exposed in November 1996 at the CERN-SPS to a beam of 158 A GeV Pb^{82+} ions. The exposures were performed at normal incidence. The total number of lead ions in a stack was about 5.8×10^4 distributed in 8 spots. The average beam particle density was about 400 ions/cm^2; the central density in the spots was around 2000 ions/cm^2. The percentage of impurities in the beam was measured to be less than 1%. The present analysis refers to data measured in a single spot for each target.

Each stack had the following composition (Fig. 1): (i) a 1.4 mm thick CR39 foil (which we refer to in the following as plate "A"); (ii) 7 mm of CR39 made up of layers of about 0.6 mm thickness; (iii) a target, typically 10 mm thick; (iv) about 15 mm of 0.6 mm CR39 layers; (v) a 1.4 mm CR39 plate labelled "B". The targets consisted of Pb, Cu, Al, C, $(CH_2)_n$ and CR39 sheets. In the present analysis only the CR39 plates "A" and "B" of Fig. 1 were measured; the others will be used for further analysis to improve the tracking reconstruction and the charge resolution.

After exposure, the CR39 detectors were etched for 268 h in a 6N NaOH water solution at a temperature of 45 °C. When an ion crosses a nuclear track detector foil, it produces damages at the level of molecular bonds forming the so called latent track. During the chemical etching of the detector, if the etching velocity along the latent track, v_T, is larger than that in the bulk material, v_B, etch-pit cones are formed on both sides of the foil. The

base area and the height of the cones are functions of the Restricted Energy Loss (REL) of the incident ion [3–5]. After etching, the etch-pit cone base diameter of a track produced by a Pb ion is around 75 μm. The calibration of our CR39, using the present etching conditions, was discussed in detail in refs. [3, 4].

The base area of each etch-pit cone, its eccentricity and central brightness were measured on both sides of the "A" and "B" plates with an automatic image analyzer, the Elbek system [6]. For relativistic ions, using only two independent measurements, this technique has an acceptable charge resolution up to $Z \sim 75$; for $Z \geq 75$ the fragment tracks cannot be distinguished from the lead tracks [3]. For each beam spot, the number of tracks retained after a tracking procedure is about 5000 before the target; after the target the number of tracks with $Z \geq 75$ are about 2000-2600.

In order to determine the percentage of different ion charges in the range $75 \leq Z \leq 83$, we performed cone height measurements on a single face before and after the targets, inside the same spot measured by the Elbek system.

The height measurements were made with a microscope with a magnification of $(20)_{ob} \times (10)_{oc}$. About 6500 tracks (in two stacks) before the target, and about 3300 tracks after the target (for each stack), with base diameters larger than 75 μm, were manually measured. The charge resolution obtained from this measurement technique is about $0.2e$ [3]. Fig. 2 shows the cone height distribution measured in plate "B" of the stack containing the lead target.

The percentages of non-lead tracks in the sample defined by diameter ≥ 75 μm are about 1% before and $18\% \div 35\%$ after the different targets.

3. Fragmentation of lead beam ions in the CR39 target

The CR39 target was used to determine the cross section on the CR39 itself and to extract the cross sections for the other targets. It was used also with the $(CH_2)_n$ and C targets to compute the cross sections in Hydrogen and Oxygen.

The total and partial fragmentation cross sections were calculated using the following propagation formula, see refs. [7, 8]

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$$N_i(x) = N_i(0) \, e^{-x\sigma_i} + \sum_{j=1}^{i-1} K_{ij}(e^{-x\sigma_i} - e^{-x\sigma_j}) \qquad (1)$$

with

$$K_{ij} = \frac{1}{\sigma_j - \sigma_i} \left(\sigma_{ij} N_j(0) - \sum_{l=j+1}^{i-1} \sigma_{il} K_{lj} + \sum_{l=1}^{j-1} \sigma_{ij} K_{jl} \right) \qquad (2)$$

where $x = \rho t N_A / A$, N_A is Avogadro's number, ρ is the target density in g/cm^3, A is the atomic mass, t is the target thickness in cm, $N_i(0)$ is the number of nuclei with charge Z_i reaching the target ($i = 1 \div 4$, corresponding to $Z = 82 \div 79$), $N_i(x)$ is the number of ions of charge Z_i after the target, σ_i is the total fragmentation cross section of ions with charge Z_i, and σ_{ij} is the partial fragmentation cross section for nuclei of charge Z_j yielding a fragment of charge Z_i.

As an input for the computation we need the total charge changing cross sections σ_i ($i = 1 \div 4$) and the partial charge changing cross sections σ_{ij}. The total charge changing cross section for lead nuclei (σ_1) was experimentally measured. For the fragments, the σ_i were evaluated by scaling σ_1 according to the following equation

$$\sigma_i = \sigma_{ni} / \sigma_{n1} \quad , \qquad (3)$$

where, see ref. [9],

$$\sigma_{ni} = 10 \pi r_0^2 [A_i^{1/3} + A_t^{1/3} - b(A_i^{-1/3} + A_t^{-1/3})]^2 \qquad (4)$$

In ref. [9], Eq. (4) was used to fit the data at $1 \div 2$ A GeV for projectiles and targets of atomic mass $A_i \geq 12$ and $A_t \geq 12$, respectively; for the parameters r_0 and b, ref. [10] gives the numerical values: $r_0 = 1.39$ fm and $b = 1.65$.

The partial fragmentation cross sections σ_{i1} were experimentally measured; the other partial fragmentation cross sections σ_{ij} were evaluated using a constant fragmentation probability for the same ΔZ.

The measured partial charge changing cross sections in CR39 are given in Table 1, where the quoted errors are the sums in quadrature of statistical and systematic uncertainties. Note that the total charge changing cross section of 158 A GeV lead nuclei in CR39 is $\sigma_{CR39} = (2590 \pm 190)$ mb. The estimated systematic uncertainties are around 5%. They are due to several sources; the

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main contribution arises from the relatively poor charge resolution at $Z \sim 74$ for measurements performed with the automatic Elbek system.

4. Fragmentation of incident lead ions in various targets

The total and partial fragmentation cross sections of lead ions in various targets were computed using the propagation formula (1), and are listed in Table 1. The results described in the previous Section were used to take into account the fragmentation in the CR39 foils.

The measured cross sections are the sum of the nuclear (σ_n) and electromagnetic (σ_{em}) cross sections. The difference between the total cross section (σ_{tot}), experimentally measured, and the nuclear cross section (σ_n), computed using Eq. (4), is the electromagnetic contribution σ_{em}, which can be described by the exponential part of formula (5).

The measured values for the total cross sections are listed in Table 1 and shown in Fig. 3 versus the target atomic mass.

The fit of our data for $A_t \leq 23$ to Eq. (4) gives $r_0 = (1.32 \pm 0.05)$ fm, $b = (1.03 \pm 0.40)$ and $\chi^2/D.o.F. = 1.3$ (in this A_t region, the electromagnetic contribution to the total cross section is small). The dashed line in Fig. 3 has been computed with Eq. (4) using the parameters obtained for the fit for $A_t \leq 23$.

In order to include a Coulomb term, we used the following equation, see ref. [11],

$$\sigma_{tot} = 10\pi r_0^2 [A_p^{1/3} + A_t^{1/3} - b(A_p^{-1/3} + A_t^{-1/3})]^2 + \alpha Z^\delta . \tag{5}$$

Assuming $r_0 = 1.32$ fm and $b = 1.03$ from our previous fit, and $\alpha = 0.6$ mb from ref. [11], we fitted our data to Eq. (5) obtaining $\delta = (2.05 \pm 0.05)$ with $\chi^2/D.o.F. = 1.16$. The result of the fit is the solid line in Fig. 3.

The measured partial cross sections for $\Delta Z = -1, -2, -3$ are listed in Table 1 for different targets.

The cross sections on Hydrogen and Oxygen targets have been determined using the measured cross sections in CR39, $(CH_2)_n$ and C.

5. Charge pick-up cross section

The charge pick-up reaction, in which the projectile nucleus increases its charge number by one unit, was also studied. The pick-up cross sections for

Target	A_t	σ_{tot}	$\sigma_{(\Delta Z=-1)}$	$\sigma_{(\Delta Z=-2)}$	$\sigma_{(\Delta Z=-3)}$	$\sigma_{(\Delta Z=1)}$
H	1	1940 ± 234	765 ± 91	117 ± 36	105 ± 38	15 ± 8
CH$_2$	4.67	2421 ± 181	522 ± 61	92 ± 23	98 ± 24	13 ± 5
(CH$_2$)$_n$+CR39	6.45	2576 ± 188	335 ± 53	112 ± 17	95 ± 17	11 ± 4
CR39	7.4	2590 ± 190	221 ± 29	117 ± 31	90 ± 25	7 ± 4
C+CR39	8.96	2900 ± 201	164 ± 35	98 ± 18	89 ± 18	10 ± 4
Al+CR39	11.5	3228 ± 229	243 ± 51	156 ± 27	103 ± 20	17 ± 6
C	12	3382 ± 220	36 ± 16	42 ± 23	83 ± 26	9 ± 5
O	16	2904 ± 959	—	—	—	—
Cu+CR39	22.9	3610 ± 243	322 ± 56	168 ± 29	74 ± 14	18 ± 7
Al	27	4651 ± 349	246 ± 68	243 ± 57	122 ± 40	34 ± 12
Pb+CR39	32.5	3832 ± 263	690 ± 98	282 ± 36	133 ± 20	21 ± 7
Cu	63.5	6108 ± 384	574 ± 78	284 ± 59	27 ± 23	27 ± 12
Pb	207	11982 ± 762	3920 ± 413	1403 ± 176	417 ± 81	74 ± 27

Table 1: The measured total, partial break-up and pick-up charge changing cross sections for lead ions of 158 A GeV on various targets. All values are in mb; quoted uncertainties are the sums in quadrature of statistical and systematic uncertainties.

the different targets were determined using the equation (see ref. [12]),

$$\sigma_{p1} = \frac{1}{x} \frac{N_p(x)}{N_1(x)} \quad , \tag{6}$$

where N_p is the number of nuclei with $Z = 83$ produced inside the target, $N_1(x)$ is the number of unfragmented beam nuclei and x has the same meaning as in Eq. (1). σ_{p1} was directly measured for the CR39 target. For the other targets we computed $N_p(x)$ as

$$N_p(x) = N'_p(x) - N'_p(0) \cdot e^{-x\sigma_p} \tag{7}$$

where $N'_p(x)$ and $N'_p(0)$ are the computed numbers of $Z = 83$ nuclei immediately after and before the target and σ_p is their estimated fragmentation cross section.

6. Conclusions

Using stacks of CR39 nuclear track detectors, we measured the total, partial break-up and pick-up charge changing cross sections for lead nuclei

of 158 A GeV in different targets. The experimental total charge changing cross sections can be described by a semiempirical formula which takes into account nuclear and electromagnetic processes.

We have tried to compare our measurements with the data available in the literature relative to lower beam energies and different beam ions [11–15]. The comparison is difficult; nevertheless the data indicate a similar A_t dependence of the cross sections.

Acknowledgements

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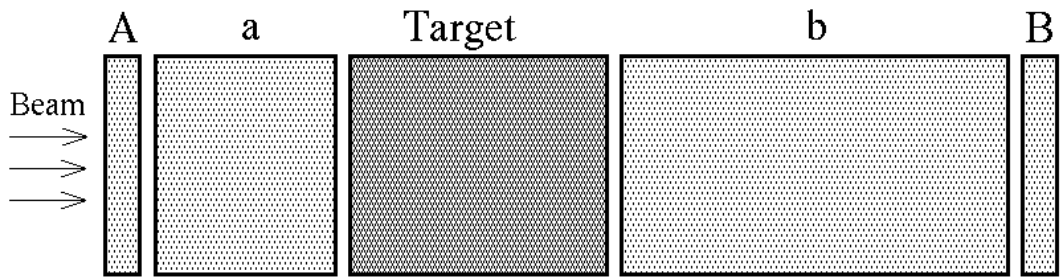[15] S. E. Hirzebruch et al., Phys. Rev. **C51** (1995) 2085.

Figure 1: Sketch of a stack used for the fragmentation studies. "A" and "B" are 1.4 mm thick CR39 sheets, "a", "b" are stacks about 1 cm thick of layers of 0.6 mm thick CR39; the target is typically 10 mm thick.
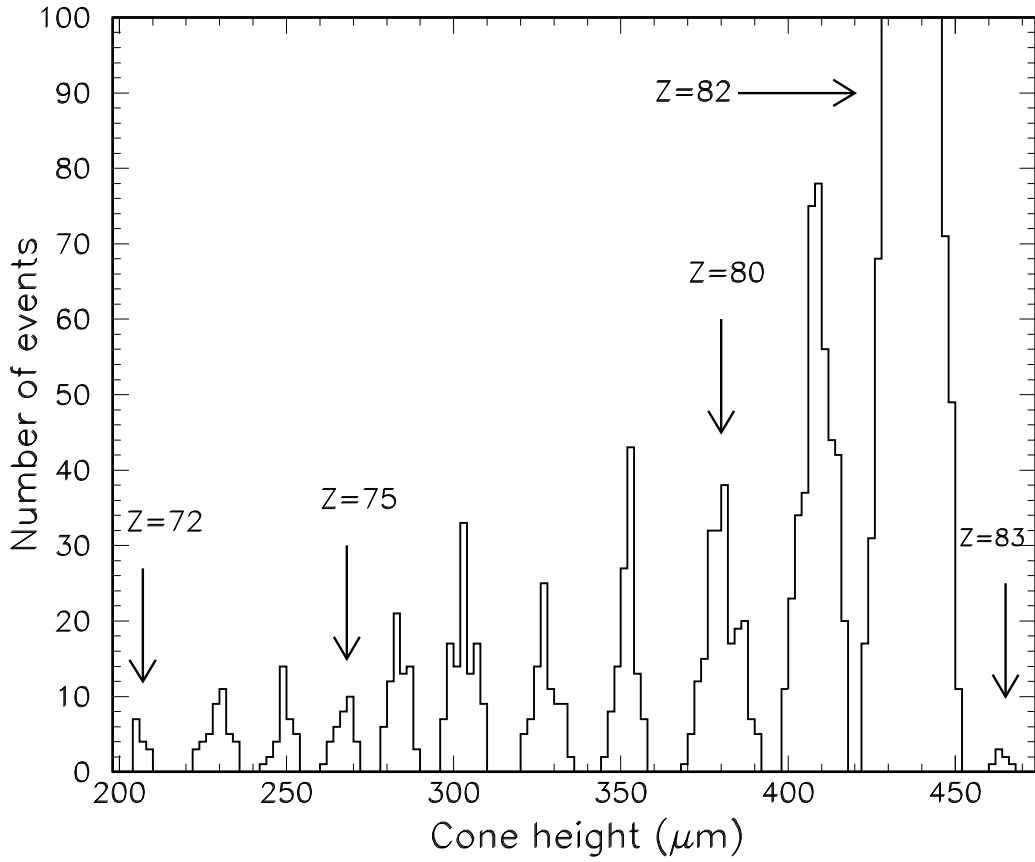
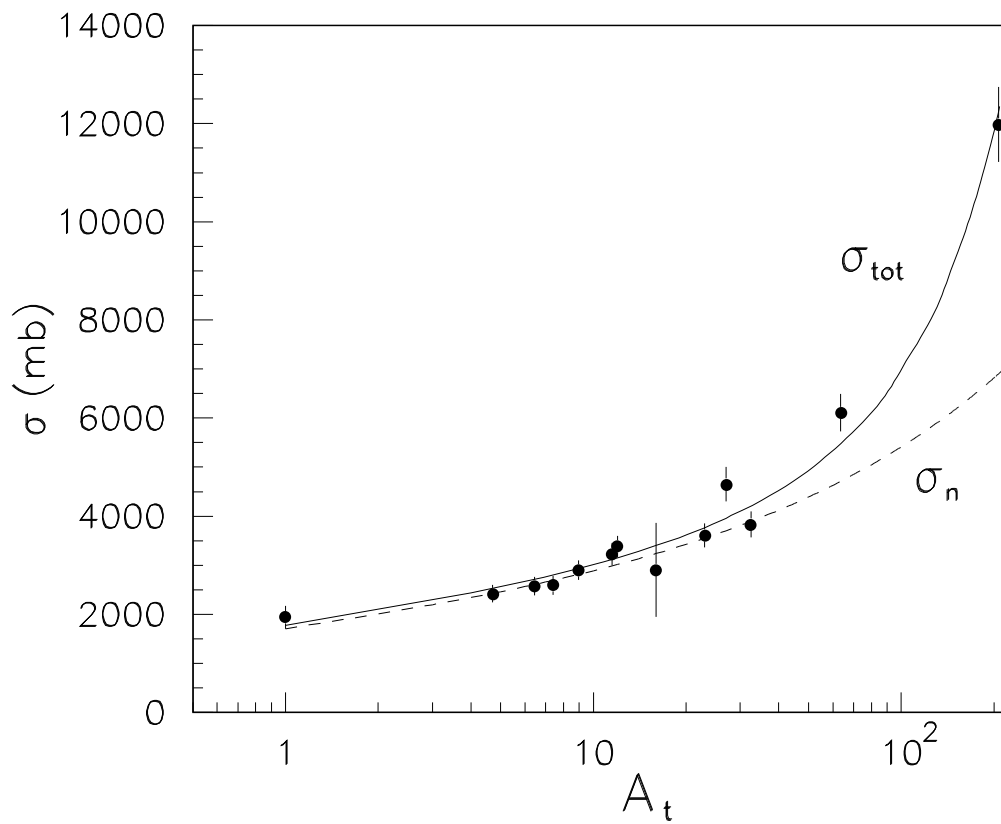Figure 2: Distribution of etched cone heights for the "B" CR39 sheet located after the lead target.

Figure 3: Measured total fragmentation charge changing cross sections for 158 A GeV Pb projectiles in various targets (black points). The solid line represents the fit of our data to formula (5); the dashed line is the nuclear cross section contribution (see text).