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Extended calibration of a CR39 nuclear track detector with 158 A GeV ^{207}Pb ions

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Abstract

Six stacks of nuclear track detectors (CR39 and Makrofol) were exposed to 158 A GeV ^{207}Pb ions at the CERN-SPS. The main purpose of the experiment was the calibration of the CR39 nuclear track detector used in a large area experimental search for magnetic monopoles at the Gran Sasso Laboratory (the MACRO experiment). Different targets (C, CH_2, CR39, Cu and Pb) were used in order to study also the fragmentation properties of ultrarelativistic lead nuclei. The exposures were performed at normal incidence and at a density of about 2000 ions/cm^2. The total number of lead ions in a stack was about 5.8×10^4. For the stack with the lead target, we measured the base area and the length of the etched cones. We obtain a unique calibration curve for the charge region $7 \leq Z \leq 83$ combining the two types of measurements. Using the cone length method, we obtain a charge resolution $\sigma_Z \simeq 0.19e$ for $Z = 82$ ions using a single measurement in one face of CR39.

1. Introduction

The nuclear track detection technique has been used to determine the fragmentation cross sections of the incoming ions into a variety of fragments [1]. Using an incoming beam of relativistic $^{207}Pb^{82+}$ ions and their fragments produced in a lead target, we made an extension of previous calibrations of the CR39 nuclear track detector [2] based on the measurements of (i) the base areas of the etched cones in CR39 with an automatic system [3] and (ii) the cone lengths for nuclear fragments with $Z > 74$.

With four base area measurements of the same fragment, we achieve a charge resolution $\sigma_Z \simeq 0.2e$ at $Z = 20$. As it is well known, the resolution of the base area measurements is worsening as the charge of the fragment increases, because in the high charge region the change in the diameter of the base cone is rather small.

In the region of $74 < Z \leq 83$, we obtain, by cone length measurements, a charge resolution $\sigma_Z \simeq 0.19e$

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for $Z = 82$ ions using a single measurement in a single face of CR39.

The used CR39 was made by the Intercast Europe Co. of Parma [2], in their scientific line of production. This CR39 is used extensively in the MACRO experiment at the Gran Sasso Laboratory in the search for magnetic monopoles [4].

2. Experimental procedure

Stacks of CR39 nuclear track detectors with different target–detector combinations were exposed to the CERN-SPS lead beam at an energy of about 158 A GeV (= 32 700 GeV/nucleus). The beam passed through some foils of CR39 detectors, interacted in the target material (typically 10 mm thick) and then passed through CR39 foils which recorded the surviving lead projectiles as well as their fragments. The typical lead beam density was about 2000 ions/cm^2.

After exposure, the CR39 nuclear track detectors were etched for 268 h in a 6 N NaOH water solution at a temperature of 45°C. Under these etching conditions the etch-pit diameter produced by a Pb ion was around 76 μm (see Fig. 1 for the geometry of an etched cone).

The bulk etch velocity v_B (measured by the thickness method) of the CR39 detector used for the length measurements, was (0.153 ± 0.001) μm/h.

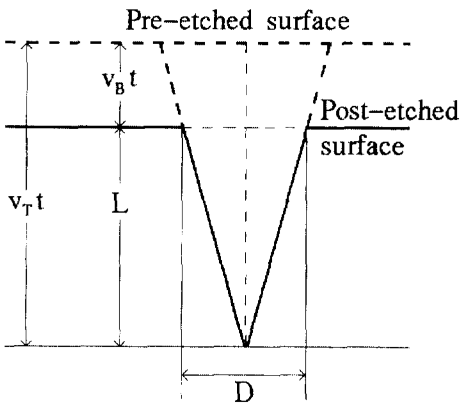

Fig. 1. Geometry of an etched cone produced by a relativistic charged particle with normal incidence on the surface of the detector.

Table 1
Charge resolution σ_Z for nuclear charge Z values in the interval $74 \le Z \le 82$; the σ_Z values were obtained from cone length measurements in a single face of the CR39 foil located after the lead target, see text

Cone length L (μm)	Charge Z	Charge resol. σ_Z
372 ± 7	74	0.27
398 ± 8	75	0.29
425 ± 8	76	0.27
456 ± 7	77	0.21
492 ± 6	78	0.18
526 ± 8	79	0.21
565 ± 7	80	0.18
607 ± 8	81	0.20
648 ± 8	82	0.19

The base area of each etch-pit cone, its eccentricity and central brightness were measured on both sides of each detector sheet with an automatic image analyzer, the Elbek system [3], which also provides the absolute coordinates of the etched cones ("tracks"); this allows the tracking of the beam ions and their fragments through the CR39 sheets.

The cone lengths were measured using a Leica microscope with a magnification of $(20)_{ob} \times (10)_{ep}$; we obtain a resolution of $\sigma_L \simeq 8$ μm (see Table 1).

3. Results

Two CR39 foils located after the lead target were measured with the image analyzer system (one of them was used for the length measurements). The background noise due to α-radioactivity and defects on the surface of each detector was removed by applying cuts on the central brightness of the base area of the etched cones and on the eccentricity values. The paths of the beam ions and of their fragments were reconstructed using a special tracking algorithm.

A valid track should be measured on at least three faces of the CR39 foils. The etch-pit base area increases with the fragment charge; however, the resolution becomes worse for high charges. Fig. 2

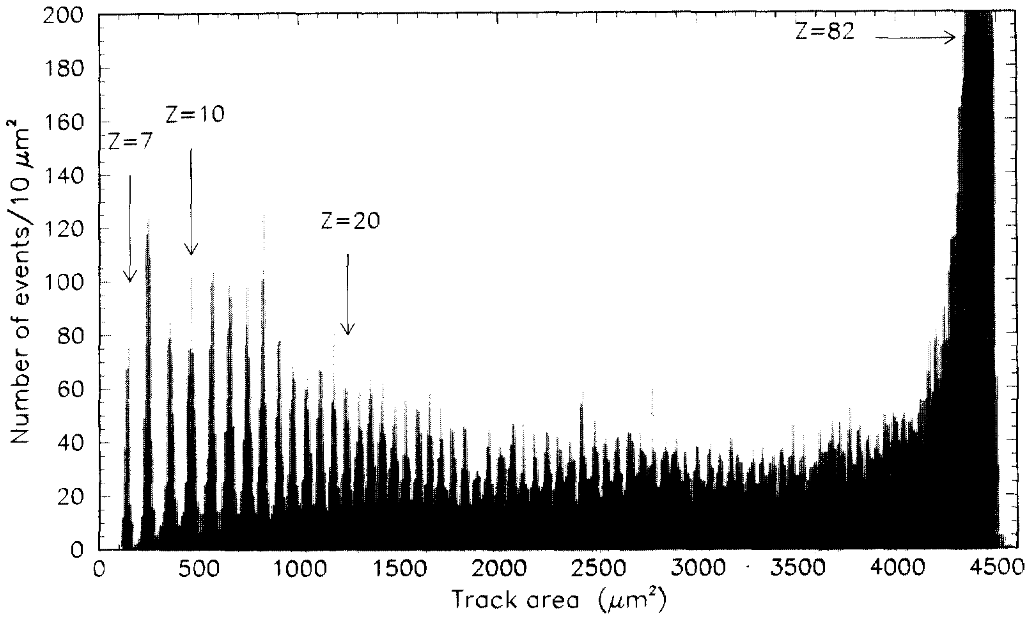

Fig. 2. Distribution of the average base areas of the etched cones produced in CR39 by relativistic lead ions and their fragments. Each peak in the graph corresponds to a different charge value, as indicated for some of the peaks.

shows the average base area distribution for the lead ions and their fragments; the averages are made over four measurements of the bases of the etched cones in two sheets of CR39. It is apparent that we have a good charge resolution up to a charge value around $Z = 60$; for $Z > 74$ the nuclear fragment peaks are mixed with the lead beam peak. At $Z = 20$ the charge resolution is $\sigma_Z \simeq 0.2e$.

In order to resolve the individual nuclear fragments with $Z > 74$ we applied a different method, measuring the etched cone length, which is more sensitive at high Z (as illustrated in Fig. 3). The measurements were made for those tracks having a base diameter $D \geq 75$ μm. One CR39 foil located after 10 mm target material was used; 3840 cone lengths have been measured on the front face of the CR39 sheet. Fig. 4 shows the cone length distribution for ^{207}Pb ions and their fragments produced in the lead target. Each peak is well separated from the others and one may assign a charge to every peak, as indicated in Fig. 4. Notice the $Z = 83$ peak, which corresponds to a charge pick-up reaction.

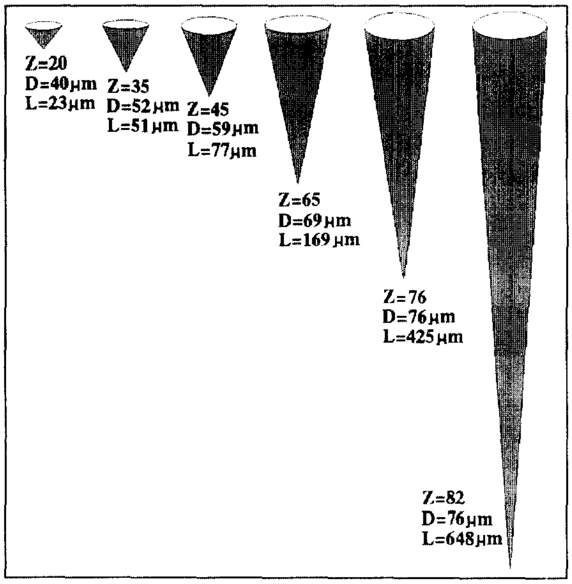

Fig. 3. Illustration of the variation of the cone length L and of the diameter D of the etched cones in CR39 for relativistic lead ions ($Z = 82$) and some nuclear fragments (with $Z = 20, 35, 45, 65, 76$). The L values were obtained from Eqs. (2) and (3) for $Z \leq 74$ and from direct measurements for $Z > 74$.

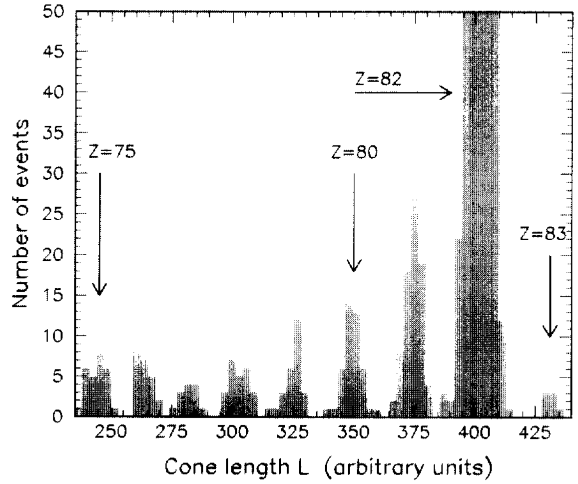

Fig. 4. Cone length distribution of Pb ions and their fragments with $Z > 74$ measured in a single face of the CR39 detector placed immediately after the lead target.

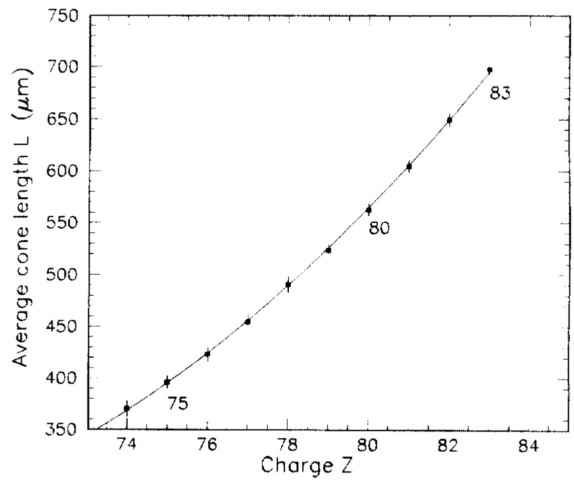

Fig. 5. Average cone lengths plotted versus the charge Z of the Pb ions and of their fragments produced in the lead target.

4. Discussion

Fig. 5 shows the correlation plot between the assigned charges of the nuclear fragments and the mean values of the length of the etched cones. The cone length is an increasing function of the charge. The charge resolution σ_Z of the CR39 detector using the cone length measurements was calculated as

$$\sigma_Z = \sigma_L/(\delta L/\delta Z) \quad (1)$$

where σ_L is the standard deviation of the individual peaks and is obtained from the data presented in Fig. 4. The numerical values for σ_L and σ_Z are given in Table 1; notice that for $Z = 82$ we have $\sigma_Z \simeq 0.19e$.

The reduced etch rate $p = v_T/v_B$, where v_T is the track etching velocity, may be calculated from the formula [5]

$$p = \frac{1 + (D/2v_B t)^2}{1 - (D/2v_B t)^2}, \quad (2)$$

where t is the etching time.

For nuclear fragments with $Z > 74$ (separated by the cone length measurements) the average diameter D is calculated from the average cone length L of the individual peaks via the relation

$$D = \frac{2v_B L}{\sqrt{(v_T^2 - v_B^2)}}, \quad (3)$$

where $v_T = v_B + L/t$, see Fig. 1.

In order to intercalibrate the two different measurement procedures, we normalized the diameters obtained from cone length measurements for the lead beam with those measured by the automatic image analyzer system. Fig. 6 shows the calibration of our CR39 with relativistic lead ions and their fragments in terms of the reduced etch rate p versus the restricted energy loss (REL). The points are the experimental data; for $7 \le Z \le 74$ and for $74 < Z \le 83$ they have been determined by area and cone length measurements, respectively. The error bars include statistical and systematic uncertainties; the main contribution to the errors comes from the uncertainty in the determination of the bulk etch velocity v_B. The experimental data points have been fitted to the empirical relation

$$p = 1 + A(\mathrm{REL})^B + C(\mathrm{REL})^D + E(\mathrm{REL})^F \quad (4)$$

obtaining $A = (0.2254 \pm 0.0007)$, $B = (1.238 \pm 0.001)$, $C = (-0.4000 \pm 0.0006)$, $D = (1.225 \pm 0.004)$, $E = (0.177 \pm 0.001)$, $F = (1.204 \pm 0.004)$, with $\chi^2/\mathrm{d.o.f.} = 1.06$.

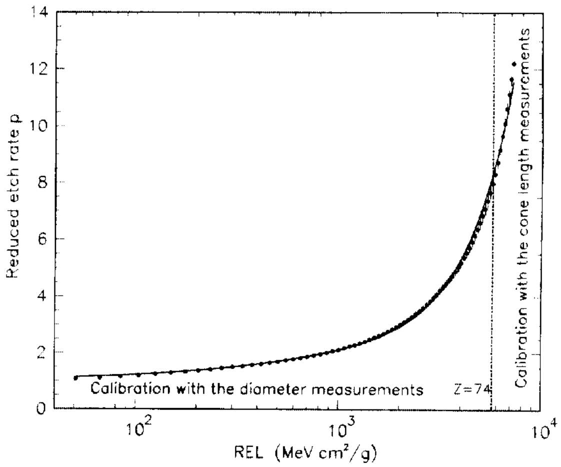

Fig. 6. Reduced etch rate p vs. REL; the points are the data, the solid line is the best fit to the data points.

5. Conclusions

We have studied the response of a CR39 nuclear track detector to relativistic lead ions and their fragments using measurements of the etch-pit base area and of the etch-pit cone length in the charge region $7 \leq Z \leq 74$ and $74 < Z \leq 83$, respectively. By measuring the cone lengths we obtain a charge resolution $\sigma_Z \simeq 0.19e$ at $Z = 82$ using a single measurement in a face of the CR39 sheet. We can thus separate nuclear fragments with high Z ($Z =$ 75–81, $Z = 83$) from the lead ions of the beam.

From the two methods, the D and L measurements, applied in separate Z-regions, a unique calibration curve has been obtained.

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