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MEASUREMENT OF CHARGE OF PROJECTILE FRAGMENTS ($1 \leq Z \leq 3$) IN 60A GeV/c ^{16}O–EMULSION INTERACTION – A SEARCH FOR FRACTIONALLY CHARGED FRAGMENT

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Measurement of charges ($1 \leq Z \leq 3$) of the projectile fragments in ultra–relativistic heavy–ion collisions (^{16}O–emulsion at 60A GeV/c) was carried out by the measurement of lacunarity (L) of the track structure in nuclear emulsion track detector. No fractionally charged projectile fragment has been found in the present investigation.

1. *Introduction*

Several groups of workers have performed quark search experiments at accelerators and in cosmic rays using different experimental techniques [1]. Still, there is no convincing evidence regarding the existence of a free quark. Recently, it has been suggested that quark search experiments should be performed in relativistic heavy–ion interactions where quarks and gluons, which are confined within individual nucleons, may be free over the whole nuclear volume to form a quark–gluon–plasma [2]. Plastic detector experiment [3], Cerenkov–radiation experiment [4], and a search technique within stable matter [5], all gave negative results regarding search for fractional charges. Bloomer, a pioneer researcher for fractional charges using nuclear–emulsion technique [6], also obtained negative result. Still, there is hope that signatures of fractionally charged projectile fragments (PF) may be found. In this paper, we report an emulsion experiment with ^{16}O beam at 60A GeV/c to search for PF having charges 4/3, 5/3, 7/3 and 8/3 times the electronic charge. Here, we followed the method of Bloomer [6]. The measurement of charge is based on the determination of lacunarity i.e., fractional transparency or fractional opacity in the linear track structure of ionization as observed in developed emulsion. This method yields an estimate of charges for relativistic PF having $1 \leq Z \leq 3$ with the standard deviation $(Sz) \leq 0.03e$ in the measured charges of each track.

2. Theory of measurement

When a charged particle traverses a silver halide crystal of the nuclear emulsion, it deposits energy in the crystal by ionization. The excited crystals are converted into metallic silver by chemical reduction and the remaining AgBr crystals are removed. The opaque Ag–grains form the structure of the track. The probability that a given crystal will develop depends on (1) the emulsion sensitivity, (2) the total energy deposited in the crystal, (3) where the particle traversed the crystal and (4) the possible contribution of secondary ionization from δ–rays. The energy loss attributable to primary ionization is called the "restricted energy loss". For a given sensitivity of the emulsion, the primary grain density, g, is assumed to be proportional to the restricted energy loss rate

$$g = ki, \tag{1}$$

where k is the sensitivity factor.

The restricted energy loss rate can be calculated from the differential energy–transfer cross–section $(\mathrm{d}\sigma/\mathrm{d}\omega)\mathrm{d}\omega$, as

$$i = n_e \int\limits_{\omega_{min}}^{\omega'} \frac{\mathrm{d}\sigma}{\mathrm{d}\omega}\omega \mathrm{d}\omega, \tag{2}$$

where n_e is the electron density, ω' the upper limit of δ–ray energies and ω, responsible for the production of primary grains, $\approx 2-5$ keV. Under the approximation that δ–rays of energy $\omega \geq \omega'$ do not contribute to primary ionization, Eq. (2) is taken to be exact. In general, the restricted energy loss has the form

$$i = \frac{Z^2}{\beta^2} f(\beta), \tag{3}$$

where βc is the particle velocity and Ze the particle charge. A semi–empirical calculation yields

$$f(\beta) = 2\pi r_0^2 mc^2 n_e \left[\ln\left(\frac{2mc^2}{I^2}\beta^2\gamma^2\omega \right) - 2\beta^2 - 2C \right], \tag{4}$$

where I is the mean ionization of excitation potential, m the electron rest mass, r_0 classical electron radius, C correction term, n_e density of electrons in stopping material and $\gamma = (1 - \beta^2)^{-1/2}$.

In actual practice, the number of grains in a track segment is not amenable to direct measurement. O'Ceallaigh [7] made the key observation that the gap length distribution is exponential in a track

$$H(\geq l) = B \exp(-g' l), \tag{5}$$

where $H(\geq l)$ represents the density of gaps greater than or equal to l, g' is the slope of the exponential distribution, known as the ionization parameter, l is the minimum chosen gap length and B is the blob density (i.e., the total number of resolvable gaps per unit length). Fowler and Perkins [8] confirmed the form of the distribution for wide range of ionization parameters and for wide gap lengths. They also determined that B, the blob density or equivalently the gap density, is identical to $H(\geq 0)$ and is governed by

$$B = g' \exp(-g' \alpha), \tag{6}$$

where α is the mean diameter of a developed grain. Barkas [9] proved that the ionization parameter, g' in the experimental distribution of gap is, in fact, the actual grain density, i.e., $g = g'$.

Some important results follow as a consequence. If we define the lacunarity, L, to be the linear fraction of a track made up of gaps, then

$$L = \int_0^\alpha \frac{\mathrm{d}H}{\mathrm{d}l} l \mathrm{d}l = \exp(g\alpha). \tag{7}$$

From Eqs. (6) and (7), it follows that measurements of both B and L over a given track segment can be used to estimate the grain density,

$$g = \frac{B}{L} \tag{8}$$

and the mean grain diameter

$$\alpha = -\frac{L}{B} \ln L. \tag{9}$$

From the above relations, the dependence of L on α, β, K and Z is

$$-\ln L = \frac{\alpha K f(\beta)}{\beta^2} Z^2. \tag{10}$$

For a given development of the emulsion, α is a constant. If we deal with sufficiently high energy, β is also a constant. In that case, the charge of an ionizing particle is simply related to L of its track by

$$Z = K_0 \sqrt{-\ln L}, \tag{11}$$

where K_0 is a proportionality constant that is most conveniently determined empirically. For convinience, the quantity proportional to charge Z can be defined as

$$\rho = \sqrt{-\ln L} = \sqrt{-\ln(1-\phi)}, \tag{12}$$

where ϕ is defined as the opacity of the track structure.

We have now ionization parameters, L and ϕ, which are operationally well defined, easy to measure and related to charge by the simple relation $Z = K_0 \rho$.

The precision, δZ, with which the charge Z of an ionizing particle can be determined from its ionization track, is obtained from Eq. (11) as

$$\delta Z = \frac{K_0^2}{2Z} \frac{\delta L}{L}, \tag{13}$$

where $\delta L/L = (\sigma_L/L) N^{-1/2}$, σ_L is the variance of L, and N is the number of cells, each of length S, over which L is measured. Barkas [10] has given a theoretical upper limit to the quantity $\delta L/L$ for a model based on completely random spacings between individual grains in blobs. It is

$$\frac{\delta L}{L} = \sqrt{\frac{2\alpha}{\Lambda}\left[-\frac{1-L}{L\ln L} - 1\right]}, \tag{14}$$

where α is the mean grain diameter in μm of the developed grains and $\Lambda = NS$ the total path length in μm over which L is measured.

3. Experimental details

We have used a stack of Illford–K2 plates exposed to the ^{16}O beam with the average momentum 60A GeV/c obtained from CERN, Geneva. A Leitz–metalloplan microscope with oil immersion objective, having a magnification 100× and ocular lens 10×, along with an image processor, is used for scanning. Data were taken with ASM 68K semi–automatic measuring system. SUSY–system disk and a suitably developed programme is used to measure lacunarity (L) and/or opacity (ϕ) of the track structure.

From a sample of 226 events, with $N_h > 8$ and $N_s > 20$ where N_h and N_s represent the number of heavy tracks and shower tracks, respectively, final measurement of charge was taken on 477 projectile fragments. We measured opacity (ϕ) for $Z = 1$ tracks for a minimum length of 1000 μm of the linear track structure. Such a long–range of measurement yields a charge precision of less than 0.03e. Lacunarity values obtained directly or calculated from the opacity (ϕ) $[L = 1 - \phi]$ belong to three distinct groups. Each group thus obtained is separately normalised to $\overline{\rho}$, where $\overline{\rho} = (-\ln L)^{1/2}$. From this value of $\overline{\rho}$, the value of K_0 is calculated using the relation $Z = K_0 \overline{\rho}$.

4. *Experimental results and discussion*

Figure 1 shows the distribution of charges of the PF. It is transparent from the figure that the charges are distributed sharply around the integer values of Z, where $Z = 1,\ 2$ and 3. To determine if any candidate really possesses a fractional charge, one has to be sure about the width of the distribution of the integer charges that is expected from statistical fluctuation for the charges. Thus we have to measure the dispersion D_z of the charge distribution around the integer charge Z ($Z = 1,\ 2$ and 3) and check if there is any candidate for which the charge lies beyond $Z \pm 3D_z$. Table 1 shows that this experiment does not find a single candidate of a PF whose charge lies beyond the $Z \pm 3D_z$ value for any of the distributions around $Z = 1,\ 2$ and 3.

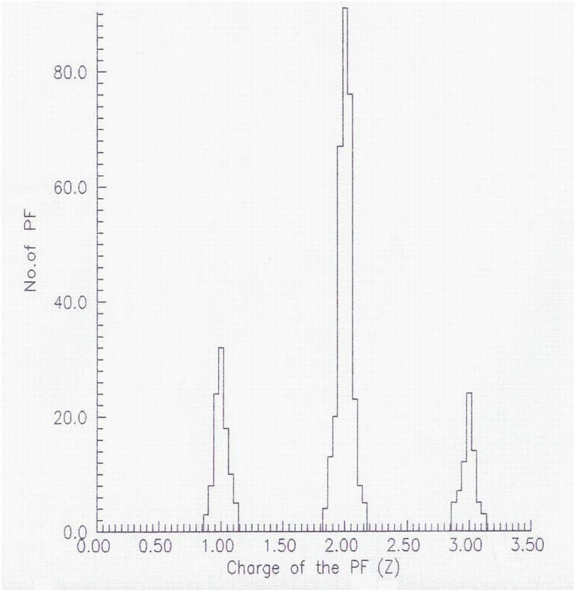

Fig. 1. Distribution of the charges (Z) *of the projectile fragments emitted in* ^{16}O–*emulsion interaction at* 60 A GeV/c.

The track saturation, i.e., conglomeration of Ag–grains into blobs may distort the linear relationship between mean gap length (g) and charge (Z) of the ionizing tracks (i.e., $g \sim Z^2$) as Z increases, and the effect is dependent on the quality of development of the emulsion–pellicle and that of the emulsion batch itself. Actually this is the cause that restricted us to measuring charges of the PFs having $1 \leq Z \leq 3$.

All possible sorts of check were performed to ascertain that these candidates are really projectile fragments. Specifically, we carried an extensive check on the emission angle of the PF and ensured that they all lie within a 3° forward cone with the incident beam direction. That resulted in the rejection of twenty one candidates. This angular cut ensures that these candidates have suffered a too small longitudinal momentum transfer in their production for precise measurement of charge with this technique.

TABLE 1.
Results of charge measurements $1 \leq Z \leq 3$ projectile fragments. $K_0 = Z/\overline{\rho}$, where $\overline{\rho} = (-\ln L)^{1/2}$, L is the lacunarity or fractional transparency of the track structure.

Z	No. of tracks	$K_0 = Z/\overline{\rho}$	Dispersion D_z	No. of PFs with charge beyond $Z \pm 3D_z$
1	100	2.973	0.068	0
2	307	2.981	0.075	0
3	70	2.974	0.073	0

5. Conclusion

The objective of the experiment was to find if there are any fractionally charged PF in ^{16}O–emulsion interaction at 60A GeV/c. The result is negative, i.e., we get no fractionally charged PF. All the PF lie within three times the dispersion (D_z) around the integer charges for the respective charge groups. Thus, this experiment shows, within experimental limit, only integrally charged PF.

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MJERENJE NABOJA ČESTICE ($1 \leq Z \leq 3$) PROIZVEDENIH U SUDARIMA 60 A GeV/c ^{16}O U EMULZIJI I TRAŽENJE ČESTICA S RAZLOMLJENIM NABOJEM

Proučavani su ultrarelativistički sudari teških iona (60 GeV/c ^{16}O) u nuklearnoj emulziji. Naboji čestica ($1 \leq Z \leq 3$) određeni su prema lacunarnosti (L) tragova čestica u emulziji. Nisu nađene čestice s razlomljenim nabojem.