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MEASUREMENT OF CHARGE OF PROJECTILE FRAGMENTS – SEARCH FOR FRACTIONALLY-CHARGED PROJECTILE FRAGMENTS AT ENERGY 14.5 AGeV

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Measurement of charges ($1 \leq Z \leq 3$) of the projectile fragments produced in silicon-emulsion interaction at 14.5 AGeV was carried out with the help of lacunarity (L) method, using nuclear emulsion track detector. No fractionally-charged projectile fragment was found in this investigation. Only integrally-charged projectile fragments with $Z = 1, 2$ and 3 were detected.

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1. *Introduction*

For last few decades, the investigation of particle interaction at high energies had been conducted extensively both in theory and experiment. Scientists were on the search for quark, so they performed quark-search experiments, in accelerators and cosmic rays employing modern scientific equipment [1] and no concrete evidence was found, as far as the existence of a free quark. It has been advised that quark-search experiments should be made more meticulously. We know that quarks bear fractional charges, i.e., 1/3-rd of elementary charge or its multiple. Being led by this idea, quite a large number of researchers conducted experiments in search of fractional-charge bearing fragments. Some evidence of projectile fragments (PFs), with large reaction cross-sections, has been reported. Such projectile fragments were found to have large reaction cross-sections in comparison to normal fragments bearing the unit charge. Some workers assume that these projectiles with abnormally large reaction cross sections may contain an extra quark. Recently, it has been suggested that quark-search experiments should be performed in relativistic heavy-ion collisions, where quarks and gluons, which are within individual nucleons, may be free over the whole nuclear volume to form a quark gluon plasma [2]. If such a plasma were formed, either isolated quarks or nuclei containing an extra quark are expected to escape [3 – 7]. To search for fractionally charged fragments, researchers carried out a number of experiments using plastic detectors [8], Cerenkov detectors [9] and emulsion [10], and applied a technique of search within stable matter, but got negative results as far as the fractional charges are concerned. Although Bloomer [11], a pioneer researcher in this field, also obtained a negative result, scientists hope that signature of fractionally charged fragments may be found.

In our previous work, we searched for fractionally charged projectile fragments using O^{16} AgBr interactions at 60 AGeV [12], and we also got negative result. Here, we discuss the nuclear emulsion experiment conducted in the search for projectile fragments with charges 4/3, 5/3, 7/3 and 8/3 times the electronic charge, considering ^{28}Si-AgBr interactions at 14.5 AGeV. We adopted the method of lacunarity measurement for the determination of charge of relativistic particles, as used by Bloomer et. al [11]. The above mentioned method can be applied only for charges $1 \leq Z \leq 3$, and also the projectile must have relativistic energy. Due to the track saturation, for higher charges, this method does is not suitable for charges greater than 3 (> 3).

2. *Theory of measurement*

Whenever a charged particle passes through a nuclear emulsion, it deposits energy by ionization in the silver halide crystals (distributed throughout the volume of the gelatin matrix). The excited halide crystals are then converted into metallic silver under a process of typical chemical reduction; the remaining AgBr crystals are then removed and the opaque silver grains form the structure of the track. The probability that a given crystal will develop depends on (1) the emulsion sensitivity, (2) on the total energy deposited in the crystal, (3) where the particle traversed the crystal, (4) the possible contribution of secondary ionization from δ-rays, which are electrons knocked free from nearby atoms by the primary ionizing particle. This last effect results in secondary grains. The term primary grain density refers to the density of the grains that results from the ionization of crystals actually traversed by the particle. 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, i,

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

where k is the sensitivity factor. The restricted energy can be calculated from the differential energy transfer cross section ($\mathrm{d}\sigma/\mathrm{d}\omega$) as

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

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

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

where βc is the particle velocity, Ze is the charge of the particle and $f(\beta)$ may be written as

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

I is called the ionization or excitation potential, m is the rest mass of an electron, r_0 is the classical radius of electron, C is the correction term (the meaning of it is explained in the paper of Bloomer [10]), $n_{\rm e}$ is the density of electrons in the stopping material and $\gamma = (1-\beta^2)^{-1/2}$.

We can not measure the number of grains in a track directly. O'Ceallaigh [13] made the key observation that the gap length distribution is exponential in a track,

$$H(\geq 1) = B\exp(-g'l)\,, \tag{5}$$

where $H(\geq 1)$ represents the density of the gaps greater than or equal to 1 and g' is the slope of the exponential distribution, termed 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 [14] ratified the form of the distribution for a wide range of ionization parameters and for all gap lengths. They further calculated B for the gap density $H(\geq 0)$ using the following relation

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

where α is the mean diameter of the developed grain. Barkas [15] showed that the ionization parameter, g', in the experimental distribution of gap is actually equal to the 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

$$L = \int\limits_0^\alpha l\frac{{\rm d}H}{{\rm d}l}\,{\rm d}l = \exp(g\alpha)\,. \tag{7}$$

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 guided by the following relation,

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

For a given development of the emulsion, α is a constant; if we deal with particles of sufficiently high energy, β will also be a constant. In this case, the charge of an ionizing particle is simply related to L of its ionization track by

$$Z = k_0(-\ln L)^{1/2}\,, \tag{11}$$

where k_0 is a proportionality constant that is most conveniently determined empirically. For convenience, the quantity proportional to the charge Z can be defined as

$$\rho = (-\ln L)^{1/2} = \big[-\ln(1-\phi)\big]^{1/2}\,, \tag{12}$$

where ϕ is defined as the opacity of the track structure. We now have two ionization parameters, L and ϕ, which are operationally well defined, easy to measure, and related to the 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 [16] has given a theoretical upper limit to the quantity $\delta L/L$ for a model based on completely random spacing between individual grains in blobs. It is

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

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*

In our experiment, a stack of ILFORD-G5 nuclear emulsion plates was exposed to the ^{28}Si beam with the average energy 14.5 AGeV obtained from CERN SPS, Geneva. The dimension of the plates were 18 cm × 7 cm × 0.06 cm. The flux of the beam was 10^3 particles per cm^2 and it was almost parallel to the plates. Leitz Metalloplan microscope with oil immersion objective, having a magnification 100× and ocular lens 40× was used for scanning. Each event was scanned by four independent observers with the maximum scanning efficiency. A graticule having 100 divisions was taken to measure the lacunarity (L) or opacity (ϕ) of the track structure. One division of lacunarity (L) or opacity (ϕ) of the graticule was equal to 0.62 μm, because in the total magnification (used with 100× oil immersion objective and 40× ocular) 100 graticule divisions were equivalent to 0.62 μm. For the measurement of the track, this graticule was superimposed onto the image of the ionizing track. Total length of the track integrated over 100 graticule divisions made up of gaps or blobs gives us the value of the lacunarity (L) or opacity (ϕ) of the track (of course in fraction) over a cell length S. The average lacunarity (L) and opacity (ϕ) of the track is

$$L = \sum_i L_i/N, \qquad \phi = \sum_i \phi_i/N\,,$$

where N such cells were taken on a track to achieve a charge precision of better than 0.03 charge units. The final measurement of charge was carried out on 145 projectile fragments (i.e. fragments emitted within 4° forward cone with the incident beam direction). Four observers checked each fragment independently in order to ensure whether it lies within 2° with respect to the incident beam direction. We have taken 2000 μm of the linear track structure for $Z = 1, 2$ and 3 tracks, i.e., 20 cell lengths each of 100 μm. Such a long range of measurement yields a charge precision of better than 0.03 units. Directly obtained lacunarity values or those calculated from the opacity ($L = 1 - \phi$) formed three groups. Each distinct group thus obtained was separately normalized to $\bar{\rho}$, where $\bar{\rho} = (-\ln L)^{1/2}$. From this value of $\bar{\rho}$, $k_0$was calculated, using the relation $Z = k_0\bar{\rho}$.

4. *Experimental results and discussion*

Taking into account all observers and generalization, the graph indicates the distribution of charges of projectile fragments having $1 \leq Z \leq 3$. It is clear from the graph that majority of the charges are distributed sharply at $Z = 1, 2$ and 3. The peaks are more pronounced at $Z = 2$ and $Z = 3$ and less pronounced at $Z = 1$. Among three peaks for $Z = 1, 2$ and 3, it is clear that the peak for $Z = 2$ is very significant because most charges are concentrated in the closest vicinity to $Z = 2$. In our sample of ^{28}Si–AgBr interactions, however, no fractional charge was detected. Figure 1 indicates the distribution of charges of projectile fragments with $Z = 1, 2$ and 3. From the figure, it is evident that the charges are distributed sharply at $Z = 1, 2$ and 3. The detailed data of measurement and statistical analysis

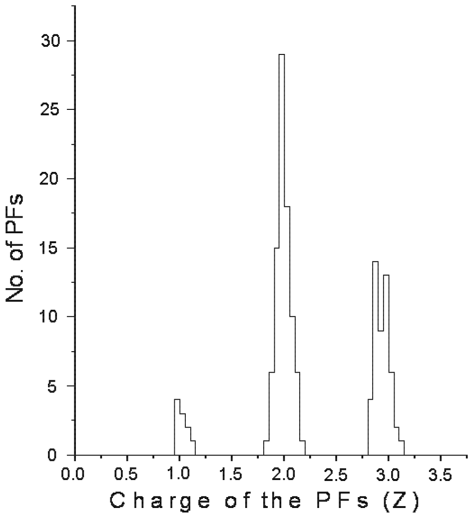

Fig. 1. Results for the distribution of the charge (Z) of the projectile fragments emitted in ^{28}Si*–emulsion interaction at 14.5* GeV *per nucleon.*

TABLE 1. Results of charge measurements of projectile fragments with $1 \leq Z \leq 3$. $k_0 = Z/\bar{\rho}$, *where* $\bar{\rho} = (-\ln L)^{1/2}$ *and* L *is the lacunarity or fractional transparency of the track structure.*

Z	No. of tracks	$k_0 = Z/\bar{\rho}$	Dispersion (D_Z)	No. of PFs with charge beyond $Z \pm 3D_Z$
1	10	3.389	0.053	0
2	86	3.429	0.081	0
3	49	3.729	0.081	0

are presented in Table 1. To determine whether any candidate really assumes a fractional charge, one has to be sure about the width of the distribution of the integer charges, which is expected from statistical fluctuation of the charges. So we measured the dispersion (D_Z) of the charge distribution, in terms of weighted standard deviation around $Z = 1, 2$ and 3, and checked if there was any candidate with charge lying beyond $Z \pm 3D_Z$. Table 1 shows that this experiment doesn't have a single candidate of a projectile fragment with charge beyond $Z \pm 3D_Z$. The track saturation, i.e., the conglomeration of Ag grains into the blobs, may distort the linear relationship between the mean gap length and charge (Z) of the ionizing track ($g \approx Z^2$). As Z increases, the effect depends on the quality of development of emulsion pellicle and that of the emulsion batch itself. Actually, this is the reason which restricts us to measure charges of PFs having $1 \leq Z \leq 3$.

5. Conclusion

Our aim was to search for fractionally charged PFs. So we performed this experiment since no measurement of projectile fragments using this method has been reported so far. Further, to have a comprehensive information about the presence of fractionally-charged projectile fragments, one should have data on all possible energies available in the accelerator beams. We conducted a similar type of experiment using ^{16}O–AgBr interactions at 60 AGeV [12], and we also got negative results. We wanted to see what happens if such interaction be taken at energy below and above 60 AGeV. By this time we got another beam of energy 14.5 AGeV available in the accelerator. The above reason prompted us to undertake this present experiment. Here ^{28}Si–AgBr emulsion interaction at 14.5 AGeV has been studied, The result is negative as in our previous experiment. Here we also have found no fractionally charged projectile fragment, as all the PFs lie within three times the dispersion (D_Z) around the integer charges. Further study with energy higher than 60 AGeV would be interesting.

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MJERENJE NABOJA DIJELOVA ČESTICA SNOPA – TRAŽENJE ČESTICA S NECIJELIM NABOJEM

Mjerenje naboja ($1 \leq Z \leq 3$) dijelova čestica upadnog snopa proizvedenih u međudjelovanju jezgri silicija u emulziji na 14.5 AGeV načinjeno je primjenom metode isprekidanosti traga čestice, rabeći nukleografsku emulziju kao detektor. U ovom istraživanju nije nađena čestica s necijelim nabojem, već samo čestice s cjelobrojnim nabojima $Z = 1, 2$ i 3.