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Search for Relativistic Projectile Fragments with Charges of 4/3, 5/3, 7/3, and 8/3

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ABSTRACT

We present the results of 1179 precise charge measurements carried out on $1 \leq Z \leq 3$ projectile fragment nuclei from relativistic nucleus-nucleus collisions in nuclear emulsion. We find no evidence for the existence of third-integral fractionally charged projectile fragments, particularly for those with charges 5/3 and 7/3.

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Recent speculation on the cause of the anomalously short reaction mean free paths of projectile fragmentation products (PF's) produced from relativistic heavy-ion (RHI) collisions with emulsion nuclei [1-5] has led to the suggestion, among others, that "anomalons" (i.e., the fraction of PF's exhibiting this anomaly) are nuclei with bound third-integral charges [6-9]. For this to happen it is assumed that local SU(3) gauge symmetry is somehow broken and all eight gluons acquire a small mass; in addition to an unconfined gluon field (which could possibly extend beyond the range of the normal nuclear force and hence explain the enhanced cross sections of these anomalous PF's), there would be unconfined quarks. Such color sources would have nonintegral electric charge, and, because of the strong color polarizability of nuclear matter, the color source would be tightly bound to nuclei, thus lowering the threshold for production from that expected from p-p collisions or e^+e^- collisions [6].

In an earlier paper [10] we described in detail how to measure the nuclear charge of $1 \leq Z \leq 3$ PF's of RHI collisions in nuclear emulsion: specifically, measurements based on the lacunarity, i.e., fractional transparency, of the linear track structure of such ionization tracks yield a precision of σ = 0.05 charge units for Z=1 and Z=2 and about σ = 0.07 charge units for Z=3. We now present the results of 1179 measurements carried out by three observers on $1 \leq Z \leq 3$ PF's produced by the extranuclear cascade of interactions initiated by a 1.88A GeV ^{56}Fe beam incident upon a stack of Ilford G-5 emulsion pellicles.

We show in fig. 1 a plot of the charge distribution for $1 \leq Z \leq 3$ PF's of all generations and all observers. No corrections of any kind described in the earlier paper [10] have been made to these data. Recall that $Z = k_0\rho$, where

$\rho = \sqrt{-\ln L}$, with L = lacunarity, i.e., fractional transparency. (1)

For Z=3 PF's, we measured the lacunarity of the ionization tracks directly; for Z=1 and Z=2 PF's, we measured the opacity ϕ, i.e., the fraction of track made up of blobs, and obtained L by the simple relation $L = 1 - \phi$. Each group of charges was separately normalized to the $\bar{\rho}_Z$ of its subsample of PF charge measurements produced directly from the ^{56}Fe beam [i.e., $k_0(Z) = Z/\bar{\rho}_Z$]. As was discussed in ref. [10], such a subsample provides a good estimate of the true proportionality between Z and ρ since it decreases the velocity spread of the population. It was also shown that the distribution of measured charge for a given Z (aside from systematics due to differences between observers, depth and lateral gradients in the sensitivities of the emulsion pellicles, and changes in one observer's mean lacunarity or opacity with time) was very nearly Gaussian, with mean $\bar{Z}$ ($=k_0\bar{\rho}$) and dispersion D_Z. The values of $k_0(Z)$ and D_Z derived therefrom are shown in table 1. Not displayed are the charge measurements for $4 \leq Z \leq 6$, since the saturation of the grain density beyond Z=3 makes measurement insufficiently precise to resolve third-integral charges.

The salient feature of fig. 1 is that all charge measurements for each PF are distributed sharply around their integer means. With the possible exception of the set of measurements scattered around Z = 7/3, there is no indication that PF's of third-integral charge are produced with the same relative abundance as reported for anomalons to date (~6% for $3 \leq Z \leq 26$) [1-4]. Since a relativistic track of $Z^* = 2/3$ would have a grain density of only 7 grains per 100 microns in our emulsion stack, it is improbable that any observer could have detected such a lightly ionizing track. Hence we limit the test of fractionally charged PF's to $Z^* = 4/3$, 5/3, 7/3, and 8/3 (henceforth Z^* will be used to denote these hypothetical fractional charges.

We can quantitatively test for the existence of fractional charge by first asking how many charge measurements lie outside intervals of $\pm 3D_Z$ centered around means of Z = 1.00, 2.00, and 3.00. Recall that we obtained the values of D_Z (displayed in table 1) from the approximately Gaussian parent distributions of charge measurements made on $1 \leq Z \leq 3$ PF's produced directly from the beam. Of the total 1179 measurements, 15 exceed the $\pm 3D_Z$ limits (seen as the black squares in fig. 1), where we would expect about three. One observer subsequently remeasured several times the charge of each candidate, making a correction for apparent charge increase due to energy losses by ionization of its ancestor nuclei. We rejected candidates whose improved charge estimate was compatible with an integer mean, as well as Z=1 PF candidates with emission space angle $\theta_{sp} > 10°$ and Z=2 PF candidates with $\theta_{sp} > 6°$, since such large angles would imply large momentum transfers, and one can then no longer assume that the projectile fragments have nearly the same velocity as their parent projectiles [11].

We now ask, of the remaining candidates, how many are compatible with the hypothesis that these charge measurements come from distributions centered at $Z^* = 4/3$, 5/3, 7/3, and 8/3. Five candidates remain: two are $-5.4\sigma_{Z*}$ and $-4.1\sigma_{Z*}$ from $Z^* = 1.33$, and three are $-4.1\sigma_{Z*}$, $-6.1\sigma_{Z*}$, and $-0.5\sigma_{Z*}$ from $Z^* = 2.33$. The error in the mean $\sigma_{Z*} = D_{Z*}/\sqrt{N}$, N = number of independent measurements, where $D_{Z*} = 0.055$ for $Z^* = 1.33$ and $D_{Z*} = 0.057$ for $Z^* = 2.33$ (a dispersion interpolated from $D_{Z=2} = 0.052$ for Z=2 and $D_{Z=3} = 0.068$ for Z=3). Of these five, only the charge measurement at $-0.5\sigma_{Z*}$ from $Z^* = 2.33$ ($Z_{meas} = 2.32 \pm 0.03$) presents any difficulty. We independently determined the $p\beta$ of this third generation PF by measuring its multiple Coulomb scattering in the emulsion stack. The estimated value of the energy for a ^{4}He from this measurement is 580 ± 140A MeV, which agrees with the value of 490A MeV obtained if we use the apparent charge (i.e., restricted energy loss) to estimate the energy. We conclude, then that this Z=2 track was most likely a low-energy fragment. In fact, all these last five candidates occur at the high end of distributions centered at Z=1.00 and 2.00, suggesting that these candidates are really victims of larger energy losses than can be accounted for by dE/dx alone.

Therefore, we conclude that we observed in 1179 charge measurements no PF's with $Z^* = 4/3$, 5/3, 7/3, or 8/3. This puts an upper limit of 3×10^{-3} at a confidence level of 99.9% on the relative number of such PF's with a charge differing from an integer by 1/3 charge units. This upper limit is strictly true only if the relative occurrence of fractionally charged PF's is independent of charge. Our result is in agreement with a similar fractional charge search recently carried out by Price et al. [12] on $10 \leq Z \leq 18$ PF's from the cascade of interactions produced by a 1.85A GeV ^{40}Ar beam incident on CR-39 plastic detector.

Evidence is mounting in favor of a short mean free path effect for Z=1 and Z=2 PF's in addition to $3 \leq Z \leq 26$ PF's ([1]; as of recently, see the contributions of Judek, El-Nadi et al., Ganssauge et al., Karant et al., and Otterlund et al. to the 6th High Energy Heavy Ion Study and 2nd Workshop on Anomalons [13]). Let us assume that a certain fraction, α, of Z=2 PF's produced from RHI collisions exhibit an anomalously short mean free path, λ_α; and, furthermore, that these PF's actually have nonintegral charge $Z^* = 2 \pm 1/3$. We choose from our Z=2 PF charge measurements a subsample of data comprised solely of PF's that interact at a distance $D \leq D_{max}$ from their emission vertices, with the expectation of increasing the relative proportion of anomalous Z=2 PF's that were charge measured. The fraction, A, of anomalous PF's in a sample of tracks that interact within an interval of distance $D_1 \leq D \leq D_2$ (= D_{max}) from their emission vertices is given by

$$A\ (D_1 \leq D \leq D_2) = \frac{\alpha\left(e^{-D_1/\lambda_\alpha} - e^{-D_2/\lambda_\alpha}\right)}{\left(1-\alpha\right)\left(e^{-D_1/\lambda_Z} - e^{-D_2/\lambda_Z}\right) + \alpha\left(e^{-D_1/\lambda_\alpha} - e^{-D_2/\lambda_\alpha}\right)} \quad (2)$$

where λ_Z = mean free path of beam nuclei of charge Z. For the sample in question, $D_1 = 0.1$ cm (the minimum distance needed to make a charge measurement), and D_2 varied between 3 and 6 cm for different plates within the stack. Assume that i) $\alpha = 0.06$ for all generations of PF's (ignoring the possibility of "memory" effects in subsequent generations [5]), ii) λ_α = 2.5 cm, and iii) λ_Z = 21.0 cm. We would expect, then, under our hypothesis, to find in the subsample of 305 tracks interacting within the specified intervals, 68 such fractionally charged candidates, when we see none. In fact, if we assume that our hypothesis is still true, then we can put an upper limit of 0.013 at a confidence level of 99.9% on A, the relative number of fractionally charged Z=2 PF's that would have appeared in our subsample if such objects were produced with frequency α. This in turn gives an upper limit on α of 0.0029 at a 99.9% confidence level, a value that appears to contradict the data to date.

In summary, if a short mean free path effect does become firmly established for Z=2 PF's, fractional charges bound to nuclei will be unable to explain it. The explanation for anomalons in the PF's from relativistic nucleus-nucleus collisions must lie elsewhere.

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Table 1. Results of charge measurements on $1 \leqslant Z \leqslant 3$ projectile fragments. $k_o = Z/\bar{\rho}_Z$, where $\rho = \sqrt{-\ln L}$, L = lacunarity, i.e., fractional transparency of track structure (see ref. 10). $\sigma_{Z*} = D_{Z*}/\sqrt{N}$, N = number of independent measurements. For $Z* = 1.33$ and 2.33, $D_{Z*} = 0.055$ and 0.057, respectively.

	# of tracks measured	$k_o(=Z/\bar{\rho})$ and D_Z for secondary PF's	$N > \pm 3D_Z$ from integer mean Z before/after remeasurement and energy loss corrections, etc.	Improved charge estimates (deviation from mean Z* in units of σ_{Z*}) of remaining candidates
Z = 1	108	$k_o = 3.096$ $D_Z = 0.055$	2 / 2	$Z* = 1.33$ / 1.160 ± 0.032 $(-5.4\sigma_{Z*})$ $Z* = 1.33$ \ 1.203 ± 0.032 $(-4.1\sigma_{Z*})$
Z = 2	1006	$k_o = 3.137$ $D_Z = 0.052$	13 / 3	$Z* = 2.33$ / 2.199 ± 0.033 $(-4.1\sigma_{Z*})$ $Z* = 2.33$ 2.131 ± 0.033 $(-6.1\sigma_{Z*})$ $Z* = 2.33$ \ 2.319 ± 0.029 $(-0.5\sigma_{Z*})$
Z = 3	65	$k_o = 3.116$ $D_Z = 0.068$	0 / 0	------

Figure Caption

Fig. 1. Charge distribution of $1 \leq Z \leq 3$ projectile fragments from the extranuclear cascade of interactions from a 1.88A GeV ^{56}Fe beam, all generations and all observers. The blackened squares are those measurements that lie outside intervals of $\pm 3D_Z$ centered around the integer means Z = 1.0, 2.0, and 3.0. Not shown are the charge measurements of $4 \leq Z \leq 6$ PF's.

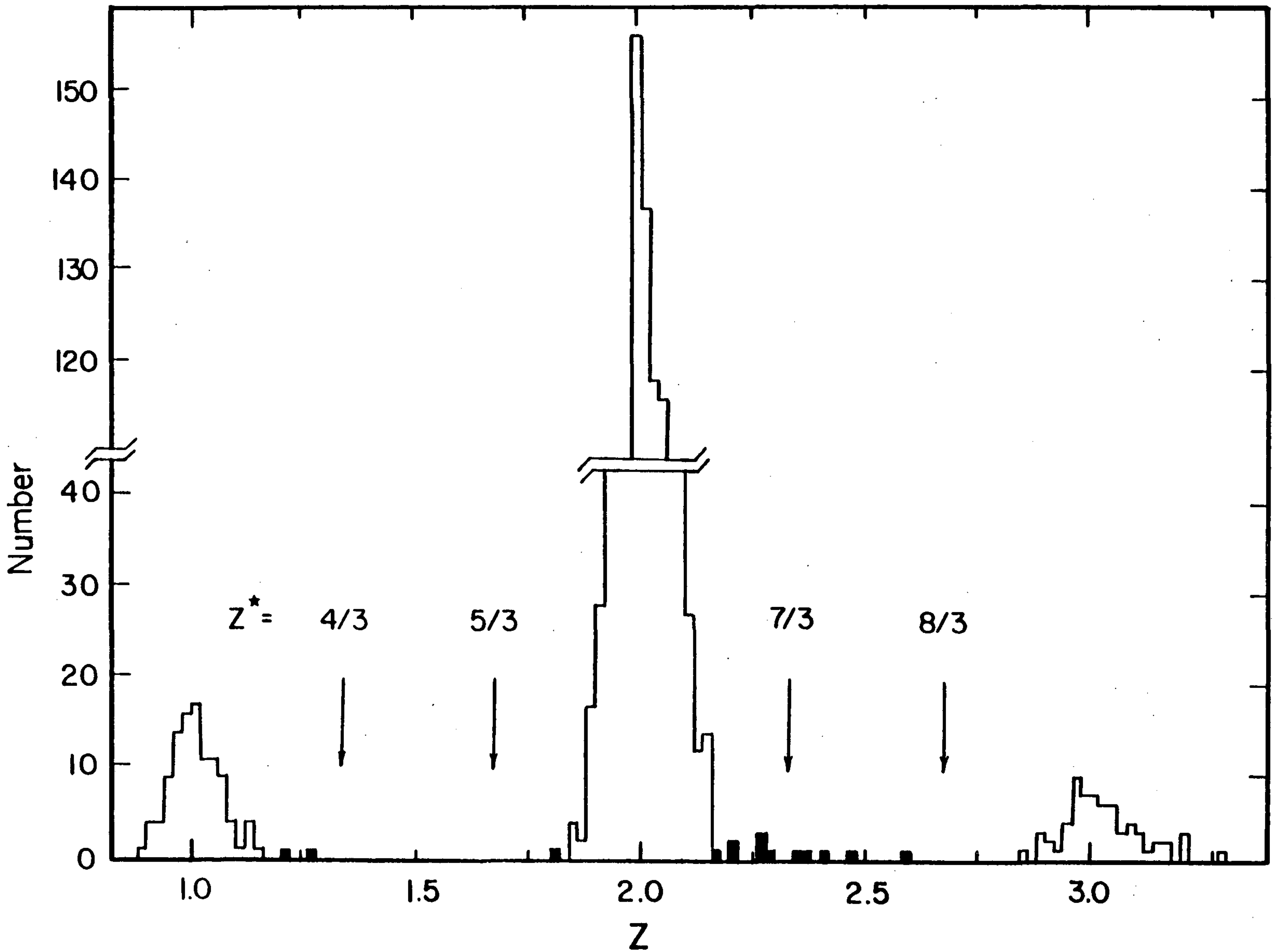

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Fig. 1

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