Search for Nonintegrally Charged Projectile Fragments in Relativistic Nucleus-Nucleus Collisions

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(Received 1 November 1982)

Using dioctyl-phthalate–doped CR-39 plastic track detectors with charge resolution $\sigma_Z \approx 0.06e$, the authors have made the first dynamic search for fractionally charged particles bound to nuclei. They find, from charge measurements in the first ~2 cm after production, that no more than 3×10^{-3} (95% confidence level) of the projectile fragments of 1.85-GeV/u ^{40}Ar interactions with $10 \leq Z < 18$ have charges differing from an integer by as much as $0.3e$. This rules out explanations of anomalons based on models in which the anomalons have nonintegral charge in such charge range.

PACS numbers: 14.80.Dq, 25.70.Np

Using nuclear emulsion as both target and detector, several groups[1-4] have found that a statistically significant fraction of the projectile fragments of high-energy nuclei exhibit mean free paths that are anomalously short in the first few centimeters after their points of origin but that return to the values for normal primary nuclei after ~3 cm (~10^{-10} sec). Within the limited statistics, the effect seems to occur in peripheral collisions with small momentum transfer leading to projectile fragments with charges throughout the region $3 \leq Z \leq 25$, to be more pronounced in interactions with light than with heavy emulsion nuclei,[3] and possibly to have an energy threshold[5] at ~1 GeV/u. The combined data of nearly 3000 secondary interactions are equally well parametrized in either of two ways: (1) About 6% of the projectile fragments are anomalous, having a mean free path in emulsion of only ~2.5 cm (Ref. 2), compared with values from ~9 to ~14 cm for primary nuclei with $3 \leq Z \leq 26$. (2) Nearly all fragments initially have a mean free path shortened by a factor ~0.65 but decay with a decay length 0.85 cm into normal nuclei (Ref. 4). The name "anomalons" has been coined to denote the (unknown) fraction of projectile fragments with anomalously short mean free paths.

A severe drawback of experiments to date is that one does not know exactly which fragments are anomalons nor any of their nuclear properties other than their very large cross sections. The recent negative results of Liss *et al.*,[6] who used lead-glass detectors to search for delayed high-energy γ rays from projectile fragments of 940-MeV/u Fe-Fe interactions, cast doubt on models in which anomalons decay electromagnetically to normal nuclei.

Several authors, stimulated by the work of De Rujula, Giles, and Jaffe[7] on broken QCD, have proposed that anomalons are objects with unusual quark configurations or are droplets of quark matter, possibly stabilized by an unconfined quark.[8-12] If the latter were true, individual anomalons could be identified, in principle, by showing that they possess nonintegral electric charge. Except at charges $Z=1$ to 2, where the effect appears to be absent, the resolution of nuclear emulsion is inadequate to resolve fractional charge. Another technique is therefore required.

Tarlé, Ahlen, and Price[13] have recently shown that the CR-39 plastic track detector, when properly made, has a uniquely high charge resolution over a wide range of charges including the region of interest to anomalon studies. In the simplest case (relevant here) of particles with fixed velocity and angle of incidence, the diameter of the etch pit formed at the intersection of a particle's trajectory with the top or bottom surface of the plastic sheet is a monotonic function of Z. (In the general case of unknown Z and β and arbitrary angle of incidence the minor axis of the etch-pit mouth and its rate of change from sheet to sheet of a stack of plastic detectors give Z and β.[14]) Tarlé, Ahlen, and Price showed, by measurements of up to four successive etch pits—two on the top and bottom of two successive sheets —that the charge standard deviation for relativistic heavy nuclei in CR-39 etched as described[13] is given by $\sigma_Z/e = 0.23/\sqrt{n}$, where n is the number of etch pits measured. They pointed out that for large n the resolution should be sufficient to detect quarks bound to fast nuclei. We have used this technique, with $n=16$, in the present study.

As part of a comprehensive study of anomalons produced in peripheral collisions we bombarded a stack of 400 sheets of 0.64-mm-thick CR-39 with 5×10^4 normally incident 1.85-GeV/u ^{40}Ar ions. We etched the odd-numbered sheets, which were pure CR-39, in 6.25*N* NaOH at 70 °C for 40 h; under these conditions projectile fragments with $Z \geq 6$ produced detectable etch pits. We etched the even-numbered sheets, which were CR-39(DOP), i.e., doped with 1% dioctyl phthalate,[13] in NaOH at 40 °C for 480 h. For high-resolution studies the superior optical quality of its etched surfaces and etch-pit mouths makes CR-39 (DOP) preferable to pure CR-39 despite its somewhat lower sensitivity (minimum detectable $Z = 9$ instead of 6). In the present study we used only the etch pits in the CR-39 (DOP) sheets.

In our first search for fractional charges we followed 1437 ^{40}Ar tracks through the first 97 sheets of the stack, locating the points of interaction for which $\Delta Z \geq 1$. We obtained an interaction length $\lambda_{\Delta Z \geq 1} = 9.55 \pm 0.46$ cm, which agrees with the 9.51 cm calculated from an overlap model for charge-changing cross section, $\sigma = [r_0(A_T{}^{1/3} + A_B{}^{1/3}) - b]^2$, with $r_0 = 1.38$ fm, $b = 0.83$ fm, taken from Westfall *et al.*[15] This, together with a measurement in a separate CR-39 stack of $\lambda_{\Delta Z \geq 1}$ for a primary ^{20}Ne beam[16] that agrees with the calculated value, indicates that our efficiency for detecting charge-changing interactions is close to 100%. The mean values of etch-pit diameter D as a function of Z varied by up to 5% from sheet to sheet and by less than 2% within a given sheet. For each sheet surface we fitted the diameters at the charge peaks by a linear function of charge with no correction for variation within the sheet. The charge resolution for etch pits measured on a single sheet surface was $\sigma_Z/e \approx 0.23$. A measurement of as few as two etch-pit diameters before and two after an interaction with $\Delta Z \geq 1$ suffices to establish that the interaction has occurred.

In the even-numbered sheets from 98 to 112 we measured 16 successive etch-pit diameters from 248 projectile fragments of the 1437 Ar nuclei with $10 \leq Z \leq 17$ as well as 115 primary Ar nuclei. Figure 1 shows the resulting charge distribution. Each of the charge peaks is consistent with a Gaussian distribution characterized by a charge standard deviation $\sigma_Z/e \approx 0.06$, as expected if the relation $\sigma_Z/e = 0.23/\sqrt{n}$ holds for $n = 16$.

We emphasize that the widths of the Gaussians in Fig. 1 are dominated by detector resolution and that the velocity distribution of the projectile fragments makes a negligible contribution. Greiner *et al.*[17] have shown that both parallel and perpendicular momentum transfers to projectile fragments of high-energy nucleus-nucleus collisions follow a Gaussian distribution with a width of only ~150 MeV/c in the projectile frame, for momentum transfers less than ~450 MeV/c. A projectile fragment thus has essentially the same velocity as the projectile. The rarity of large momentum transfers in projectile fragmentation reduces the task of identifying the charges of projectile fragments to the determination of a single parameter, which depends only on charge, and makes our search for fractional charges practicable.

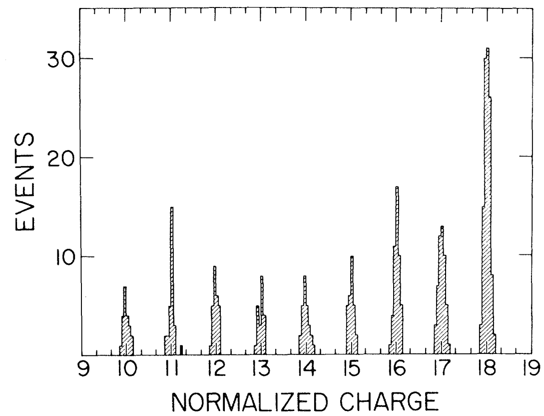

FIG. 1. Charge distribution of projectile fragments from 1.85-GeV/u ^{40}Ar interactions measured at a depth of 6.2 cm in CR-39 stack. After making a cut to remove all but 10% of the primary Ar events, 16 etch pits were measured for each event, leading to a $\sigma_Z = 0.06e$. Abscissa is labeled at intervals of $e/3$. Bin width is $0.05e$.

One event in Fig. 1 falls 4σ beyond the peak at $Z = 11$ and 2σ below the expected position of a nucleus with fractional charge $\frac{34}{3}$. Its Ar parent fragmented in sheet 91 and the projectile fragment interacted again in sheet 136, dropping in charge below the minimum detectable value $Z = 6$. Figure 2 shows data for the Ar parent, which had mean charge $\bar{Z} = 18.08 \pm 0.05$, and for the fragment. On the basis of the sixteen measurements in sheets 98 to 112 and an additional six measurements in sheets 92, 94, and 96, and with the assumption that it had the same velocity, $\beta = 0.937$, as its Ar parent at the time of interaction, its mean charge would be $\bar{Z} = 11.23 \pm 0.04$. The more likely explanation, however, is that its charge was actually $Z = 11$ and that the fragment emerged from the collision with a velocity $\beta = 11 \times 0.937/11.23 = 0.918$, which required a momentum loss $\Delta p_{\parallel} = -2.97$ GeV/c in the projectile frame. (In the short path length available between sheets 91 and 136 the difference in slowing of particles with $Z = 11.23$, $\beta = 0.918$, and with

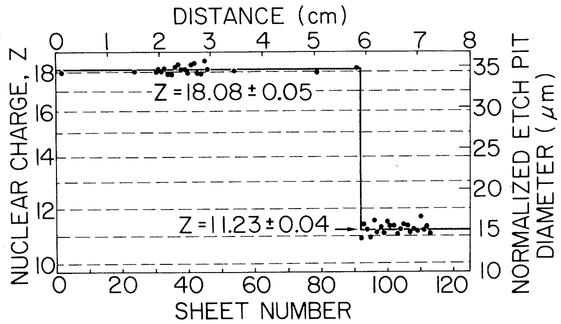

FIG. 2. Charge measurements for the one event with an apparent nonintegral charge in Fig. 1.

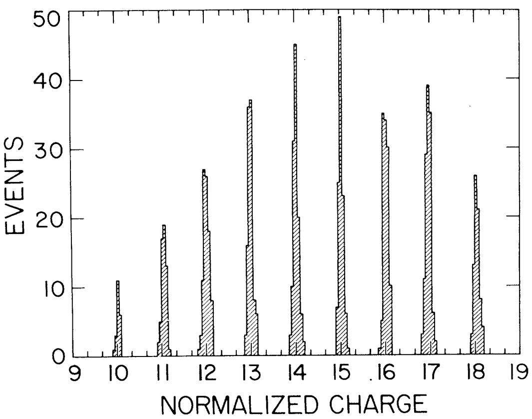

FIG. 3. Charge distribution of projectile fragments measured within 1.7 cm of their points of interaction. 75 primary Ar nuclei were included for calibration.

$Z = 11$, $\beta = 0.937$ would be undetectably small.) Clearly, a momentum transfer as large as 2.97 GeV/c is unusual, but it is not in conflict with any previous data. In fact, deviations from a Gaussian distribution at large momentum transfer have been seen for both projectile[18] and target[19,20] fragments.

The fragments measured in Fig. 1 interacted at distances from 0 to 6.2 cm upstream from where we measured their charges. In our second search, to increase the possible yield of anomalons we scanned sheet 30, locating 822 fragments that entered the stack as 1.85-GeV/u ^{40}Ar ions and interacted less than 1.7 cm before reaching sheet 30. Figure 3 shows the charge distribution of the 747 of these fragments that passed through sheet 44 without interacting again (thus permitting 16 successive etch pits to be measured), together with 75 primary Ar nuclei. In addition, we measured 16 etch pits for 32 nuclei that fragmented before sheet 16 and fragmented again between sheets 30 and 44. These nuclei, having fragmented twice within a distance of ~1 cm, might be expected to be an enriched sample of anomalons. We found no fragments with nonintegral charge or with large $\Delta p_{\parallel}$.

These negative results of our study of the charges of 1027 projectile fragments, of which the majority were measured within 1.7 cm of their interaction points, enable us to set a 95%-confidence-level upper limit of 3×10^{-3} on the fraction of projectile fragments with charge differing from an integer by as much as 0.3. If 6% of the fragments had $\lambda \approx 2.5$ cm and fractional charge, about 30 of them should have shown up in Fig. 1 or Fig. 3. In order for 6% of the fragments to have fractional charge and be missed in our search, they would have to have interacted with λ less than ~0.5 cm (95% confidence level). If all of the fragments were fractionally charged and had 65% of the normal mean free path but decayed with $\tau c \approx 0.85$ cm as proposed in Ref. 4, we should have detected more than 100.

Independent of the question of the nature of anomalons, there is considerable interest in the possibility that quark deconfinement may be facilitated by strong nuclear binding and that such fractionally charged matter might be produced in high-energy nucleus-nucleus collisions either in the cosmic rays or in some future accelerator. Suppose that heavy nuclei ($Z \gtrsim 20$) in the cosmic rays at energies above 10 GeV/u produce stable, fractionally charged nuclei with a cross section 10^{-4} b that stop in the Earth's crust. The irradiation time of the Earth's crust is limited by its erosion rate, which has been estimated to be ~1 m per 10^6 yr, to within a factor 10, by considering the total influx of soil matter into the oceans (Refs. 21,22). This would result in a steady-state concentration of fractional charges of ~10^{-20} per nucleon in the absence of chemical fractionation. Such a concentration has been reported by LaRue, Phillips, and Fairbank.[23] The CR-39 technique we have used here ought to be able to detect fractionally charged fast fragments at a concentration as low as 10^{-4}, produced with a cross section ~10^{-4} b in a future high-energy heavy-ion accelerator.

We are indebted to Bojana Grabez for her assistance in the measurements, to Shi-lun Guo for determining the interaction length of ^{20}Ne, to the Bevalac staff for the irradiation, and to the U. S. Department of Energy and NASA for support.

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Vector Gluonium as a Possible Explanation for Anomalous ψ Decays

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Recent experiments at SLAC show unexpectedly large values for the ratios (1) $B(\psi\to\rho\pi)/B(\psi'\to\rho\pi)$ and (2) $B(\psi\to K^*\bar{K})/B(\psi'\to K^*\bar{K})$. It is proposed that these anomalies are caused by the mixing of the ground-state isoscalar vector mesons (ω, φ, ψ) with a $J^{PC}=1^{--}$ vector glueball (O) which was first postulated by Freund and Nambu in 1975. Its mass is estimated at $\simeq 2.4$ GeV and direct experimental searches for the O are suggested.

PACS numbers: 14.40.Cs, 13.25.+m

Recent experiments at SLAC have revealed a very interesting set of anomalies in ψ, ψ' decays.[1] Measurements of the ψ, ψ' decay widths for the exclusive reactions $\psi\to X$, $\psi'\to X$ for $X=\bar{p}p$, $\bar{p}p\pi^0$, $K^+K^-\pi^+\pi^-$, $2\pi^+2\pi^-\pi^0$, $\omega\pi^+\pi^-$, $3\pi^+3\pi^-\pi^0$, $K^{*\pm}K^{\mp}$, $\rho\pi$, and e^+e^- are now available. From these data it is found that for each of these modes but two (namely $K^*\bar{K}$ and $\rho\pi$) the ratio

$$R_{\psi'\psi}\equiv B(\psi'\to X)/B(\psi\to X) \tag{1}$$

is constant (within experimental errors), being given by

$$R_{\psi'\psi}=(12\pm 2)\%. \tag{2}$$

Theoretically, if the three-glue continuum produces the final hadronic state, such a constant (i.e., independent of X) value for the ratio is easy to understand since one expects[2]

$$B(\psi'\to X)/B(\psi\to X) = [|\psi'(0)|^2/|\psi(0)|^2]\Gamma_{tot}^{\psi}/\Gamma_{tot}^{\psi'}. \tag{3}$$

However, for the $\rho\pi$ and $K^*\bar{K}$ modes it is found that (to 90% confidence level)[1]

$$B(\psi'\to K^*\bar{K})/B(\psi\to K^*\bar{K})<1.96\% \tag{4}$$

and

$$B(\psi'\to\rho\pi)/(B\psi\to\rho\pi)<1.25\%, \tag{5}$$

each one of which is many times smaller than the theoretical expectations of $(12\pm 2)\%$. So far no theoretical solution to this puzzle has been advanced. We suggest a very simple, but, we be-

