Charges and Angular Distributions of Fast Fragments Produced in 3.2-TeV ^{16}O Collisions with Pb

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Out of 30000 interactions of 3.2-TeV ^{16}O nuclei in Pb, we found that no fast fragments had a charge $Z > 8$, none with $Z \gtrsim 5.5$ had a charge that differed from an integer by as much as $\frac{1}{3}$, and none with $Z \gtrsim 5.5$ had an angle to the beam > 0.8 mrad. The cross section for production of a fast fragment with $Z > 8$ or a stable particle with charge $\frac{19}{3}e$, $\frac{20}{3}e$, $\frac{22}{3}e$, or $\frac{23}{3}e$ is less than 240 μb at 90% confidence level. Using a measurement technique with a position resolution of 30 μrad, we found the transverse-momentum distributions for C, N, and O to be Gaussians with widths $\simeq 100$ MeV/c, similar to those measured in projectile fragmentation of ^{16}O at a factor 100 lower energy.

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There is no solid theoretical basis for the popular idea of absolute quark confinement. Several authors[1-4] have proposed mechanisms by which free-quark production, though inhibited in electron-positron or proton-antiproton collisions, could occur in high-energy nucleus-nucleus collisions. De Rújula *et al.*,[1] Chapline,[2] and Arbuzov[3] have suggested that free quarks would strongly bind to nuclei, forming nonintegrally charged quark-nucleus complexes (QNC's) containing 10 to 20 nucleons. Gyulassy[5] and Arbuzov[3] have concluded that the energy of the ion beams available at the Berkeley Bevalac and at the Dubna synchrophasotron, where searches of QNC's have been carried out,[6-9] is probably too low to achieve quark separation. Their calculations suggest that at center-of-mass energies above $\simeq 2$ GeV/nucleon, attainable now at the CERN superproton synchrotron (SPS), free quarks might be produced. A QNC might be detectable in flight as a particle with large, nonintegral charge, given a detector system with sufficiently high resolution. It has been suggested by others[10-12] that quark-gluon matter might take the form of a long-lived droplet of abnormally dense matter that would stand out from normal matter by having an abnormally large mass defect and a charge (perhaps integral) higher than that of the individual nuclei participating in a nucleus-nucleus collision, as a result of fusion with part of a target nucleus. One might also expect fragments to have unusually high transverse momentum p_T. Searches for such abnormal objects at the Bevalac have given null results.[13,14]

With the availability of a beam of 3.2-TeV ^{16}O nuclei at the CERN SPS, we have searched for collision products with unusual electric charge or unusually high p_T that might signal the production of metastable droplets of quark matter with nonintegral charge or abnormally high density. Our technique uses the fact that when particles of charge Z (and with velocity βc and angle of incidence both fixed) pass through a sheet of CR-39 plastic track detector, the diameter of the etchpit produced in subsequent chemical etching is a monotonic function of Z. In an experiment at the Bevalac[6] this technique has been used to set an upper limit (95% confidence level) of 0.003 on the fraction of projectile fragments of 74-GeV ^{40}Ar interactions in plastic having nonintegral charge in the interval $10.33 \leq Z \leq 17.67$. In that experiment the resolution of a single measurement on Z was demonstrated to be $\sigma_Z \approx 0.23$, and it was shown that successive measurements of 16 etchpits per track led to a statistical accuracy of $\sigma_Z \approx 0.06$. In the present experiment the CR-39 detectors[15] are sensitive to values of $Z/\beta \gtrsim 5.5$.

Guided by models in which QNC's and abnormally dense droplets would be most readily produced within a large nuclear volume, we used a Pb slab 113 g/cm^2 thick ($=1.18$ mean free path for fragmentation with $\Delta A \geq 1$) as the target, followed by fifty sheets of 12×13.5 cm^2 CR-39 each $\simeq 0.1$ g/cm^2 thick. We irradiated this assembly at normal incidence with 3.2-TeV ^{16}O nuclei distributed in six spots each about 4 cm^2 in area. We etched some of the sheets for 30 h and some for 42 h in 6.25 normal NaOH solution at 70 °C to reveal conical etchpits at the intersections of trajectories of highly ionizing particles with the top and bottom surfaces of the plastic sheets.

By inspection in a stereomicroscope we found that visible etchpits fell into two qualitatively distinct groups: (1) those due to uninteracted ^{16}O nuclei and fast "projectile fragments" almost exactly parallel to the beam, and (2) those due to very slow "target fragments" at large angles to the beam. Our measurements with a Leitz Metalloplan microscope showed that, of the ^{16}O

nuclei that entered the target, $\simeq 70\%$ of them disintegrated in the Pb into fragments too light to detect, and $\simeq 30\%$ penetrated the target and emerged either as oxygen nuclei or as projectile fragments with $Z/\beta \gtrsim 5.5$ and at an angle $\theta < 1$ mrad to the beam. We now discuss how the quantities Z/β and θ are measured automatically.

To trace the trajectories of particles through many sheets, for each of the six spots we chose as fiducials two tracks of uninteracted oxygen nuclei at opposite corners of a rectangular scan area. For each spot the top and bottom of five sheets (=ten surfaces) were successively scanned automatically and independently with a motorized stage attached to the Leitz microscope and controlled by a VAX 11/750 computer. We used a Vicom Image Processor to digitize each of the set of overlapping rectangular fields of view seen by a Pulnix CCD camera attached to the microscope. With the 10× objective used, the images of circular etchpits due to nuclei of oxygen ($Z=8$), nitrogen ($Z=7$), and carbon ($Z=6$) contain about 245, 145, and 60 dark pixels, respectively, on a light background when viewed in transmitted light. Focusing was done automatically by interpolation between stage heights chosen manually for best focus at a lattice of positions selected before the scan.

In order to measure the size and location of the dark, circular etchpits, a threshold operation was applied to the gray value of each pixel of the image, forming a binary image (one bit per pixel). As soon as sixteen images were acquired, they were packed into a single sixteen-bit-deep image and transferred to the VAX over a direct-memory-access link. While the next batch of sixteen images was being acquired, the computer analyzed the previous batch by locating all sets of connected black pixels and storing those between preselected upper and lower size limits. The scanning and analysis required $\simeq 3$ sec per image. The density of etchpits was $\simeq 3$ per image, resulting in a scan rate of $\simeq 1$ etchpit/sec. On-line analysis provided the location and area of the mouth of each conical etchpit.

The scanning of the ten surfaces provided ten sets of events that could be attributed either to fast particles that penetrated all five sheets, to slow particles, or to background flaws in the plastic. In order to reject the last two catagories of events, visible on only one surface, the events of the ten sets were matched according to their location relative to the fiducial events. Because of the relatively low density of events, it was possible to do the matching with loose constraints on proximity, corresponding to a half cone angle of 60 mrad. We observed systematic deviations in the alignment of as much as 20 μm, which we attributed to astigmatism of the stage position encoders and to dilation of one sheet relative to another due to humidity changes. To correct for these effects, we chose an arbitrary reference surface (top surface of the first sheet) and allowed the position of the matching events on any other surface to "move" and match as well as possible the location on the reference surface, by an iterative procedure. It turned out that a linear transformation involving six parameters, defined for each spot of each surface, dramatically improved the alignment of the $\simeq 1600$ events of each spot, resulting in a residual alignment error of $\sigma \approx 0.6$ μm for a single etchpit. In what follows we refer to the "angle" of a fragment as that relative to the beam of ^{16}O nuclei. With ten etchpits distributed in five consecutive sheets, the error in angle resulting from alignment errors was $\simeq 0.2$ mrad.

To reduce this alignment error and study the p_T distribution of a sample of $\simeq 3500$ events with charges 8, 7, and 6 determined as described later, we analyzed etchpits at four additional surfaces 1 cm deeper in the stack. The angular errors in this data set decreased to the remarkably small values of 0.029 mrad for events with $Z=8$, 0.032 mrad for $Z=7$, and 0.043 mrad for $Z=6$. Figure 1 shows the angular distributions, fitted with Gaussians by a routine that computes the width, its error, and χ^2. The χ^2 criterion indicates that each distribution is well fitted with a Gaussian. In Table I column 3 gives the measured width, σ_θ, and its error. Note that σ_θ increases with a decrease in fragment charge by an amount that is far outside the error.

To infer the contribution due to projectile fragmentation, we assumed σ_θ to be the convolution of three Gaussians, due to angular resolution (column 2), multiple Coulomb scattering,[17] and projectile fragmentation.[16] To infer the variance due to projectile fragmen-

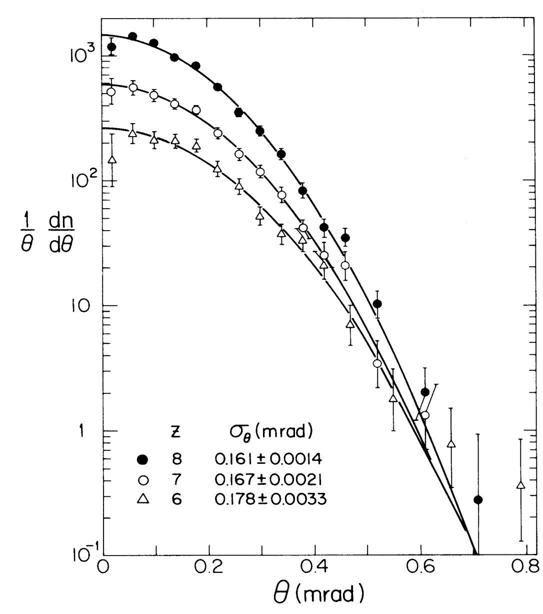

FIG. 1. Angular distributions of projectile fragments fitted with Gaussians.

TABLE I. Fragment angular distributions and transverse momenta.

Z	Resolution (mrad)	σ_θ(meas.)	σ_θ corrected for resolution[a]	Residual σ_θ due to proj. frag.[b]	σp_T calc. from col. 5 (MeV/c)	σp_T meas. at 34 GeV[c] (MeV/c)
8	0.029	0.161 ± 0.0014	0.158	$\equiv 0$	0	0
7	0.032	0.167 ± 0.0021	0.164	0.044 (if $A=14$)	123	109
6	0.043	0.178 ± 0.0033	0.173	0.070 (if $A=12$)	168	151

[a]Deconvolution of measured σ_θ (col. 3) from resolution (col. 2) assuming Gaussians.
[b]Deconvolution of corrected σ_θ (col. 4) from contribution due to multiple Coulomb scattering, assumed to be equal to that observed for the oxygen beam ($\sigma_\theta = 0.158$ mrad).
[c]Reference 16.

tation alone, we deconvolved by subtracting the variances for angular resolution and for multiple Coulomb scattering. Column 4 gives σ_θ corrected only for angular resolution. Column 5 gives σ_θ corrected for multiple Coulomb scattering as follows. We estimate from the total mass-changing cross section and the partial cross sections for fragmentation of ^{16}O in Pb at 34 GeV (Lindstrom *et al.*[18]) that 85% of the O in our data set represented unfragmented nuclei with $A/Z=2$ (the remainder being due mostly to ^{15}O), and that the average A/Z for the N and C fragments is also close to 2. Since most of the O nuclei in the data set had undergone no fragmentation, we assume that the width $\sigma_\theta = 0.158$ mrad for O in column 4 is due only to multiple Coulomb scattering. This value for σ_θ agrees rather well with that calculated in the small-angle approximation to multiple-scattering theory.[17] Since the multiple Coulomb scattering width goes as (Z/p), it should be the same for N and C fragments with the same momentum per nucleon and same A/Z as the ^{16}O beam. Subtraction of the variance for this width led to the values of σ_θ shown in column 5. Column 6 gives the corresponding widths in terms of transverse momentum, which can be seen to be similar to those previously reported for fragmentation of 34-GeV ^{16}O (Ref. 16). Thus, the increase in width of the angular distribution from O to N to C is consistent with momentum transfers during projectile fragmentation that are very similar in magnitude to those observed at energies a factor 10^2 lower.[16]

For the quark search, a valid event was required to have been found on at least eight surfaces out of ten. In this study 30000 ^{16}O nuclei fragmented in the Pb target. We analyzed tracks of 9378 fast particles, of which about 4000 were ^{16}O that penetrated the Pb without interacting. Figure 2 shows the distribution of average etchpit mouth areas of the 9378 events. One sees three clearly separated populations attributed to charges 6, 7, and 8. The efficiencies for finding the O, N, and C events with the selection defined above were 100%, 100%, and 70%, respectively. The charge standard deviation for measurements on a single surface was in the range 0.16 to 0.24, depending on post-etch surface roughness. The net charge standard deviation, based on the average of etchpit measurements on all ten surfaces, was $\sigma_Z \approx 0.065$. No event had a mean charge that deviated from an integer by as much as $\frac{1}{3}$.

We conclude that our experiment has placed an upper limit, at 90% confidence level, of $2.3/30000 = 8\times10^{-5}$ for production of particles with charge $\frac{19}{3}e$, $\frac{20}{3}e$, $\frac{22}{3}e$, or $\frac{23}{3}e$, as well as for particles with $Z>8$ such as would be produced by charge exchange or fusion of part of a target nucleus with a projectile. This limit is equivalent to a cross section of 240 μb. It applies to particles that survive passage through several centimeters of Pb and 1 cm of plastic. It also applies only within a limited range of values of longitudinal and transverse momentum transfer. For small δp_L, our cut at $\theta = 60$ mrad corresponds to an upper limit of $\delta p_T = 12.5$ GeV/c per nucleon for collisions to which our negative results apply. For small δp_T, the existence of sharp peaks in the etchpit mouth area, which is a measure of Z/β, indicates not only that charge is quantized in integral values but also that the velocities of the fragments deviate from c by only a small

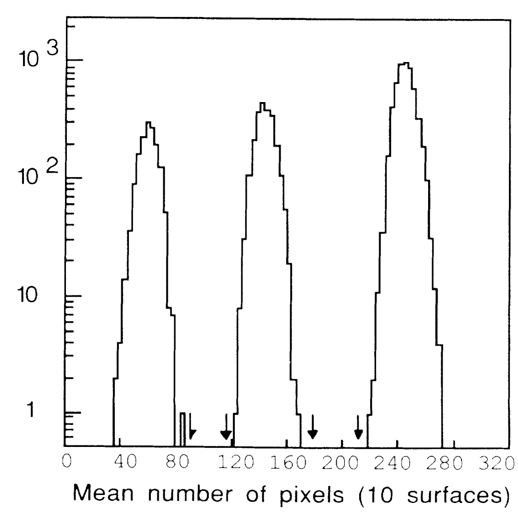

FIG. 2. Distribution of means values of etchpit mouth areas (in pixels) averaged over ten CR-39 detector surfaces. Charge standard deviation is 0.065e.

amount, enabling us to set a limit on the longitudinal momentum transfer. For example, for the nitrogen peak, inferring a lower limit $\beta \gtrsim 7/7.2 = 0.97$ corresponds to allowing values of δp_L only up to -217 GeV/c per nucleon in the laboratory frame or values of δp_L up to -26 GeV/c per nucleon in the projectile frame.

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