Search for fractionally charged nuclear fragments in relativistic heavy ion collisions

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We have investigated about 11 000 fragments with charge $6 \leqslant Z \leqslant 10$ produced by 200 GeV/nucleon ^{32}S projectiles and about 11 000 fragments with charge $6 \leqslant Z \leqslant 10$ produced by 10.6 GeV/nucleon ^{197}Au projectiles. Charges were measured using stacks of CR-39 plastic nuclear track detector foils. By multiple measurements on the surfaces of adjacent detector foils a charge resolution sufficient to identify fragment charges $Z \pm 1/3$ could be achieved over a minimum track length of a few mm. We found no evidence for a fast fragment with a charge differing from an integer by as much as 1/3.

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I. INTRODUCTION

In theoretical considerations it has been speculated that QCD might be slightly broken, i.e., quarks could in principle be unconfined [1,2]. Within this framework it is assumed that the production of free quarks in high energy particle interactions, e.g., [3,4], is strongly suppressed, since the energy which is put into the gluon field by the separation of the quarks is used for the creation of quark-antiquark pairs out of the vacuum. These combine with the separated quarks to form particles with an integer charge.

However, in nucleus-nucleus collisions it could be much more likely to produce fractionally charged particles. Due to a hypothetical reduction of the color field in nuclear matter by polarization of the nucleons, it might be possible to separate quarks and bind polarized nucleons without producing quarks out of the vacuum. As a consequence, fractionally charged fragments with high baryon numbers could be produced in high energy heavy ion collisions. It has been estimated [1,2], that these quark-nuclear complexes (QNC's) could bind up to 20 nucleons and could have a mean free path which is reduced up to a factor of 2 in comparison to that of normal nuclear fragments with the same mass. If these QNC's are formed in high energy heavy ion collisions and their lifetime is not too short, they should be observable as an admixture to the normal nuclear fragments.

The excellent charge resolution which can be achieved with CR-39 track detectors allows one to perform experiments to search for fractionally charged projectile fragments. Negative results have been reported by Gerbier *et al.* [5] for 200 GeV/nucleon ^{16}O projectiles and from our first experiment with 14.5 and 200 GeV/nucleon ^{16}O projectiles [6], by He and Price [7] for 14.5 GeV/nucleon ^{28}Si projectiles, and by Cecchini *et al.* [8] for 200 GeV/nucleon ^{32}S projectiles and 14.5 GeV/nucleon ^{28}Si and ^{16}O projectiles.

Here we present results of additional experiments which we have performed to continue the search from two points of view. The first one was to extend the search at the highest available energy to projectiles heavier than oxygen, i.e., using the 200 GeV/nucleon ^{32}S beam at CERN. The second was to extend the search towards heavier projectiles available at high energy, i.e., the 10.5 GeV/nucleon ^{197}Au projectiles at the Brookhaven Alternating Gradient Synchrotron (AGS).

II. EXPERIMENTAL METHOD

Tracks of radiation damage are formed in CR-39 plastic foils by the ionization energy loss along the path of the penetrating ions. These tracks can be developed by etching. We used 6N NaOH at 70 °C for 24 h (^{32}S beam) and at 70 °C for 48 h (^{197}Au beam). The size of the conical shaped etch pits along the tracks increases with the ionization energy loss, i.e., for relativistic particles with their charge. We restrict our measurement to the detector surface. The position and size of the mouth of the etch cones on all foil sides were measured using the Siegen automatic measuring system [9]. Trajectories of the particles were reconstructed by tracing etch cones along the particle's path across adjacent detector foil surfaces. A charge calibration can be determined based on a histogram of measured etch cone areas. By multiple measurements along a particle's path a charge resolution which was sufficient for this experiment was achieved. For fragments of ^{32}S with charge $6 \leqslant Z \leqslant 10$ the resolution is better than $\sigma_Z = 0.05e$ (minimum ten etch cones) and in the case of the ^{197}Au projectiles it is better than $\sigma_Z = 0.06e$ for the shortest tracks (minimum six etch cones) and about $\sigma_Z = 0.002e$ for the longest tracks (maximum 240 etch cones). For our ^{197}Au experiment, the charge distribution for tracks of ions with charges $6 \leqslant Z \leqslant 79$, which has been determined based on $\geqslant 20$ etch cone measurements, is shown in Fig. 1.

Our experiments were designed to look for candidates with different lifetimes. Upstream the beam a thick Pb target (2 cm for the ^{32}S beam and 5.2 cm for the ^{197}Au beam) was used for the production of fragments. Behind this target a stack containing 600 μm thick detector foils with an area of 8×10 cm^2 has been installed to measure the charges of the fast fragments produced in the Pb target. For the ^{197}Au beam the Pb target was put 50 cm in front of the stack to allow a separation of light fragments emerging from the same interaction. This part of the experiment allowed us to look for candidates with lifetimes greater than 1.7 ns (time of flight from the target to the detector). The downstream part of the stack contained alternating CR-39 foils and 200 μm thick Ag foils. This allowed us to study fragments with short lifetimes of about 6.7 ps produced either in the detectors ($C_{12}H_{18}O_7$) or in the Ag foils. The total length of the detector stack containing the Ag foils was 13.5 cm for the ^{32}S beam and 14.5 cm for the ^{197}Au beam.

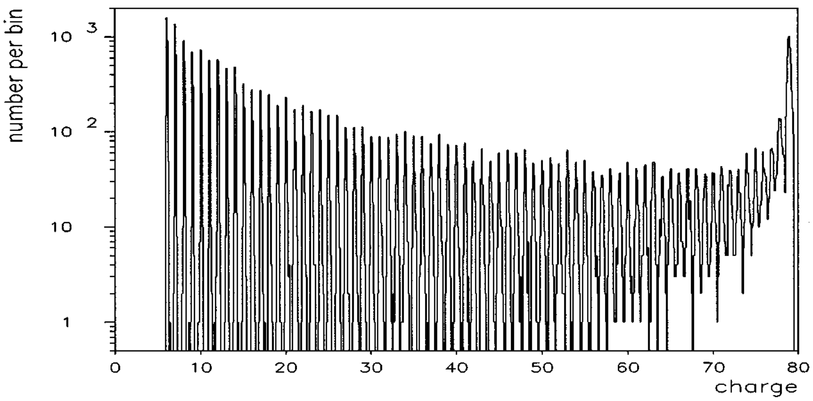

FIG. 1. Histogram of measured charges for fragments and projectiles of the 10.6 GeV/nucleon ^{197}Au beam (tracks of $\geqslant$20 etch cones).

III. RESULTS

We found a few candidates which deviated from an integral charge number by more than $0.2e$. However, they all had to be excluded after a careful reanalysis. These events typically were caused by systematic errors of the measured etch cone area in cases where the paths of two particles came close to each other. Another few tracks were attributed to He particles with low velocities. For these particles the energy loss (and etch cone size) increases along their path. Therefore the averaged energy loss deviates from that of a relativistic particle with an integral charge. So we must conclude that we have observed no projectile fragment with nonintegral charge in either of our experiments.

We restrict our further analysis to fragments with $Z\leqslant10$ observed in the experiments, since as mentioned above QNC's are expected with a maximum number of about 20 nucleons, if they exist at all. In Table I we present the conditions and results of our experiments in comparison to earlier ones. In the third column the mean number of projectile nucleons participating in the collision is given for different combinations of projectiles and targets. These numbers were determined based on a simple geometric picture as described by Nagamiya and Gyulassy [10]. Separating quarks and binding polarized nucleons requires a minimum volume filled with nuclear matter and a certain formation time. An increased number of participant nucleons leads to a prolonged compression phase. This could significantly enhance the production probability of fractionally charged fragments.

At a confidence level of 95% we find the probability that an analyzed fragment with charge $6\leqslant Z\leqslant10$ is nonintegrally charged to be 1.6×10^{-3} for collisions of ^{32}S with Pb (mean value of 13.5 projectile participants) at 200 GeV/nucleon. For collisions of ^{197}Au with Pb (mean value of 50 projectile participants) at 10.6 GeV/nucleon this probability is 6.2×10^{-4}. Furthermore, we analyzed fragments with charge $6\leqslant Z\leqslant10$ produced in interactions of projectiles and projectile fragments in the Ag target foils or in the detector material. For the 8800 fragments of the ^{32}S experiment the probability that a fragment is nonintegrally charged is 3.4×10^{-4}. For the ^{197}Au experiment with 6000 fragments we get a probability of 5.0×10^{-4}.

It should be mentioned that these probabilities are not the

TABLE I. Summary of existing experiments in the search for fractionally charged particles in relativistic heavy ion collisions. The ^{16}O+Pb experiments include $Z=8$ fragments from collisions with neutron loss with a number estimated based on target thickness and interaction cross sections. For the experiments of Cecchini *et al.* [8] the number of fragments with $Z\leqslant10$ was estimated based on charge distributions or measured cross sections given in their paper. In column 3 the mean number of projectile nucleons ⟨Part.⟩ participating in the collision is given. Column 4 shows the thickness of the target used. Column 5 gives the minimum lifetime $t_{\min}$ of fractionally charged particles to be detectable. The number of interacting beam particles, estimated with experimental total interaction cross sections, is presented in column 6. $Z_{\min}$ is the lowest detectable charge. In column 8 the numbers of analyzed particles with charges $\leqslant10$ are given. Column 9 shows the probability that an analyzed fragment with $Z_{\min}\leqslant Z\leqslant10$ is nonintegrally charged at a confidence level of 95%.

Energy (GeV/nucleon)	Collisions	⟨Part.⟩	Target (cm)	$t_{\min}$ (ns)	No. of int. proj.	$Z_{\min}$	Total no. $Z_{\min}\leqslant Z\leqslant10$	Prob. (10^{-4})	Ref.
200.0	^{16}O+Pb	7.9	9.9	0.011	30 000	6	5 400	5.6	[5]
14.5	^{16}O+Pb	7.9	15.0	0.010	113 000	6	11 866	2.5	[6]
200.0	^{16}O+Pb	7.9	15.0	0.010	139 500	5	16 116	1.9	[6]
14.5	^{28}Si+Cu	9.0	1.0	0.007	11 700	8	1 651	18.0	[7]
14.5	^{28}Si+Pb	12.2	1.6	0.007	18 200	8	2 735	11.0	[7]
16.0	^{16}O+Cu	6.0	1.4	0.023	17 000	6	4 500	6.7	[8]
14.5	^{28}Si+Cu	9.0	1.4	0.023	23 000	7	4 000	7.5	[8]
200.0	^{32}S+Cu	9.9	1.4	0.023	10 000	6	1 700	18.0	[8]
200.0	^{32}S+Pb	13.5	2.0	0.010	24 300	7	1 900	15.8	This paper
10.6	^{197}Au+Pb	50.0	5.2	1.667	16 000	6	4 850	6.2	This paper

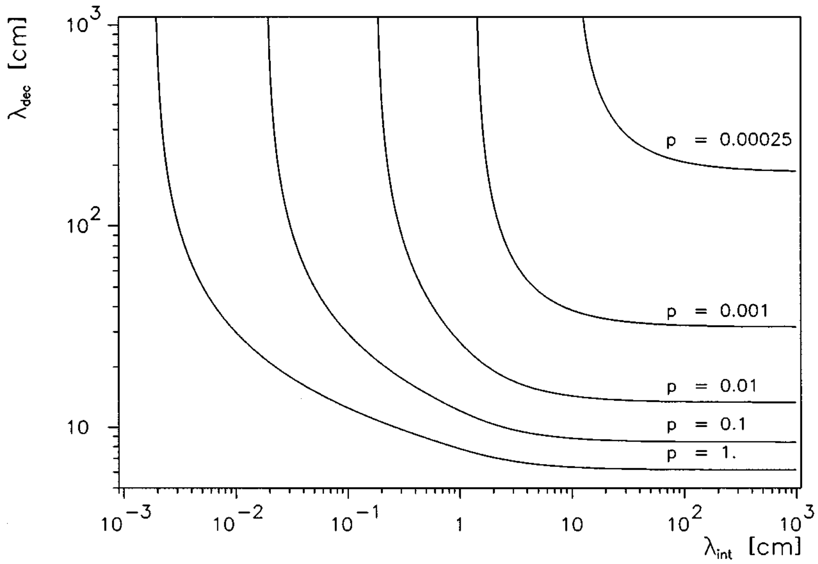

FIG. 2. Dependence of the upper limit for the production probability p of fractionally charged particles at a confidence level of 95% on the interaction cross section and lifetime in cases where no fractionally charged object could be seen. The decay mean free path λ_{dec} is plotted versus the interaction mean free path λ_{int} with the production probability p as a parameter ($p=0.000\,25$, 0.001, 0.01, 0.1, and 1) for the conditions of our ^{197}Au experiment.

upper limits for the production probability of fractionally charged fragments, as stated in [7,8]. To determine upper limits for the production probability one must know the number of interacting projectiles in the target (column 6 of Table I) as well as the probability that a produced QNC survives and can be measured in the track detectors. The survival probability depends on the interaction cross sections and lifetimes of the hypothetical QNC's. So the number given by Gerbier *et al.* [5] is only the upper limit for the production probability of fractionally charged fragments in the case that each QNC produced in the target can be seen in the detector. For our experiment with 10.6 GeV/nucleon ^{197}Au on a Pb target, with about 16 000 interacting ^{197}Au projectiles, this value is $3/16\,000=1.875\times10^{-4}$ at a confidence level of 95%. For the more realistic assumption that the survival probability for the QNC's would be less than 1 in our experiment, this upper limit for the production probability is larger.

Assuming an interaction mean free path λ_{int} and a decay mean free path λ_{dec} we can calculate the number of QNC's leaving the Pb target (thickness $x_1=5.2$ cm):

$$N_{\mathrm{QNC}}(x_1)=\frac{p\lambda_q}{(\lambda_q-\lambda_b)}\,N_b(0)[e^{-x_1/\lambda_q}-e^{-x_1/\lambda_b}],$$

where

$$\frac{1}{\lambda_q}=\frac{1}{\lambda_{\mathrm{dec}}}+\frac{1}{\lambda_{\mathrm{int}}},$$

λ_b is the interaction mean free path of ^{197}Au in Pb, $N_b(0)$ is the number of ^{197}Au nuclei entering the target, and p is the production probability of QNC's in an interaction of a beam particle.

The number of QNC's entering our detector behind $x_2=50$ cm of air is determined by

$$N_{\mathrm{QNC}}(x_1,x_2)=N_{\mathrm{QNC}}(x_1)e^{-x_2/\lambda_{\mathrm{dec}}}.$$

In our experiment, where we have observed no fractionally charged particle, a confidence level of 95% would allow for three particles. So we must take $N_{\mathrm{QNC}}(x_1,x_2)=3$. In Fig. 2 we have plotted curves for $N_{\mathrm{QNC}}=3$ and $p=0.000\,25$, 0.001, 0.01, 0.1, and 1.0 as a function of λ_{int} and λ_{dec}. For the example of a stable QNC ($\lambda_{dec}=\infty$) having $\lambda_{int}=4$ cm (about half the interaction mean free path of ^{16}O in Pb) we get about $p=0.0004$. For the same particle with a mean lifetime $\tau=1.83$ ns in the laboratory system (decay mean free path $\lambda_{dec}=55$ cm, with $\beta\approx1$) we find for $\lambda_{int}=4$ cm the value of $p=0.001$.

IV. CONCLUSION

We have extended the search for QNC's to interactions with an increased mean number of participating nucleons. No fractionally charged particle was detected. We can exclude the production of exotic configurations like quark-nuclear complexes with high reliability, if they have lifetimes greater than a few ns and interaction cross sections similar to those of normal nuclei.

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[1] G. F. Chapline, Phys. Rev. D **25**, 911 (1982).

[2] M. Gyulassy, in *Short-Distance Phenomena in Nuclear Physics*, edited by D. H. Boal and R. M. Woloshyn (Plenum, New York, 1983), p. 237.

[3] ARGUS Collaboration, H. Albrecht *et al.*, Phys. Lett. **156B**, 134 (1985).

[4] UA2 Collaboration, M. Banner *et al.*, Phys. Lett. **156B**, 129 (1985).

[5] G. Gerbier, W. Williams, P. Price, and R. Guoxiao, Phys. Rev. Lett. **59**, 255 (1987).
[6] A. Hoffmann, C. Brechtmann, W. Heinrich, and E. Benton, Phys. Lett. B **200**, 583 (1988).
[7] Y. He and P. Price, Phys. Rev. C **44**, 1672 (1991).
[8] S. Cecchini *et al.*, Astropart. Phys. **1**, 369 (1993).
[9] W. Trakowski *et al.*, Nucl. Instrum. Methods Phys. Res. **225**, 92 (1984).
[10] S. Nagamiya and M. Gyulassy, Adv. Nucl. Phys. **13**, 201 (1984).