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Search for Fractional Charges Produced in Heavy-Ion Collisions at 1.9 GeV/nucleon

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An experiment was performed to capture fractionally charged particles produced in heavy-ion collisions and to concentrate them in samples suitable for analysis by various techniques. Two of the samples so produced have been searched, with use of an automated version of Millikan's oil-drop apparatus. The beam was ^{56}Fe at 1.9 GeV/nucleon, incident on a lead target. Less than one fractional charge per 1.0×10^4 Fe-Pb collisions was found to be produced, and, with further assumptions, less than one per 2.0×10^6 collisions.

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Searches for fractionally charged particles have been made in many kinds of elementary-particle interactions, including searches at e^+e^- and hadron storage rings.[1] These experiments typically look for tracks with ionization below the minimum for singly charged particles. They have seen no evidence for fractional charges.

With the high-energy beams of heavy nuclei available at the Bevalac, it is possible to search for fractional charge produced in interactions involving huge numbers of quarks and large hadronic volumes.[2] Processes that involve heavy nuclei might yield fractional charge by mechanisms not possible in elementary-particle interactions.[3,4] That is, where it is difficult to separate a particle with fractional charge from the remaining colored fragment in the vacuum, the separation process may be greatly enhanced in the environment of a quark-gluon sea created in a heavy-ion collision.

The experiment is done in two steps. The first stage is a scheme to collect and concentrate fractional charges produced in heavy-ion collisions at the Bevalac. In the second stage, the target and concentrated materials from the Bevalac exposure are brought to one of the existing experiments designed to look for free fractional charge in bulk material. These include magnetic levitometers,[5] Van de Graaff charge spectrometers,[6] and droplet experiments.[7,8] In this paper we report the details of the initial Bevalac exposure, and then describe the analysis of this exposure with the San Francisco State University automated Millikan apparatus. Other analyses of the Bevalac materials will be reported elsewhere.

A total of 3×10^{10} Fe ions of 1.9 GeV/nucleon kinetic energy were incident on a target configuration consisting of a number of heavy materials (mainly Pb). Within a 30° cone behind the target were 26 five-gallon tanks of carbon tetrachloride. The layout of the tanks and the composition of the target are described more completely in Fig. 1. Each tank had a thin central wire maintained at a potential of ± 90 V with respect to its inside wall. Fractionally charged particles that stop in the tank form fractionally charged atoms or molecules which drift to the wire[9] and are trapped there by the image charge, since no subsequent reaction can make them natural.

The choice of fully ionized Fe was made to optimize the energy per nucleon, atomic number, and intensity of the beam. The Pb target was selected to optimize the probability of a central collision. Since following the nuclear collision, fractional charge may be part of a nuclear fragment, the total collection configuration was designed to stop both low- and high-charge fragments. Most high-charge fragments ($Z>6$) are expected to stop in the target, while most low-charge fragments pass through the target plates

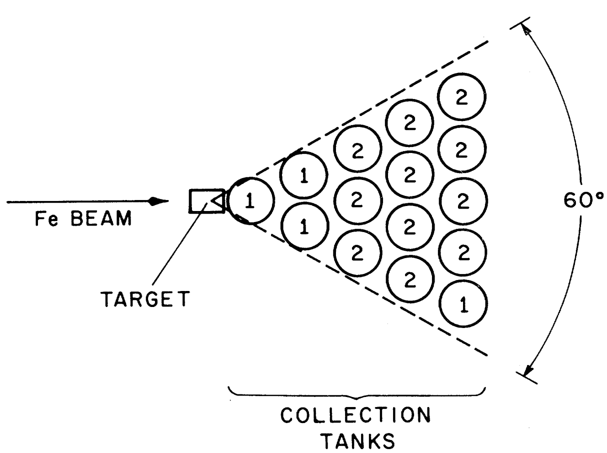

FIG. 1. Schematic top view of the experimental setup at the Bevalac showing the target configuration and the stopping tanks of CCl_4. Some of the five-gallon tanks are arranged in a double layer as denoted by the 2. The 26 central collection wires included Au, In, Cu, Nb, and W wires, each maintained at + 90 V or − 90 V with respect to the inside wall of its tank. The target configuration consisted of 22 Pb and 9 In (interspersed) wafers $\frac{1}{8}$ in. thick and 3 cm in diameter. Near the middle of the target there were some Cu plates, totaling $\frac{1}{8}$ in. in thickness, 10 g of Hg, and several hundred steel balls, each with a mass of about 0.1 m. The Fe beam was 1.5 cm in diameter and was accurately maintained in the center of the target.

into the tanks. The stopping efficiency of the tanks was estimated with use of Monte Carlo techniques and the Bethe-Bloch formula. We find, for a large range of mass and reasonable momentum distributions for the produced particles, that about 1% of all particles with charge $e/3$ and about 8% of those with charge $4e/3$ are stopped in each of the forward tanks. The collection efficiencies of the other tanks decrease with production angle and distance from the target.

We now turn to the analysis of some of these samples by the automated Millikan technique.[7] One sample was prepared from the 36-μm-diam central gold wires from two of the forward tanks, one of each polarity. Each wire was passed twenty times through a small drop of mercury in a capillary tube in order to remove the surface layer of the wire. These two drops were combined to form sample A. In this process the fractional charge is transferred to the mercury with an unknown efficiency. As this efficiency could be small, a second sample B was prepared by dissolving the gold wires in some mercury from the target assembly. Thus sample B combines collection from the target and the tanks.

The measuring apparatus is a modification of the Millikan oil-drop experiment in which small drops are introduced one at a time into a measuring chamber by a piezoelectric drop ejector. The drop's drift velocity in a switched electric field is measured by timing the passage of an image of the illuminated drop over a series of slits. The measured velocity of a typical drop as a function of time is shown in Fig. 2. The field switches from positive to negative at slit 39. The change in velocity seen at this point corresponds to a charge on the drop of $14e$. The field returns to its original polarity at slit 74, and the velocity returns to nearly its original value. A change in charge during the measurement can be detected by comparing the final velocity with the original one. Drops which change charge during the measurement are identified in this way and rejected. The occurrence of such charge changes is less than one per 1000 drops.

Drops with substantial residual charge are further analyzed to ensure that their charge measurements are not erroneous. Limits are placed on the initial and final transverse positions, the charge change, the χ^2 of the velocity fit, and the drop radius such that 5% of all drops would fail any one cut. These limits remove twenty drops which compose a fairly flat distribution

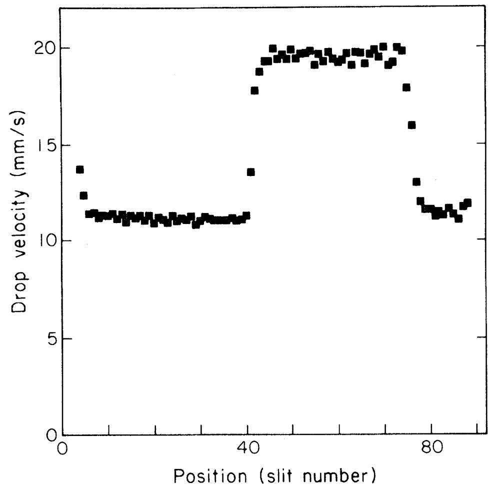

FIG. 2. Drift velocity as a function of position for a typical mercury drop. Reversals of the electric field occur at slits 39 and 74.

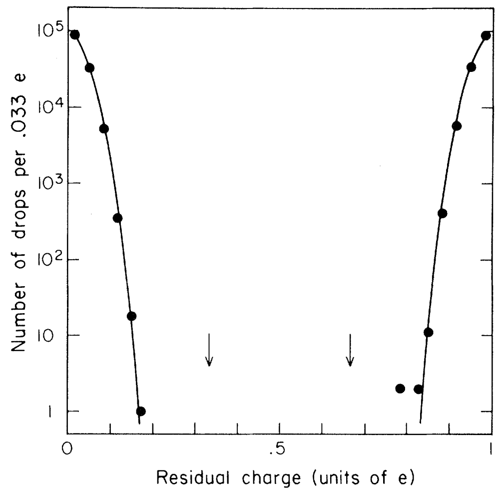

FIG. 3. Combined distribution of residual charge for samples A and B. The arrows indicate the positions where measurements of drops containing 1/3-integer charges would fall. The curve shown is a Gaussian with standard deviation of $0.035e$.

of residual charges between $0.2e$ and $0.8e$. The radius limit is particularly significant since most disturbances that affect the charge determination also affect the radius determination. Under good running conditions the radius is constant to 0.1%. The radius test rejects drops which have radii about 0.7% too big or too small.

To ensure objectivity in the analysis, $\pm e/3$ is added at random intervals to a drop's measured charge. There are 236 of these test events, of which 197 remain in the sample after all limits have been applied. The test events are identified as such and removed from the sample only at the end of the analysis.

Drops can be measured at a rate of 1 $\sec^{-1}$, and 5 μg of mercury can be measured in an hour of good running. The charge on a 6-μm-diam mercury drop is measured to an accuracy of about 3.5% of e. To keep the charge on the drops near zero, a bias wire is inserted into a column of water which is in contact with the mercury drop in the drop ejector's tip. The potential of this wire (a few volts) is adjusted by the computer. Drops with charge between $-16e$ and $+16e$ are accepted.

A total of 500 μg of mercury was measured, 200 μg from sample A and 300 μg from sample B. A histogram of residual charge for both samples, a total of 260 000 drops, is shown in Fig. 3. The residual charge is the charge in excess of an integral value. The charge measurement is calibrated directly from the integral-charge peaks by assuming that the peak to peak separation is e. There are no measurements near fractional-charge values of $e/3$ or $2e/3$.

A limit on the fractional-charge production rate can be set for sample A by noting that 200 μg is 2% of the mercury bead used to rinse the gold wire and by using the calculated 1% capture efficiency of the tanks for particles of charge $\pm e/3$. If the efficiency in transferring fractional charges from the gold wires to the mercury in sample A is 100%, then we obtain a production limit of less than 5×10^{-7} fractionally charged particles per collision with 95% confidence. If the fractional charges were not removed by the mercury rinse and remained on the gold wire, then the fractional charges from the two tanks are concentrated instead in sample B. We measured approximately 0.02% of sample B. Thus, assuming that the mercury rinse did not remove the fractional charges, the 95% confidence level on the production rate is less than 5×10^{-5} fractionally charged particles per collision. (More restrictive limits apply if the produced particles have total charge greater than $e/3$, for then the stopping efficiency is greater.)

Sample B is also used to set the limit on the production of high-Z fractionally charged nuclear fragments, all of which would be stopped in the portion of the target covered by the beam. The mercury measured from sample B corresponds to 1×10^{-6} of the target, which gives a production limit of less than 1×10^{-4} fractional charges per collision with 95% confidence.

In summary, we have carried out a first-generation experiment to detect fractionally charged particles produced in Fe-Pb nuclear collisions at 1.9 GeV/nucleon incident beam energy. We detect no $\frac{1}{3}$-integrally charged particles. We can rule out production of fractional charges in the target at the rate of one per 1×10^4 collisions, or under certain assumptions, to one per 2.0×10^6 collisions.

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