Search for Fractionally Charged Ions in Helium Gas

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A Van de Graaff accelerator facility has been used as a supersensitive mass spectrograph in a search for free $+\frac{1}{3}|e|$ and $+\frac{2}{3}|e|$ charged ions in helium gas. No such ions were found at a level of sensitivity better than 1 part in 3.9×10^{14} He atoms. The mass ranges spanned were 0.13 to 7.5 amu for $+\frac{1}{3}|e|$ ions and 0.27 to 15.0 amu for $+\frac{2}{3}|e|$ ions.

Searches for fractionally charged particles began soon after quarks were proposed,[1] and have taken a variety of experimental forms.[2] These have generally produced null results, the principal exception being the experiment of LaRue, Fairbank, and Hebard (LFH).[3] Recent results[4] (LFP) from that group not only confirm the earlier result, but provide evidence that the fractional charges exist primarily on the surfaces of the experimental samples. Since a basic assumption of modern elementary-particle theory is that of quark confinement, the effect of a confirmation of the LFH-LFP result on such theory would be profound indeed. Thus, several other experiments focusing on the possibility that the fractional charges exist either in the small amount of tungsten contained in the superconducting niobium spheres,[5-7] or in the niobium or other elements of the spheres,[6] have been performed. Because the LFH and LFP experiments were conducted in a helium environment, the He itself may well contain the fractional charges, a possibility not previously tested. In this Letter, we report our search for fractional charges in He carried out over a broad mass range using a Van de Graaff accelerator as a supersensitive mass spectrometer. Our measurement is sensitive both to free quarks and to fractionally charged ions created by binding a quark to an atom or a nucleus. Both are denoted hereafter as Q.

Because the LFH and LFP experiments were conducted at 5 K in about 10 Torr of He, all surfaces are expected to be coated with one to two monolayers[8] of He. Assuming that the Q ions are in the He, their frequency of occurrence can be estimated from those experiments to be at least 0.9×10^{-13} per He atom. This estimate involves the radius of the Nb spheres (0.14 mm), the density,[9] and hence interatomic spacing, of liquid He, and the fact that about one in three of the spheres in the LFH and LFP experiments were observed to contain fractional charges. This frequency of occurrence implies a substantial beam of Q particles in our experiment if they are indeed in the He.

The Ohio State University Van de Graaff accelerator facility was used as a mass spectrograph, applying the experimental arrangement sketched in Fig. 1. Briefly, ions emitted by the source in the high-voltage terminal were accelerated vertically through a potential difference of about 1.5 MV and then deflected into a horizontal plane by an analyzing magnet. The ions, dispersed in mass by the magnet, then passed through an electric-field region to a detector assembly. The deflection of the beam ($\theta \approx 5°$) in the electric field rejected all ions except those which originated in the ion source and which maintained their ionic identity throughout the accelerator. The detector consisted of a 5-cm$\times$1-cm position-sensitive detector (PSD) of 500 μm depletion depth,

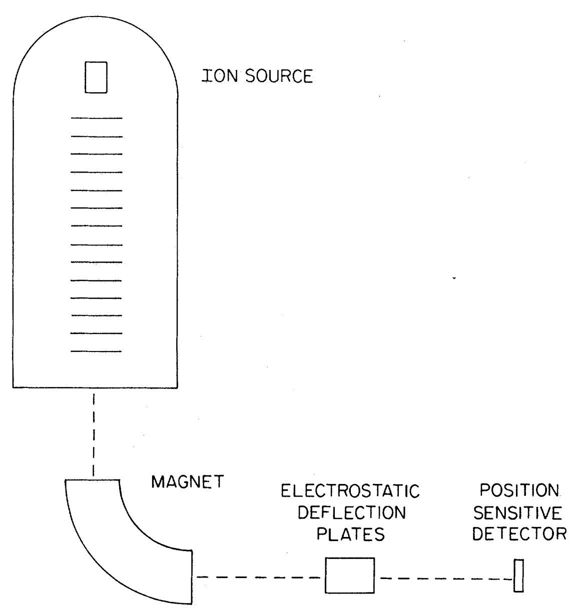

FIG. 1. Sketch of the experimental setup. The accelerator axis is in the vertical direction. The magnetic field direction in the 90° magnet and the electric field in the region of the electrostatic deflection plates are into the page. The PSD position axis is in the vertical direction, and subtends a $\Delta M/M$ bite of 2.0%.

which served to measure the energy of the ions selected by the electric and magnetic fields. Since ions from the accelerator have an energy of qV, where q is the ion's charge and V is the total acceleration voltage through which the ion passes, the energy signal from the PSD yields directly the charge of the ions. Spectra from the PSD were acquired in a pulse-height analyzer (PHA). The PSD was replaced periodically by a Faraday cage to monitor the constancy of the extraction, acceleration, and transmission efficiency of $^4He^+$ ions through the entire system. The accelerator voltage was stabilized to ± 2 kV by a generating voltmeter system.

The accelerator ion source used in the present experiment was a standard 2.5-cm-diam, 14-cm-long Pyrex bottle which had a brass cap at one end, and an aperture (extraction canal) at the opposite end. In normal operation, rf power is applied to the bottle to ionize the gas, and the positive ions are extracted by means of an electrostatic potential across the bottle. Because such an arrangement produces a plethora of beams, the rf power to the bottle was switched off for the Q-search runs of the present experiment, resulting in a vastly improved sensitivity over a broad mass range. Since the (electrostatic) extraction and focusing potentials were the same with or without the rf power, the extraction and acceleration of any Q ions in the He source gas should be the same with or without the rf power. In the present experiment, the gas to the source bottle was fed through the brass cap which was biased at a positive high voltage with respect to the extraction aperture. To ensure that any positive ions contained in the He gas could reach the extraction region unimpeded, the entire source-gas–handling system was floated at the voltage of the brass cap.

In order to obtain a relationship between the occurrence of Q ions in He and the number of counts observed in the PSD at the fractional-charge-state locations, it is necessary to consider the details of the operation of the source. The Q ions and He atoms move from the He gas bottle through copper tubing to the source. Once ionized, the He^+ ions will have an extraction efficiency ϵ_{ext}. Since the focal properties of the (electrostatic) extraction field do not depend on charge or mass, the Q ions will have the same extraction efficiency, barring collisions. To obtain an estimate of the collision probability of ions in the source bottle, the pressure under operating conditions was measured to be about 1×10^{-2} Torr: This implies a mean free path of roughly the same size as the source dimensions, suggesting that the assumption of the same ϵ_{ext} for Q and He^+ ions is a reasonable one. Thus, the particle currents, $(I/q)_j$, emitted by the source will be related by

$$\frac{(I/q)_Q}{(I/q)_{He^+}} = \rho^{-1}\frac{n_Q}{n_{He}}\frac{T_Q}{T_{He^+}}. \qquad (1)$$

In Eq. (1), ρ is the probability that the He atom will be ionized before it exits from the source bottle, the T_j are the transmission efficiencies of atoms or Q through the copper tubing connecting the He gas bottle to the source, and the n_j are the densities of the atoms or Q in the ion-source bottle. If it is assumed that the Q ions are transported through the tubing from the He gas bottle to the source by the same mechanisms as are the He atoms, then the T_j values are given by standard vacuum-technology equations[10]: Aside from factors associated with the geometry of the constriction, they are inversely proportional to the masses of the atoms being transmitted. While this assumption may not be strictly true, it is virtually impossible to measure a meaningful correction to it. The mechanisms which would impede a normal ion, e.g., electron exchange at the tubing walls or collisions with other atoms, might be quite different for an ion which could not be neutralized by any mechanism. However, the He buffer gas was fed into the LFH-LFP apparatus through a very similar system, some of which also involved copper surfaces. Thus, while the *absolute* result of the present experiment might be affected by an anomalous efficiency for passage of the Q ions through the copper tubing, the present result *relative to the LFH-LFP result* would not be so affected.[11] By taking $\rho=1$, the most conservative possible assumption, the ratio of abundance of Q to He atoms in He gas, $R=n_Q/n_{He}$, is then given as

$$R = \frac{(I/q)_Q}{(I/q)_{He^+}}\left(\frac{M_Q}{M_{He}}\right)^{1/2}. \qquad (2)$$

In order to relate this value to the counts observed at the PSD, it was assumed that the transmission efficiency through the accelerator was independent of mass and charge. This should be a good assumption for all electrostatic fields, but might not apply to the focusing from the 90° magnet. Thus, the transmission through a 3-mm-wide slot (which is half the width used for the Q scans) at the location of the PSD was measured for 90° magnet settings corresponding to beams ranging in M/q from 1 (H^+) to 16 (O^+). That there was no observable difference in that transmission shows that the beam spot width was less than 3 mm over the entire M/q range. The transmission from the source to the PSD was therefore taken to be the same for both He^+ and Q beams. The quantity $(I/q)_{He^+}$ was determined by measuring the He^+ beam intensity at the PSD location with the source rf on. This beam intensity was monitored frequently during the runs, and was found to be extremely stable. The quantity $(I/q)_Q$ was determined by summing the number of counts in the PHA channels which corresponded to the peak locations and widths of the $+\frac{1}{3}|e|$ and $+\frac{2}{3}|e|$ charge states. Finally, M_Q was determined by the analyzing-magnet setting.

Each setting of the analyzing magnet differed from the previous one by 0.8% (or 1.6% in $\Delta M/M$). Since the $\Delta M/M$ bite at the PSD was 2%, the increment used ensured that no point in M/q was missed. Over 300 settings of the magnet were required to span an M/q range from 0.4 to 22.5 amu/e. 2- to 10-min runs were taken at each M/q setting. Where the number of counts observed in a q_Q peak region was anomalously high, that point and several neighboring points were reexamined. At no M/q setting did there appear to be a peak at the expected locations of either the $+\frac{1}{3}|e|$ or the $+\frac{2}{3}|e|$ charge state. The energy spectrum from the PSD was calibrated by detecting peaks due to real beams of H, He, C, and O (a few of these ions were produced even with the source rf off). The number of channels in the PHA spectrum which were included in determining the number of possible fractional-charge-state ions was taken to be 20% larger than the widths of the peaks of the real beams. The PSD allows an additional constraint, as any Q peak would have to be localized in position as well as in energy. The position width of a real peak was also calibrated by observing the real beams at the PSD. In each run, then, the number of possible Q counts in the $+\frac{1}{3}|e|$ group consisted of the maximum number of counts which both fell within the energy window and which were localized to the required position-peak width. Because so few counts were observed in the $+\frac{2}{3}|e|$ energy window, only the energy-peak constraint was used in establishing the limit for that charge state.

A feature of detection which had to be considered was that of pulse-height defects[12] associated with the PSD. The peak shifts resulting from this effect were well calibrated by the observed (1.5 MeV) H, He, C, and O background beams. This effect depends on the ionization density of the ion passing through the detector, hence on its average charge. Thus, the pulse-height defect for a free quark would be somewhat different from that for a Q ion based, e.g., on ^{12}C. Since the pulse-height defect was observed to be less than 30% of the pulse height at a mass of 16 amu, it was accounted for by appropriately increasing, at higher M_Q values, the size of the Q energy window.

The range in M/q spanned in this experiment corresponds to a mass range for $q_Q = +\frac{1}{3}|e|$ ions of 0.13 to 7.5 amu, and a range for $q_Q = +\frac{2}{3}|e|$ ions of 0.27 to 15.0 amu. The upper limit for the existence of $q_Q = +\frac{2}{3}|e|$ at large M_Q was affected by the existence of impurity peaks at integral masses which, because of the pulse-height defect, began to overlap the region in which the $q_Q = \frac{2}{3}|e|$ would have occurred. Counts which were observed in the $q_Q = \frac{1}{3}|e|$ region appeared to result from detector noise; a run with a beam stop in front of the PSD gave about the same number of counts as was typically observed with the stop removed. Because of the small number of counts involved (typically about five per run) no subtractions were made for the noise count rate.

Because of the mass dependence in Eq. (2), the limit imposed by the present experiment is a function of Q mass. This limit is given both for $q_Q = +\frac{1}{3}|e|$ and $+\frac{2}{3}|e|$ in Fig. 2; it is seen to be roughly two orders of magnitude below that suggested by the LFH-LFP experiments over the M_Q range scanned. The sharp spikes seen in Fig. 2 correspond to the integral M/q settings at which impurity peaks were observed, thereby producing (as noted above) somewhat more than the usual number of counts in the Q-energy windows. Different run times and/or I_{He^+} values during the various parts of the scan produced the other structure in the limit curves. The upper limits shown in Fig. 2 include 1 standard deviation; those curves therefore represent a 67% confidence limit.

The relationship between experiments of the present type and that of LFH and LFP is worthy of some discussion. In the present experiment fractional charges were found not to exist in He, within the mass range examined, at a considerably more sensitive level than that implied by the LFH-LFP experiment, subject to the present hypothesis. In addition to the possibility that the Q mass could lie outside the mass scanned, sev-

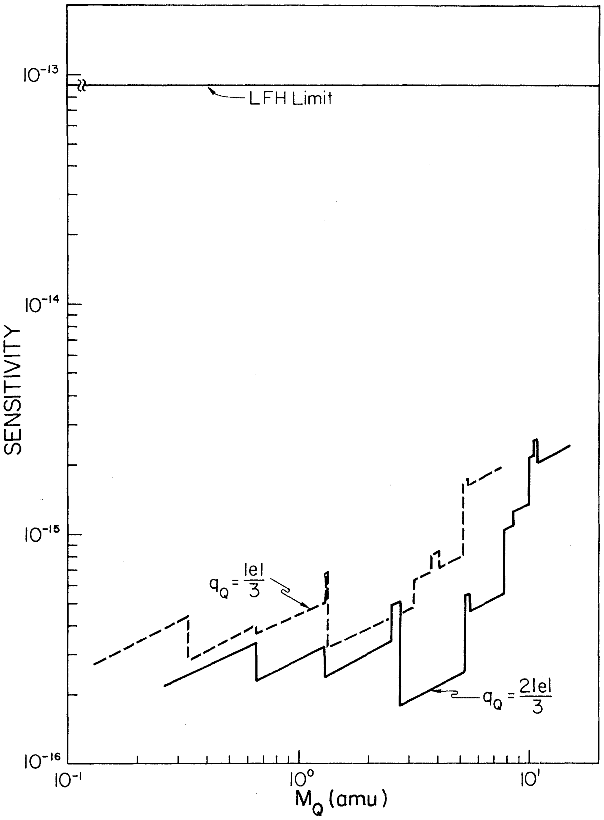

FIG. 2. The upper limit on the number (sensitivity) of Q ions, either with $q_Q = +\frac{1}{3}|e|$ or $+\frac{2}{3}|e|$, per He^+ ion as a function of M_Q. The structure of the curves is explained in the text.

eral other explanations are also suggested by the LFH and LFP experiments as the vehicles for the fractional charge. While the explanation of the LFH-LFP result remains elusive, its importance demands its further investigation.

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[9]*Handbook of Chemistry and Physics*, edited by C. D. Hodgman (Chemical Rubber Publishing Company, Cleveland, Ohio, 1959), 40th Ed., p. 2102.

[10]See, for example, M. Pirani and J. Yarwood, *Principles of Vacuum Engineering* (Barnes and Noble, New York, 1961), p. 10.

[11]W. F. Fairbank, private communication. Although there are differences in the gas-handling systems used in the present experiment and in the LFH-LFP experiments, the restrictions in the latter systems are probably greater than in the former. In the present experiment the He gas bottle was connected to the source bottle through a valve and 1.0 m of copper tubing. In the LFH-LFP experiments, the He passed through a valve and 1 m of stainless steel tubing, and then through 30 cm of cooled copper gauze, before entering the experimental apparatus.

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