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# Observations of Collective Ion Acceleration by a Relativistic Electron Beam in a Magnetic Cusp*

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We have observed ion pulses of $10^{13}$ protons by passing hollow relativistic electron beams through a magnetic cusp. Ion pulses are observed with drift-chamber fill pressures from 75 to 600 mTorr of $H_2$. Magnetic fields of 0.8 kG suppress the mechanism responsible for acceleration without magnetic field. A different mechanism appears to turn on and peaks as the cusp threshold is approached. More than $10^{11}$ protons with energies greater than 2 MeV are observed.

In conventional particle accelerators, the electric and magnetic fields at the particle are produced externally and are subject to limitations imposed by $\nabla\times\vec{B}=0$ and $\nabla\cdot\vec{E}=0$ in addition to the usual technical limitations of electrical breakdown. In a collective accelerator the electromagnetic fields that accelerate a particle are internal and produced by many charged particles. The magnitude of the internal field is determined mainly by the beam density that can be achieved.

The first observations of collectively accelerated ions with intense electron beams were in the experiment of Graybill and Uglum.[1] They injected a 1.6-MeV, 40-kA beam into a drift chamber filled with 200 mTorr of hydrogen and observed 100 A of 5-MeV protons. The electric field was about 100 MV/m which is a factor of 10 greater than in conventional accelerators. However, the acceleration took place over a distance of only 5 cm. In conventional accelerators the design and control of the fields at the particle is a highly developed science. In collective accelerators, since the fields are internal and created by many particles, the problem of design and control is still at a very early stage and involves much more complicated physics. One of the few methods available for design and control of the electron beam is the application of an externally produced magentic field. In previous experiments this suppressed the collective acceleration.[2] We report new experiments where collective acceleration is enhanced by an external magnetic cusp.

Collectively accelerated ions have been observed in a number of experiments[1-10] when an intense beam is propagated through a low-pressure gas without an external magentic field. There has been considerable theoretical effort in conjunction with these experiments.[11-13] The experimental results are usually interpreted in terms of the acceleration of the space-charge well at the head of the beam as it breaks down the neutral gas or in terms of a localized pinch.

Figure 1 is a sketch of the apparatus. The electron-beam generator produced a 1.3-MeV,

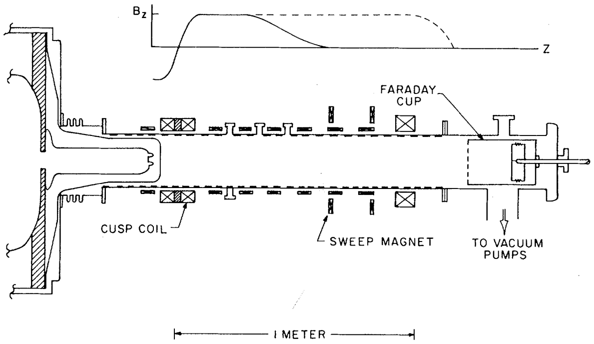

FIG. 1. Experimental apparatus. The vacuum chamber is a 20-cm i.d. Lucite tube lined with a stainless steel screen (dashed lines).

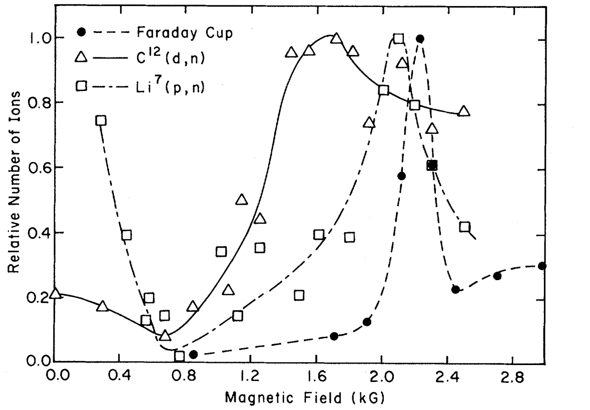

FIG. 2. Relative number of ions versus magnetic field. The relative number of ions is inferred from the neutron counts for the reactions and the total charge of the Faraday cup. Each curve is normalized to its maximum value.

50-kA beam for 50 nsec in these experiments. The current rise time was 35 nsec. The hollow cathode is made from graphite and has a 5-cm o.d. with a 4-cm i.d. The center of the cusp is 10 cm from the anode and has a width of 9 cm [full width at half-maximum (FWHM)] at a radius of 2.5 cm. Most of the data were taken with only the first three coils after the cusp connected. This resulted in a magnetic field which decayed before the 2-kG sweep magnetic field. When all of the coils are connected the field is uniform for 1 m after the cusp. At the end of the drift chamber is a large-aperture (18 cm) Faraday cup. The collection plate is connected to the center conductor of a 50-Ω rigid coax and to ground with twenty resistors in parallel to give a 1-Ω source impedance. There is a 50% transparent screen at ground potential over the aperature to shield the cup from electromagnetic noise. The Faraday cup has a sensitivity of 1 V/A and a rise time of less than 1 nsec. The Faraday cup gives us the time-resolved ion pulse shape and total number of ions. We also observe the ions by two other methods. One is by detecting the neutrons from the reactions $\mathrm{Li}^7(p,n)$ or $\mathrm{C}^{12}(d,n)$ with a neutron detector of the type described by Santer and Bauerman.[14] In these measurements a graphite disk or a mixture of lithium fluoride and epoxy is placed in the chamber 50 cm from the cusp as a target for deuterons or protons. The reaction threshold is 2 MeV for protons 0.33 MeV for deuterons. Thus the neutron counter gives a measure of the number of ions with energies in excess of 2 MeV for protons and 0.33 MeV for deuterons. In addition we have done several experiments with helium using cellulose nitrate film[15] to detect the ions. This method is insensitive to light, x rays, and electrons. The film gives us a measure of the energy and spatial distributions.

Figure 2 is a plot of the relative number of ions versus magnetic field. The measurements are made with the Faraday cup (with $\mathrm{H}_2$), and with the reactions $\mathrm{Li}^7(p,n)$, and $\mathrm{C}^{12}(d,n)$. The drift chamber is filled to a background of 300-mTorr hydrogen (or deuterium). We see a decrease in the number of ions to a minimum at about 0.8 kG and thereafter an increase with magnetic field to a peak (field magnitudes are maximum $B_z$ of Fig. 1). The initial decrease of the number of ions appears to be the suppression of the acceleration mechanism without magnetic field. The ion pulse widths are approximately 5 nsec wide for $B_z$ below 0.8 kG. When the cusp coils were wired to add rather than oppose, no neutrons were detected from the reaction $\mathrm{Li}^7(p,n)$. The peak in the number of ions with magnetic field comes as the critical magnetic field for cusp transmission of the electron beam is approached. For an ideal cusp (i.e., zero width), the velocity of an electron after passing through the cusp is $V_f^2 = V_i^2 - r^2\Omega^2/\gamma^2$, where $V_f$ and $V_i$ are the final and initial velocities, respectively, $r$ is the injection radius, $\Omega$ is the electron-cyclotron frequency, and $\gamma$ is the relativistic factor.[16-19] The critical field ($V_f^2 < 0$) for a 1.3-MeV electron is $B_{\mathrm{cr}} = (5.8\ \mathrm{kG\ cm})/r$. This gives a $B_{\mathrm{cr}}$ of 2.3 kG for electrons at the outer cathode radius and 2.9 kG for the inner cathode radius. Measurements with the reaction $\mathrm{C}^{12}(d,n)$ have a minimum at 0.8 kG and a broad peak extending from 1.5 to 2.1 kG.

As a check that the ion peak is correlated with the critical magnetic field, the number of ions versus magnetic field was measured with the Faraday cup using a 10-cm o.d., 9-cm i.d. cathode. The peak in the number of ions was reduced to 1.3 kG. Measurements of the peak number of ions as a function of pressure showed a decrease of about a factor of 2 from 150 to 450 mTorr of hydrogen. The $C^{12}(d,n)$ measurements show that the peak number of ions with magnetic field is 5 times greater than without.

An estimate of the energy distribution of the ions for the case of $H_2$ can be obtained from the various reactions. At the peak we have approximately $10^{13}$ ions, less than 10% of these have energies greater than 2 MeV [reaction $Li^7(p,n)$], less than 1% are in excess of 3 MeV [reaction[5] $B^{11}(p,n)C^{11}$], and we were unable to observe any neutrons from the 4.5-MeV threshold reaction $Cu^{63}(p,n)$.

We compared measurements with a uniform magnetic field (all the coils were connected) with those made after the gradient. Within the experimental error the results were the same. From this we conclude that the ion acceleration is not a result of the field gradient.

Figure 3(a) is an oscilloscope trace of the ion current to the Faraday cup. The peak current is about 70 A. The half-width is approximately 20 nsec in contrast to pulse widths less than 5 nsec without magnetic field. The width of the ion pulse can be explained by the spread in ion energy if the acceleration region is near the cusp. Some caution must be exercised when interpreting the Faraday-cup measurements. For example, when the sweep field is sufficiently strong to reject the electrons we can also sweep out the low-energy ions.

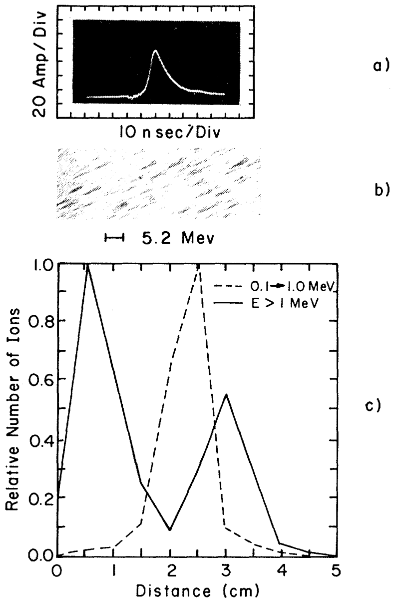

FIG. 3. (a) Faraday cup signal. The current scale has been multiplied by 2 because of the 50% transparent screen over the aperture. (b) Photomicrograph of He ion tracks. Magnification is 80 μm/in. The scale shown is 0.25 in. which is equivalent to 5.2 MeV. (c) Spatial distribution of ions. This shot was made with uniform magnetic field after the cusp of 2 kG, a pressure of 300 mTorr helium, and a 5-cm-diam hollow cathode.

Cellulose nitrate film was used to obtain a measure of the energy and spatial distributions of helium ions. A 4-mm graphite plate with a 1-mm by 3-cm slit was placed 50 cm from the cusp and the film mounted at 45° 15 cm behind the slit. An image of the ion beam is formed on the film by the $\alpha$-particle tracks. The energy is given by the length of the tracks and local density by the number per unit area. Figure 3(b) is a photomicrograph of the ion tracks on the fringe of the image taken with a uniform 2-kG field after the cusp and 300 mTorr of He. An area of the image 15 cm along the slit and 5 cm wide was divided into 0.5 cm × 1 cm rectangles. The number of particles with energies greater than or less than 1 MeV were counted in a $3\times10^{-4}$ $cm^2$ area in each of the rectangles. This gives us two 10×15 matrices, one for $E>1$ MeV and one for 0.1 MeV $<E<1$ MeV. The rows of the matrix give local ion density as a function of distance perpendicular to the slit and the columns give local ion density parallel to the slit. We sum the columns and plot the resulting rows as a function of distance from the slit. The results are shown in Fig. 3(c). The solid line is for $E>1$ MeV. The high-energy ions make an asymmetric hollow image, whereas the low-energy-ion image is not hollow. Estimates of the total number of particles from the film give about $10^{12}$ with about one in twenty having energies greater than 1 MeV. Hollow ion-beam images were also observed with a 10-cm-diam solid cathode and with circular apertures.

We placed small samples of the cellulose nitrate film at 45° along the drift chamber 15 cm from the cusp and 7 cm below the electron-beam channel. We were unable to observe any $\alpha$'s with energies greater than 0.1 MeV. From this we conclude that the acceleration is localized to the electron-beam channel in the direction of the electron-beam flow.

Although the results of the experiment do not give a definite conclusion as to the ion-acceleration mechanism when an electron beam is passed through a cusp magnetic field, some remarks can be made about the data with regard to various suggested acceleration schemes. Since the high-energy ion beam is hollow and localized to the electron-beam channel, the acceleration does not appear to be a result of a localized pinch. Without magnetic field, open-shutter photographs indicate the electron beam pinches and kinks. As a result the ion pulse is not reproducible since it does not always hit the target. This is not the case with magnetic field. The mechanism does not appear to be that of the electron ring accelerator[20] or the autoresonant accelerator,[21] since these mechanisms depend on the magnetic field gradient.

The decrease in the number of ions with magnetic field below 0.8 kG appears to be suppression of the acceleration mechanism without magnetic field. The acceleration at higher fields results from the effect of the cusp on the electron beam, but the mechanism remains an open question. Acceleration by the space-charge well at the head of the beam appears to be a possible candidate.

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# Flow Phenomena in Superfluid $^3$He-$A$*

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Flow phenomena in the $A$ phase of superfluid $^3$He have been studied by observing the transverse NMR signal. Marked changes occur in the presence of flow, including structure and satellite signals, step changes in signal amplitude at particular velocities, and rapid attenuation of the signal beyond some critical velocity. Little, if any, change of frequency of the signal is produced by flow.

In this paper we report the observation of some interesting effects of flow on the transverse NMR in superfluid $^3$He-$A$. The flow was in a channel connecting two Pomeranchuk cells of the type described by Kummer.[1] A greatly simplified schematic of the apparatus is shown in Fig. 1, and full details will be given elsewhere.[2] The volume of each cell could be varied independently by adjusting the $^4$He pressure applied to that cell. To produce flow, the $^4$He pressure applied to the low-

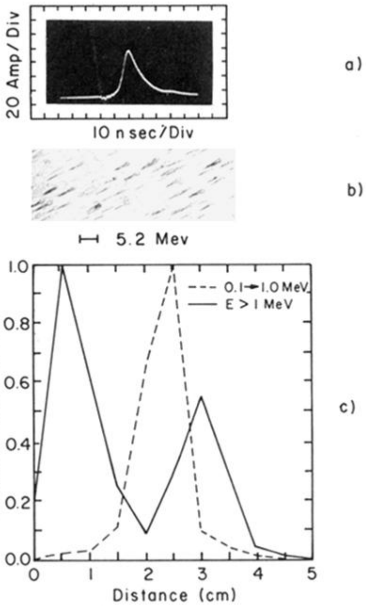

FIG. 3. (a) Faraday cup signal. The current scale has been multiplied by 2 because of the 50% transparent screen over the aperture. (b) Photomicrograph of He ion tracks. Magnification is 80 $\mu$m/in. The scale shown is 0.25 in. which is equivalent to 5.2 MeV. (c) Spatial distribution of ions. This shot was made with uniform magnetic field after the cusp of 2 kG, a pressure of 300 mTorr helium, and a 5-cm-diam hollow cathode.