Focusing of Negative Ions by Vortices in Rotating ^{3}He-A

J. T. Simola, K. K. Nummila, A. Hirai,[a] J. S. Korhonen, W. Schoepe,[b] and L. Skrbek[c]
Low Temperature Laboratory, Helsinki University of Technology, SF-02150 Espoo 15, Finland
(Received 9 July 1986)

Experiments with negative ions in rotating superfluid ^{3}He-A show strong retardation and deformation of ion pulses drifting parallel to the angular velocity $\mathbf{\Omega}$. This is caused by the interaction between the ions and the $\mathbf{l}$ texture in the soft cores of A-phase vortices. The interaction is mediated by the anisotropic ion mobility: $\mathbf{v}=\mu_\perp \mathbf{E}-\Delta\mu(\mathbf{E}\cdot\mathbf{l})\mathbf{l}$. The (Ω,T) dependence of the retardation is explained by a model that assumes focusing of ions into the vortex cores, along which the mobility μ_c is lower than that in the bulk liquid, $\mu_\perp$. We find $\mu_c=\mu_\perp-0.6\,\Delta\mu$.

PACS numbers: 67.50.Fi

The structure of the order parameter of superfluid ^{3}He gives rise to a variety of different vortex states when the superfluid is set into rotation. Recent NMR experiments[1] on ^{3}He-A have demonstrated the effect of rotation on the texture of the $\mathbf{l}$ vector (angular momentum of Cooper pairs). These experiments have inspired efforts to identify the vortices and especially the nature of the vortex cores,[2] but a complete identification has not been achieved yet. In this situation we felt it worthwhile to investigate the rotation-induced textures with a different technique: We studied the influence of rotation on the motion of negative ions through a sample of ^{3}He-A.[3] In this Letter we report on our first results of these experiments.

We find that an ion pulse moving parallel or antiparallel with $\mathbf{\Omega}$ is considerably delayed compared to the nonrotating case. Furthermore, large changes in the shapes of the pulses are observed. We attribute this behavior to a deflection of the ion trajectories by the $\mathbf{l}$ texture in the soft cores of the vortices present under rotation. This deflection is due to the anisotropic ion mobility and leads to a focusing effect which concentrates the ion paths along the vortex cores. We analyze our results quantitatively by using a model that relates the observed time of flight to the properties of the focusing texture.

The experimental volume is a cylinder with its axis along the common direction of $\mathbf{\Omega}$ and $\mathbf{H}$; see Fig. 1. Pulses of negative ions, produced by a field-emission tip, were driven along the axis of the cylinder and detected by an electrometer. The driving electric field was obtained by biasing of the cell base to $V_0=-20$ to -60 V, the casing to $V_c=\frac{2}{3}V_0$, and the top to $V_t=\frac{1}{3}V_0$. In addition to this "converging" field configuration where the electric field is roughly uniform and along $\hat{\mathbf{z}}$, a "diverging" one with $V_c=V_t=V_0/3$ was used where the field is more spherical, thus spreading the ion pulses partly onto the cylindrical electrode.

The measurements were performed at $P=29.3$ bar, at $H=28.4$ mT, and in the temperature range $T/T_c \geqslant 0.7$. Pulsed NMR on platinum (powder immersed in the liquid) was used as the primary thermometer. The superfluid transition temperature T_c, marked by a rapid change in the ion mobility,[4] and the $B\rightarrow A$ transition during warmup provided the calibration points. At T_{AB} the pulse shape changes and we also observe an increase in the mobility.

The time of flight of the ions was measured by injecting short (1–5 ms) pulses at a constant frequency $f=0.6$–1.2 Hz and detecting the electrometer output by a vector lockin amplifier. The phase output Φ of the lockin amplifier is determined by the "center of mass" of the current pulses $I(t)$. Therefore, Φ and the time of flight $\langle t\rangle$ averaged over all the ions in a pulse are related by $\Phi=\Phi_0+2\pi f\langle t\rangle$, where Φ_0 is an arbitrary constant. Because of the steep temperature

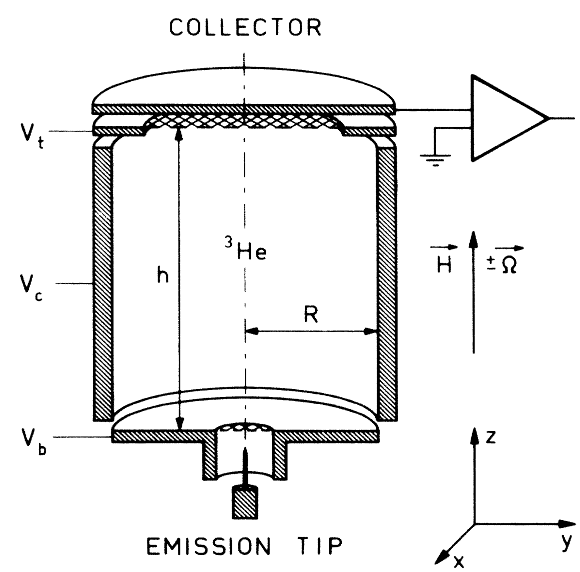

FIG. 1. Our time-of-flight spectrometer. The walls facing the experimental volume ($h=20.5$ mm, $R=9.3$ mm) consist of three electrodes made of gold-plated copper. The base and top electrodes have circular windows ($r=2$ and 7.3 mm, respectively) covered with thin grids made of gold.

dependence of mobility μ, the time-of-flight measurement provides a sensitive secondary thermometer[5] below T_c with an on-line display and a noise level corresponding to 1–10 μK.

The drift velocity $\mathbf{v}$ of ions in ^{3}He-A is given by $\mathbf{v}=\mu_\perp \mathbf{E}-\Delta\mu(\mathbf{E}\cdot\mathbf{l})\mathbf{l}$ where $\mu_\perp(T)$ and $\mu_\parallel(T)\equiv \mu_\perp(T)-\Delta\mu(T)$ are the mobilities perpendicular and parallel to the anisotropy axis $\mathbf{l}$. For negative ions $\mu_\perp,\mu_\parallel<0$, and the anisotropy $\Delta\mu/\mu_\perp$ grows toward lower temperatures being 0.57 at $T=0.7T_c$.[6,7] When $\Omega=0$ we basically measure $\mu_\perp$ in the converging electric field, because $\mathbf{E}\parallel\mathbf{H}\perp\mathbf{l}$ (dipole-locked condition). A natural temperature scale for the focusing phenomena is provided by the normalized mobility $\mu_\perp/\mu_N$ where μ_N is the mobility in the normal ^{3}He. Consequently we use $\mu_\perp/\mu_N$ as our temperature variable.[8]

The experiments were done by cooling the sample below T_c and then accelerating ($\dot{\Omega}=0.02$–0.04 rad/s^2) the cryostat to a constant angular velocity $\Omega\leq 2$ rad/s. After a few minutes of rotation the cryostat was brought back to rest. Our basic observable was a rotation-induced increase in the time of flight of the ion pulses, $\Delta\langle t\rangle\equiv\langle t\rangle^*-\langle t\rangle$, in the converging electric field. Here $\langle t\rangle^*$ denotes the time of flight during rotation. The retardation was accompanied by a distinct deformation of the current pulses and a decrease in the total charge reaching the collector; see Fig. 2. All these effects were absent in the normal fluid and also in the B phase, which was used to check for a possible change in the time of flight caused by rotation-induced heating. Alternatively, in diverging electric field the amount of charge reaching the collector was increased by a factor of 2–8 when the cryostat was set into rotation.

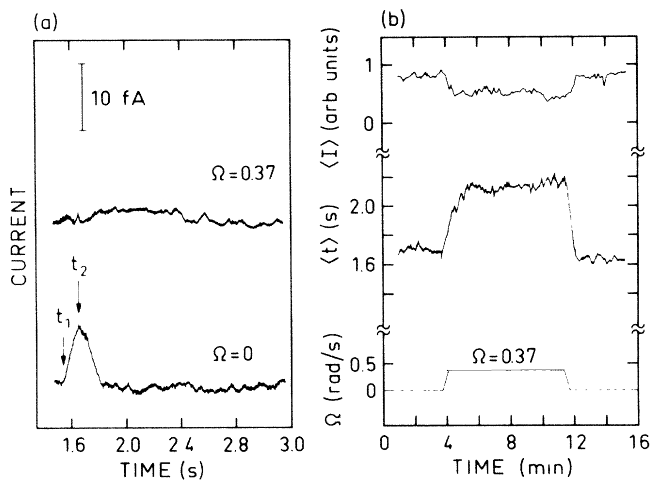

FIG. 2. The effect of rotation on pulses of negative ions drifting parallel to the angular velocity $\mathbf{\Omega}$ in a converging electric field $\mathbf{E}\simeq E_0\hat{\mathbf{z}}$, with $E_0=-6.55$ V/cm. (a) The current pulses recorded by the electrometer. When $\Omega=0$ the leading and the trailing edges of the ion pulse reach the top grid at t_1 and t_2, respectively. During rotation the current pulse prolongs drastically. In the experiment ion pulses are fired at a constant frequency and the electrometer output is fed into a vector lockin amplifier. (b) The amplitude and phase outputs of the amplifier recorded over an 8-min-long rotation period. The angular velocity of the cryostat is also shown. The phase output is converted into averaged time of flight $\langle t\rangle$, and the rotation-induced increase in $\langle t\rangle$ is our basic observable. The data shown are recorded at $T=0.73T_c$.

The observed $\langle t\rangle^*/\langle t\rangle$ versus Ω is shown in Fig. 3. The relative retardation $\Delta\langle t\rangle/\langle t\rangle$ is large, of the order of $\Delta\mu/\mu_\perp$. It depends on the size of the ion pulses and is not strictly linear in Ω ($\propto$ density of vortices). The temperature dependence of $\langle t\rangle^*/\langle t\rangle$ is illustrated in Fig. 4. These data also show that $\Delta\langle t\rangle/\langle t\rangle$ is independent of the sense of rotation as well as of the strength of the electric field.

We attribute the observed delay $\Delta\langle t\rangle$ to focusing of the ions by the $\mathbf{l}$ texture in the soft cores of the vortices. The reasoning is as follows. The retardation $\Delta\langle t\rangle$ vanishes in the B phase, and in the A phase it scales well with the calculated[6] temperature dependence of the mobility anisotropy (as shown quantitatively below). Therefore, $\Delta\langle t\rangle$ is associated with some rotation-induced changes in the $\mathbf{l}$ texture. On the other hand, any textural defect created by rotation would lead to retardation of the pulses because at $\Omega=0$ we measure the maximal mobility in the A

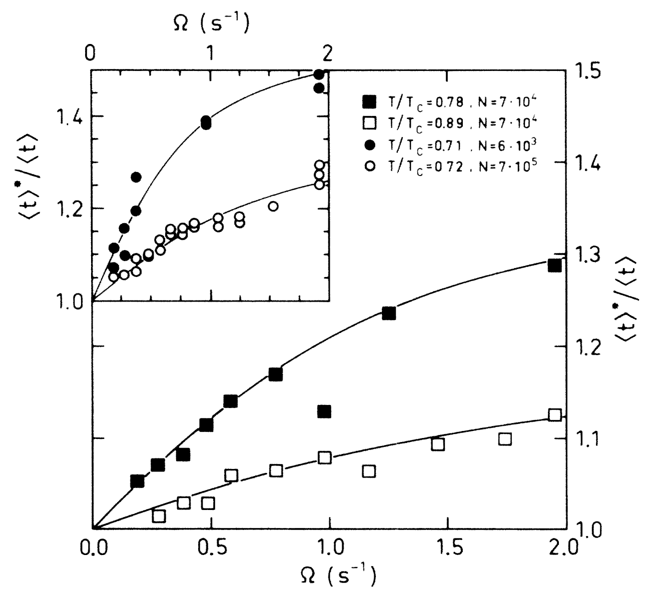

FIG. 3. Reduced time of flight $\langle t\rangle^*/\langle t\rangle$ of ion pulses vs Ω in a converging electric field. N indicates the number of ions per pulse. Inset: The dependence of $\langle t\rangle^*/\langle t\rangle$ on pulse size. All solid lines correspond to fits of Eq. (1) with the corresponding values for parameters α and Ω_0 indicated in the text.

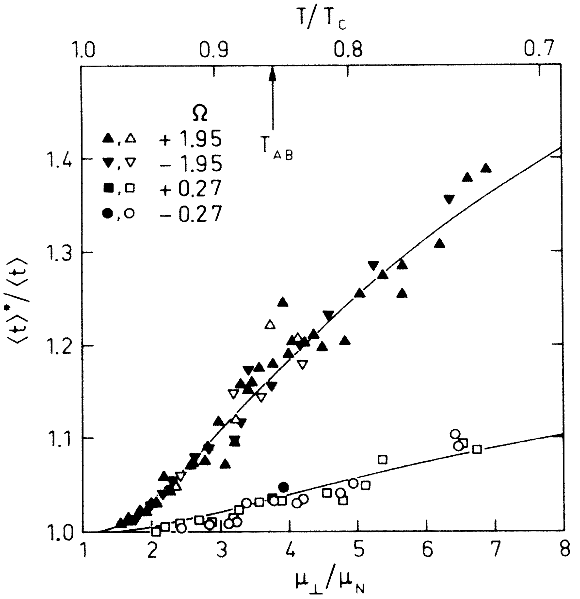

FIG. 4. Reduced time-of-flight data vs temperature. In addition to the natural temperature variable $\mu_\perp/\mu_N$ the proper temperature scale is shown at the top. A considerable fraction of the temperature range covered is in supercooled A phase. Plus and minus signs indicate that $\mathbf{\Omega}$ is parallel and opposite to $\mathbf{H}$, respectively. Open and filled symbols correspond to $V_0=-30.0$ and -20.1 V. The solid lines are obtained from a fit of Eq. (1) to all our data with the $N=7\times10^4$ pulses.

phase, $\mu_\perp$. The hypothesis that the ions are indeed focused into the vortex cores is, however, supported by several experimental observations: The observed increase of the charge collected in the diverging electric field indicates that during rotation the motion of ions is strongly modified by an effect that favors an ion current parallel with $\mathbf{\Omega}$. The crucial finding is that $\Delta\langle t\rangle/\langle t\rangle \simeq \Delta\mu/\mu_\perp$. This large retardation can result only if there is strong concentration of the ions into regions where $\mathbf{l}$ is essentially along $\hat{\mathbf{z}}$ and $\Delta\mu(\mathbf{E}\cdot\mathbf{l})\mathbf{l}\cdot\hat{\mathbf{z}} \simeq \Delta\mu\, E$, that is into soft vortex cores.[9] The fact that $\Delta\langle t\rangle$ is not linear in Ω and depends on the size (rigidity) of the pulses also indicates that the pulses are severely deformed instead of staying uniform and simply sampling the $\mathbf{l}$ texture of the vortex lattice. The rotation-induced decrease of the current in converging electric field (see Fig. 2) may be due to partial pinning of the vortex lattice on the grid wires in front of the collector; ions coming along the pinned vortices never reach the collector.

Assuming complete focusing immediately after the ions enter the vortex lattice would give $\langle t\rangle^*/\langle t\rangle \simeq (1-\Delta\mu/\mu_\perp)^{-1}$, which is larger than our experimental values and independent of Ω. Therefore a more detailed treatment of the focusing process is necessary. Let us consider the converging field case where $\mathbf{E}\simeq E_0\hat{\mathbf{z}}$ ($E_0<0$). In our low-density pulses focusing by texture dominates over Coulomb repulsion between the ions.[10] Consequently, we make two assumptions: (1) The focused charge concentrates into relatively small focal regions[10] where it is left behind the ion pulse propagating in the bulk, because the velocity of the ions along the soft core $\{v_z\}_c=(\mu_\perp-\Delta\mu\{l_z^2\}_c)E_0\equiv(\mu_\perp-\alpha\,\Delta\mu)E_0\equiv\mu_c E_0$ is less than the velocity in the bulk $v_z=\mu_\perp E_0$.[11] Here $\{\ \}_c$ denotes averaging over the focal region and $\{l_z^2\}_c\equiv\alpha$. (2) Once focused, the ions stay in the core and propagate along it even when left behind the pulse in the bulk. Additionally, to explain the size of the observed $\Delta\langle t\rangle$ it is necessary to assume continual focusing: the asymptotic ($r\to\infty$) form of the $\mathbf{l}$ texture must be such that there is a continual flux of ions into the core ($\int \mathbf{v}\cdot\mathbf{r}\,d\phi<0$). This implies that we can take the charge density being focused at each moment to be proportional to the roughly uniform charge density in the part of the pulse propagating in the bulk: $\{\rho\}_c(t)=c\rho_b(t)$ and $c>0$ constant. With these assumptions a straightforward calculation[5] of the time of flight $\langle t\rangle^*$ averaged over all the ions in one unit cell of the vortex lattice leads to

$$\frac{\langle t\rangle^*}{\langle t\rangle}=1+\alpha\frac{\Delta\mu}{\mu_\perp}\frac{\langle t\rangle^*}{\langle t\rangle}-\frac{\Omega_0}{\Omega}\left[1-\exp\left(-\alpha\frac{\Delta\mu}{\mu_\perp}\frac{\Omega}{\Omega_0}\frac{\langle t\rangle^*}{\langle t\rangle}\right)\right], \quad (1)$$

where a characteristic angular velocity Ω_0 is defined by $\Omega_0/\Omega=A_\mu d/cA_c h$. Here h and d are the length of the drift space and the thickness of the ion pulse in the z direction, respectively. A_c and $A_\mu=p\pi\hbar/2m_3\Omega$ are the areas of the soft core and the unit cell of the vortex lattice; p is the number of circulation quanta in one vortex.

Equation (1) is a good fit to the (Ω,T) dependence of our data when $\Delta\mu/\mu_\perp$ from Ref. 6 is used. For the fitting parameters we find $\alpha=0.58\pm0.05$ and $\Omega_0=0.16\pm0.02$ rad/s when pulses with $N=7\times10^4$ electrons are used. The curves in Figs. 3 (not in the inset) and 4 correspond to these values. The current pulses measured at $\Omega=0$ give us $d/h\simeq(t_2-t_1)/t_1$ (see Fig. 2), and if $p=2$ is also assumed,[2] the observed Ω_0 implies $cA_c=4.4\times10^{-8}$ m^2. This being larger than the core size (3×10^{-9} m^2) calculated for continuous, doubly quantized vortices[2] probably results from the fact that $\mathbf{v}$ in the bulk liquid is not strictly along $\mathbf{\Omega}$, which increases the effective capture cross section of the cores.

Our data taken with small ($N=6\times10^3$) and large ($N=7\times10^5$) pulses (see insert in Fig. 3) give $\Omega_0=0.13$ rad/s, $\alpha=0.66$, and $\Omega_0=0.17$ rad/s, $\alpha=0.49$, respectively. Ω_0 changes more than d, which suggests that also c depends on the pulse size. The decrease of α toward larger pulses is explained by Coulomb repulsion: A larger focal region is sampled by larger pulses having a higher charge density. This results in a lower averaged l_z^2.

In summary, our experiment on ion motion in rotating superfluid ^{3}He has given the first evidence that ions, because of their anisotropic mobility, are a useful probe for the vortex textures in the A phase. The observed focusing phenomenon is sensitive to both the core structure in the focal region where the ions gather and the asymptotic form of the $\mathbf{l}$ texture far from the center of the core. Further studies with this technique appear promising for a more detailed identification of the vortices.

We thank P. J. Hakonen, M. Salomaa, and Y. Takano for discussions and O. V. Lounasmaa for continual interest and encouragement. This work was supported by the Academy of Finland and the Emil Aaltonen Foundation.

[(a)]Permanent address: Department of Physics, Kyoto University, Sakyo-ku, Kyoto 606, Japan.

[(b)]Permanent address: Sektion Physik, Universität Regensburg, D-8400 Regensburg, West Germany.

[(c)]Permanent address: Physical Institute of the Czechoslovak Academy of Sciences, Na Slovance 2, 18040 Prague 8, Czechoslovakia.

[1]P. J. Hakonen, O. T. Ikkala, S. T. Islander, O. V. Lounasmaa, and G. E. Volovik, J. Low Temp. Phys. **53**, 425 (1983); P. J. Hakonen, M. Krusius, and H. K. Seppälä, J. Low Temp. Phys. **60**, 187 (1985).

[2]H. K. Seppälä and G. E. Volovik, J. Low Temp. Phys. **51**, 279 (1983); V. Z. Vulovic, D. L. Stein, and A. L. Fetter, Phys. Rev. B **29**, 6090 (1984); H. K. Seppälä, P. J. Hakonen, M. Krusius, T. Ohmi, M. M. Salomaa, J. T. Simola, and G. E. Volovik, Phys. Rev. Lett. **52**, 1802 (1984).

[3]The first to discuss probing of rotating textures by ions were H. R. Williams and A. L. Fetter [Phys. Rev. B **20**, 169 (1979)].

[4]A. I. Ahonen, J. Kokko, M. A. Paalanen, R. C. Richardson, W. Schoepe, and Y. Takano. J. Low Temp. Phys. **30**, 205 (1977).

[5]J. T. Simola, K. K. Nummila, J. S. Korhonen, and L. Skrbek, to be published.

[6]M. Salomaa, C. J. Pethick, and G. Baym, J. Low Temp. Phys. **40**, 297 (1980); M. Salomaa, private communication.

[7]P. D. Roach, J. B. Ketterson, and P. R. Roach, Phys. Rev. Lett. **39**, 626 (1977).

[8]Any textural defects, e.g., planar solitons, could blur the measured $\mu_\perp(T)$ relation, but from one cooling to another we always reproduced $\mu_\perp(T)$ within two percent.

[9]Neglecting focusing ($\mathbf{v}_\perp = 0$) leads to $\langle t\rangle/\langle t\rangle = \{[1 - (\Delta\mu/\mu_\perp) l_z^2]^{-1}\}_u = 1 + \gamma\xi_D^2 2m_3\Omega/p\hbar$, where $\{\ \}_u$ denotes averaging over the unit cell area in a lattice of vortices (p quanta of circulation per vortex). For the continuous vortex textures proposed in Ref. 2, $\gamma \simeq 1$, while experimentally $\gamma \simeq 100$.

[10]With $\nabla\cdot\mathbf{v} = \mu_\perp\nabla\cdot\mathbf{E} - \Delta\mu\nabla\cdot[(\mathbf{E}\cdot\mathbf{l})\mathbf{l}]$ and $\mathbf{E} \simeq E_0\hat{\mathbf{z}}$ ($E_0 < 0$) the equation of continuity becomes $d\rho/dt + \rho[\rho\mu_\perp/\epsilon - \Delta\mu E_0\nabla\cdot(l_z\mathbf{l})] = 0$, where ϵ is the dielectric constant of ^{3}He. In a focal region where the ion trajectories gather and $\nabla\cdot(l_z\mathbf{l}) > 0$, the Coulomb repulsion and the focusing forces (the terms in square brackets) are in balance when $\rho \simeq \epsilon E_0(\Delta\mu/\mu_\perp)\nabla\cdot(l_z\mathbf{l}) \simeq \epsilon E_0(\Delta\mu/\mu_\perp)/\xi_D$. In a typical field $E_0 \simeq -10$ V/cm; this corresponds to an ion density $n \simeq 10^9$ cm^{-3} well in excess of the average $n \simeq 10^6$ cm^{-3} in our pulses.

[11]We assume that the vortices in A phase are continuous, i.e., A phase throughout the core. This is plausible in view of the earlier NMR experiments. If, however, this is not the case, μ_c should be considered as the mobility of ions in the "hard" core superfluid.