duces quantized vortices into the superfluid to establish the initial stationary shear flow.

I am indebted to Dr. P. W. Anderson for a detailed discussion of his ideas and experiments. I am also grateful for several discussions with Professor G. Wentzel, Professor J. C. Phillips, Dr. J. E. Mercereau, and Dr. J. J. Domingo.

---

*This research is supported by National Science Foundation Grant No. NSF GP-2693, and by U. S. Air Force Office of Scientific Research Grant No. AF-AFOSR-785-65. General support from the Advanced Research Projects Agency for the Institute for the Study of Metals is also acknowledged.

[1]P. L. Richards and P. W. Anderson, Phys. Rev. Letters 14, 540 (1965).

[2]S. T. Beliaev, Zh. Eksperim. i Teor. Fiz. 34, 417 (1958) [translation: Soviet Phys.–JETP 7, 289 (1958)].

[3]J. G. Daunt and K. Mendelssohn, Nature 157, 829 (1946).

[4]R. P. Feynman, Progress in Low Temperature Physics, edited by C. J. Gorter (North-Holland Publishing Company, 1955), Vol. I, Chap. II.

[5]E. P. Gross, J. Math. Phys. 4, 195 (1963).

[6]T. Tsuneto, Prog. Theoret. Phys. (Kyoto) 31, 330, 516 (1964).

[7]P. W. Anderson has pointed out that if the chemical-potential histories of the two baths have not been identical, the phases will have changed, and a current will flow on reuniting the film.

[8]P. W. Anderson, Lectures on the Many-Body Problem, edited by E. R. Caianiello (Academic Press, Inc., New York, 1964), Vol. 2, p. 113.

[9]V. L. Ginzburg and L. P. Pitaevskii, Zh. Eksperim. i Teor. Fiz. 34, 1240 (1958) [translation: Soviet Phys.–JETP 7, 858 (1958)].

[10]H. A. Snyder and R. J. Donnelly, Phys. Fluids 2, 408 (1959). The author's value 8.59×10^{-5} cm^2/sec was measured at 1.5°K and is to be multiplied by ρ/ρ_S to compare with (8).

[11]R. J. Donnelly and K. W. Schwarz, Proc. Roy. Soc. (London) A283, 531 (1965).

[12]R. J. Donnelly, "On the Hydrodynamics of Superfluid Helium," thesis, Yale University, 1956 (to be published).

[13]S. Chandrasekhar and R. J. Donnelly, Proc. Roy. Soc. (London) A241, 9 (1957). The equations of motion used here have been superseded by those of I. L. Bekarevich and I. M. Khalatnikov, Zh. Eksperim. i Teor. Fiz. 40, 920 (1961) [translation: Soviet Phys.–JETP 13, 643 (1961)].

[14]R. J. Donnelly, Phys. Rev. Letters 3, 507 (1959).

FLOW VISUALIZATION IN He II: DIRECT OBSERVATION OF HELMHOLTZ FLOW*

T. A. Kitchens,† W. A. Steyert, and R. D. Taylor

University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico

and

Paul P. Craig

Brookhaven National Laboratory, Upton, New York

(Received 6 May 1965)

It has recently been suggested[1] that in the flow of He II about obstacles, such as Rayleigh disks and airfoils, perfect potential flow does not invariably obtain, and flow separation of the type discovered by Helmholtz[2] commonly occurs. In this Letter we report experiments verifying this suggestion by means of direct observation of the motion of particles of frozen H-D gas about obstacles placed in a bath of rotating He II.

One of the most unambiguous methods of studying the nature of hydrodynamic flow is by introducing into the flow tracer particles which follow trajectories known as path lines. In steady-state flow, path lines are identical with streamlines. Dyes and gas bubbles are typically used in classical studies, but these techniques are impractical in He II. An alternative approach is the use as tracers of small particles of density equal to that of He II. Such particles are unaffected by gravity and remain suspended for long periods. An excellent material for this purpose is frozen H-D gas, which was originally used by Chopra and Brown[3] in studies of acoustic streaming.

In our experiments He II was brought into rotation inside a horizontally mounted cylinder (length 2.9 cm, diameter 2.3 cm) of wire mesh which was driven from outside the cryostat. One end of the cylinder was closed with an optically blackened cover and the other with a glass plate, thereby permitting viewing along the cylinder axis. H-D gas could be introduced above the He level. Upon freezing, particles of 20-100 μ diameter were found, some of which drifted through the mesh and into the viewing space. The particles were observed as they flowed past a "wing" (a flat plate 2.3 mm wide by 0.14 mm thick by 14 mm long) mounted with the long axis parallel to but radially displaced 6 mm from the axis of the rotating cylinder. Dark-field illumination was provided by an external light source and a Pyrex light pipe. The observed particle motion was essentially two dimensional as expected. Particle motion was recorded at unit magnification on 16-mm motion picture film at 24 frames/sec. Particle trajectories and velocities were later obtained from frame-by-frame analysis.

Experiments were performed at a number of temperatures and angular velocities, and for wing attack angles of 27°, 45°, and 90° (the attack angle is the angle between the plane of the wing and the fluid velocity vector in the absence of the wing). Approximately 3×10^4 suspended particles have been photographed, occasionally with as many as 50 present simultaneously. Figure 1(a) displays typical trajectories obtained at 2.08°K with an attack angle of 45°. The average fluid velocity at the wing is $v = r\omega = 0.9$ mm/sec. The points are plotted at $\frac{1}{2}$-second intervals, so that the spacing between points is proportional to the particle velocities. The broken curve is a section of a circle of 6-mm radius, and typifies particle trajectories in the absence of the wing. Particles some distance from the wing are essentially uninfluenced by it. Particles approaching head-on slow down and move around the wing. Behind the wing particles are caught in back eddies. Dashed lines represent the motion of large numbers of particles in such eddies. This type of flow pattern is found over the entire temperature and velocity ranges studied ($1.3°\mathrm{K} < T < 2.1°\mathrm{K}$ and $0.9 < v < 26$ mm/sec). Results obtained at a 90° attack angle are similar to those at 45° except that at the highest velocities a turbulent pattern of alternate vortex shedding is evident, closely resembling the classical von Kărmăn vortex street. In none of the studies at these high attack angles did the flow show evidence of closing in upon itself behing the wing. The region of turbulence extended downstream to the edge of the field of view.

The behavior at an attack angle of 27° is similar at high velocities to that at the larger attack angles. However, at 27° there exists a (temperature-dependent) critical velocity below which there are no large eddies in the wake; instead there is only a small eddy close behind

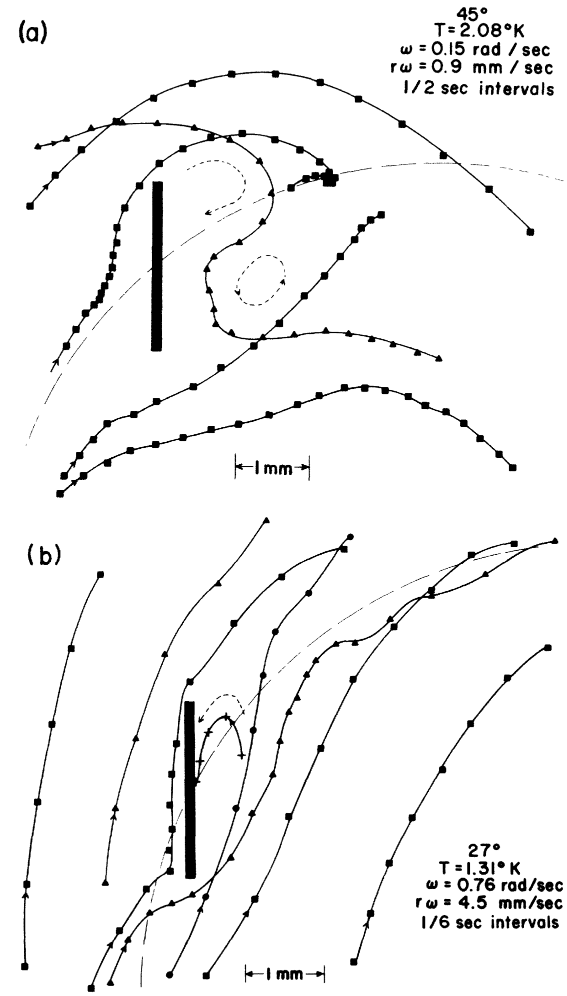

FIG. 1. (a) Typical trajectories of frozen particles of H-D about an airfoil immersed in clockwise-rotating He II. On the downstream side of the wing the flow is turbulent with discontinuities in the velocity streamlines, indicating the existence of Helmholtz flow. The wing attack angle is 45°. (b) Flow about a wing at 27° attack angle. Flow separation is not complete, and approaches much more closely to potential flow than Fig. 1(a).

the wing. This transition has not been fully characterized as yet, but appears to occur near $v = 5$ mm/sec at 2.07°K and near $v = 10$ mm/sec at 1.30°K. A typical case of this type is illustrated in Fig. 1(b), which shows the closing of the flow pattern about a bound vortex behind the wing, indicating only partial flow separation.

Because of the possibility of excess viscosity effects[4] in rotating He II, we are performing classical studies on wings in rotating water-glycerol mixtures as a function of Reynolds number and attack angle, for comparison with the He II results. Flow patterns may be visualized by sprinkling aluminum dust on the liquid surface. Figure 2 shows typical classical flow patterns obtained at a Reynolds number (referred to the wing width) of 80. The velocity discontinuities associated with Helmholtz flow are apparent, and the flow is closely analogous to that of Fig. 1. In this situation, because of the low Reynolds number, the streamlines close upon themselves a few wing chords downstream.

The results presented above demonstrate that H-D particles in He II undergo motion approximating classical Helmholtz flow. In order to relate this conclusion to the forces on the wing, we must consider the forces acting on the H-D particles. The superfluid component of He II is known to undergo perfect potential flow at low velocities.[5,6] This result implies that the drag force is zero (d'Alembert's paradox).[7]

(a)

(b)

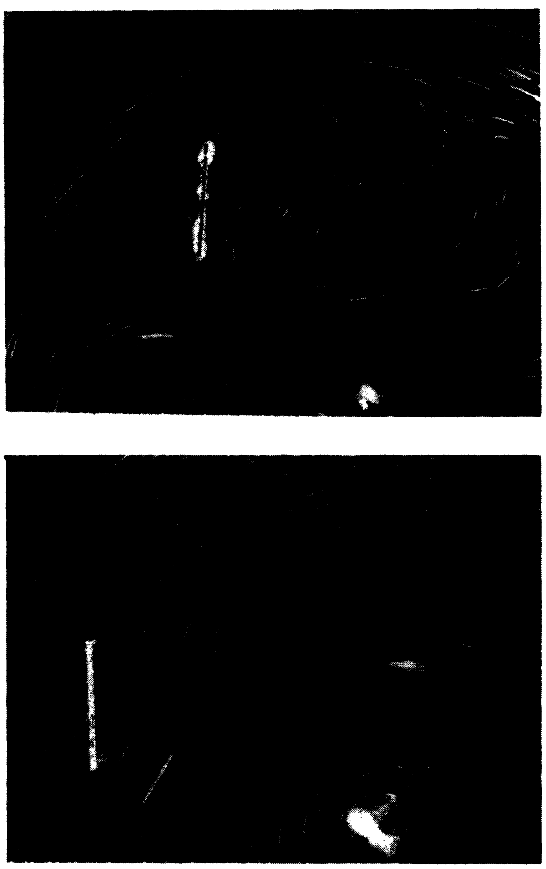

FIG. 2. A classical illustration of Helmholtz flow in a rotating water-glycerol mixture. The attack angle is 47° in Fig. 2(a) and 27° in Fig. 2(b). In both cases the Reynolds number Re = 80. The center of rotation is the light flare in the lower right.

The normal fluid (velocity v_n) is expected to exert a drag force varying between v_n and v_n^2, depending on Reynolds number; and, therefore, the particles are expected to move with the normal fluid (though possibly at a reduced velocity). This contention finds partial support in measurements we have performed on the motion of H-D particles in a heat current counterflow experiment, in which the particles were observed to move with the normal fluid, away from the heater. Our preliminary results suggest that for $1 < v_n < 10$ mm/sec and $1.24 < T < 2.07$°K, the particle velocities lie between $0.4 v_n$ and $1.0 v_n$.

Although the H-D particles appear to move with the normal fluid, the normal fluid motion is intimately related to that of the superfluid, for even in the absence of nonlinear terms (e.g., the Gorter-Mellink force), the superfluid and normal fluid are coupled through the quadratic terms (Bernoulli forces) which occur in the substantial derivatives in the equation of motion.[8]

Because our results in rotating He II are substantially temperature independent, they do not appear to lead to an understanding of the remarkable temperature dependence of the torque on a Rayleigh disk observed by Pellam.[9] It is, however, now clear that Helmholtz flow can play an important role in the flow of He II about obstacles, and that in many cases the angular dependence and magnitude of torque and of lift and drag forces will differ appreciably from the predictions of perfect potential flow.

---

*Work performed under the auspices of the U. S. Atomic Energy Commission.

†Now at Brookhaven National Laboratory, Upton, New York.

[1]P. P. Craig, Phys. Rev. Letters 13, 708 (1964).

[2]A. Sommerfeld, Mechanics of Deformable Bodies (Academic Press, Inc., New York, 1950), Vol. II. See in particular Figs. 47 and 49 illustrating Helmholtz flow.

[3]K. L. Chopra and J. B. Brown, Phys. Rev. 108, 157 (1957).

[4]P. P. Craig, Proceedings of the Eighth International Conference on Low-Temperature Physics, London, 1962, edited by R. O. Davies (Butterworth Scientific Publications, Ltd., London, 1962), p. 102.

[5]T. R. Koehler and J. R. Pellam, Phys. Rev. 125, 791 (1962). In reference 1 it is asserted that the experimental results of this paper are in accord with Helmholtz rather than potential flow. This conclusion resulted from a misprint in the tunnel diameter, which was actually 0.99 rather than 0.36 cm. At the velocities studied the torque on the Rayleigh disk was quantitatively within 5% of that expected from perfect po-

tential flow.

[6]P. P. Craig and J. R. Pellam, Phys. Rev. 108, 1109 (1957).

[7]J. L. d'Alembert, Essai d'une Nouvelle Théorie de la Résistance des Fluides (David, Paris, 1752).

[8]F. London, Superfluids, Vol. II (John Wiley & Sons, Inc., New York, 1954).

[9]J. R. Pellam, Phys. Rev. Letters 5, 189 (1960).

BLOCKING EFFECTS IN THE EMERGENCE OF CHARGED PARTICLES FROM SINGLE CRYSTALS*

D. S. Gemmell and R. E. Holland

Argonne National Laboratory, Argonne, Illinois

(Received 26 April 1965)

When a beam of energetic positively charged particles is passed through a thin single crystal oriented with a major symmetry axis close to the beam direction, one observes many effects produced by "channeling" of the incident beam.[1-6] These effects are presumed[1,7] to result from the influence of parallel strings of atoms which collectively confine a fraction of the beam within the open "channels" lying between low-index atomic planes.

This Letter reports the observation of a related but distinct phenomenon seen when one detects charged particles emitted from atomic nuclei occupying sites within the crystal lattice. Our experiments were prompted by the expectation that the spatial and energy distributions of charged reaction products produced in a crystalline target should be strongly modified in directions corresponding to major crystallographic axes and planes. For example, consider a simple model in which the atoms of the crystal do not vibrate. Suppose also that the nuclei of these atoms emit particles with charged Z_1e and energy E in a direction in which there is a chain of atoms with interatomic spacing l. Such a model would predict the complete extinction of particles emitted in a small cone about this direction. The extinction is entirely due to the blocking effect of Rutherford scattering at the nucleus of the nearest-neighbor atom in the chain. Neglecting recoil effects, electronic screening effects, and possible channeling effects, the total angular width of the region of extinction is given to a good approximation by

$$\beta = \left\{ \frac{16 Z_1 Z_2 e^2}{lE} \right\}^{1/2}, \qquad (1)$$

where Z_2e is the nuclear charge of an atom in the crystal. Recoil and screening effects may be expected to reduce the angular width of the anomaly. Thermal vibrations and channeling effects may also be expected to modify the angular width and to permit some transmission in the direction of the atomic chain. For 4-MeV protons in a silicon lattice, the value of the expression in Eq. (1) is about 1°.

Evidence for such an axial blocking effect has been found by Domeij and Björkqvist[8] who studied the distribution of α-particles emitted from Rn^{222} ions lodged in a tungsten crystal.

We have used two experimental techniques to look for effects of the type discussed above. Firstly, we have employed photographic emulsions to examine the spatial distribution of protons, deuterons, and alpha particles scattered from a silicon single crystal and of protons scattered from a germanium crystal. Protons from the (d,p) reaction in a silicon crystal were also studied by use of emulsions. Secondly, by using a position-sensitive semiconductor detector,[9] we have performed two-parameter pulse-height analyses (256×256 channels) of both the energies and positions of charged particles scattered at wide angles from a silicon single crystal. The emulsion technique permitted simultaneous measurements over a wide range while the detector gave more detailed information over a small angular range.

The photographic emulsions, on glass backings, were exposed inside an 18-in. scattering chamber. The incident beam was produced by the Argonne tandem Van de Graaff and was restricted by a series of collimators to have a total angular divergence of less than 0.03°. The size of the beam spot at the target position was less than 0.8 mm. Initially, without the emulsion in the chamber, the target crystal was suitably oriented by observing the fluorescence pattern of a transmitted beam of 4-MeV protons on a quartz plate at the end of the chamber. In this manner one can easily

(a)

(b)

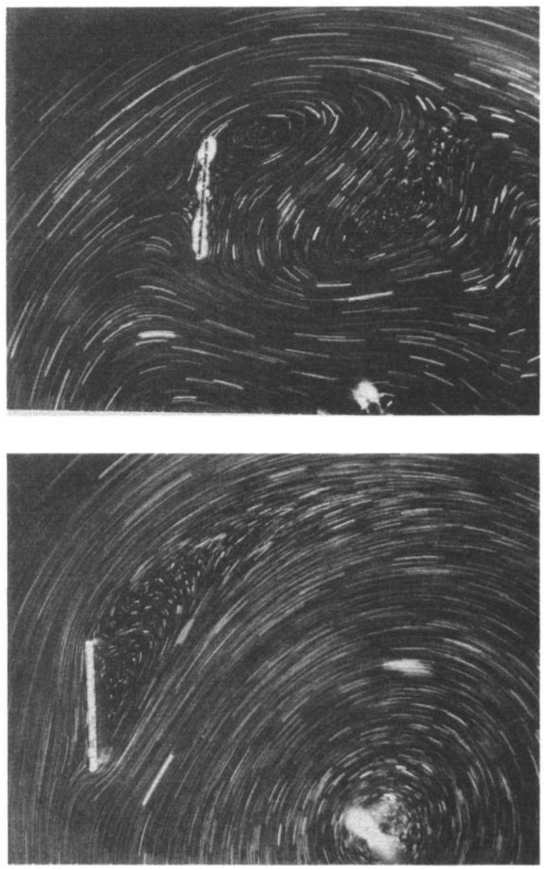

FIG. 2. A classical illustration of Helmholtz flow in a rotating water-glycerol mixture. The attack angle is 47° in Fig. 2(a) and 27° in Fig. 2(b). In both cases the Reynolds number Re = 80. The center of rotation is the light flare in the lower right.