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# Inhibition of the Scintillation of Stationary and Rotating He II†

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The intensity of the scintillations produced by 5.28-MeV alpha particles in stationary and rotating He II has been observed at temperatures between 1.1 and 3.0°K. The results indicate a structure in the intensity-versus-temperature curve which was not apparent in previous less precise measurements. No change in intensity ( $<0.5\%$) was observed upon the establishment of rotation-induced vortex lines.

## INTRODUCTION

RECENT experiments have demonstrated that the superfluidity of liquid He II affects its scintillation properties. The most striking effect is a decrease in the intensity of alpha-particle-produced scintillations as the temperature is reduced below the lambda point,[1] an effect which does not occur when scintillations are produced by beta particles.[2]

The application of an electric field and the collection of ions from the alpha track region further diminish the He II scintillation intensity,[3] indicating that recombination luminescence contributes significantly to the scintillation. If the field-induced decrease in intensity and the collected ion current are measured simultaneously at various temperatures, an unexpected temperature dependence of both quantities becomes apparent.[4] More specifically, both the magnitude of the decrease in intensity and the ion current rise below 2.18°K but level off at approximately 1.75°K, remaining roughly constant (possibly decreasing somewhat) as the temperature is further reduced to 1.2°K.

This behavior is similar to that predicted by Donnelly[5] and observed by Springett *et al.*[6] and by Douglass[7] with regard to the temperature dependence of the cross section for the capture of ions by rotation-induced vortex lines in He II. Comparison of these experiments suggests the possibility that ion capture by vortex lines or rings, which might be produced in the wake of alpha particles, may play a role in the scintillation process.

In order to explore this question further, we have observed the temperature dependence of the scintillation intensity with greatly increased precision and, also, have studied the effect of rotation-induced vortex lines on the intensity. The measurements of the temperature dependence, as described below, have demonstrated a structure, including a "break" at approximately 1.75°K which was not apparent in our earlier measurements. With regard to the introduction of vortex lines by rotation of the He II container, no effect was observed.

## EXPERIMENTAL ARRANGEMENT

The experiments were performed in a 1-in. by 1-in.-diam. cylindrical scintillation chamber constructed of polished aluminum with a Plexiglas window at the bottom end (see Fig. 1). The inner aluminum walls and top were coated with an evaporated layer of *p*-bis(2,5-phenyloxazolyl)benzene to shift the primary He scintillation radiation (wavelength below 1000 Å) into the visible region. Vents at the top of the chamber were provided for the filling of the chamber and the release of accumulated vapor.

The chamber was located near the bottom face of a glass liquid-helium vessel (not shown in Fig. 1) and was supported by a stainless steel tube which could be rotated at angular velocities up to 11 rad/sec. Throughout the course of measurements, the scintillation chamber remained immersed in liquid helium.

Alpha particles of 5.28-MeV energy were provided by $Po^{210}$. Both a flat source of 0.75 sq. in. area and a source deposited on a 0.032-in.-diam. nichrome wire were employed, the former being situated at the top of the chamber and the latter along its axis. Both source configurations produced the same results in the experiments to be described.

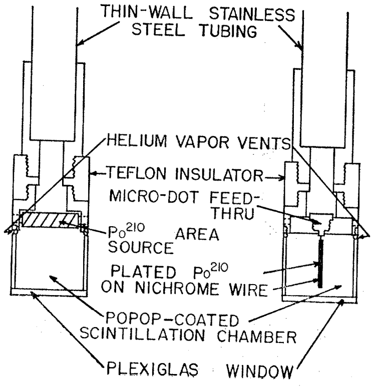

FIG. 1. The scintillation chamber with the flat $Po^{210}$ alpha source (a) and with the axial source (b).

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† Supported by the U. S. Army Research Office.

[1] Frank E. Moss and Frank L. Hereford, Phys. Rev. Letters **11**, 63 (1963).

[2] J. R. Kane, R. T. Siegel, and A. Suzuki, Phys. Letters **6**, 256 (1963).

[3] Frank E. Moss and Frank L. Hereford, in *Proceedings of the Ninth International Conference on Low Temperature Physics, Columbus, Ohio, 1964* (Plenum Press, Inc., New York, 1965), pp. 360–363.

[4] Frank L. Hereford and Frank E. Moss, Phys. Rev. **141**, 204 (1966).

[5] R. J. Donnelly, Phys. Rev. Letters **14**, 39 (1965).

[6] B. E. Springett, D. J. Tanner, and R. J. Donnelly, Phys. Rev. Letters **14**, 585 (1965).

[7] R. L. Douglass, Phys. Rev. **141**, 192 (1966).

Scintillations were detected by an EMI9558B photomultiplier which projected through an O-ring seal at the bottom of the helium cryostat. The rim of the tube face rested against a polished aluminum shield at liquid-nitrogen temperature, the face being 0.375 in. from the bottom of the scintillation chamber shown in Fig. 1.

Photomultiplier pulses were fed into a multichannel pulse analyzer. Pulse-height resolution of approximately 17% was achieved, and the position of the 5.28-MeV alpha peak could be located with good repeatability to within approximately 0.5%. The liquid-helium well was evacuated by a high-speed pump to reduce the temperature, and the temperature below the lambda point was measured by means of a calibrated 22 000-Ω Allen-Bradley carbon resistor.

## THE SCINTILLATION INHIBITION EFFECT

The position (in channel number) of the peak in the pulse-height spectrum is proportional to the number of photons per alpha particle and was taken as a measure of the scintillation intensity. Previous experiments[1] with a variety of wavelength shifters and plastic scintillators have provided evidence that no "instrumental" effects arise as the temperature of the helium bath is lowered.

The intensity of scintillations was observed at various temperatures between 1.1 and 4.2°K with the results depicted in Fig. 2. As the temperature dropped below 2.18°K, the intensity underwent a sharp decrease of approximately 1%, remained approximately constant as the temperature dropped further to about 1.75°K, and then began to decrease significantly again.

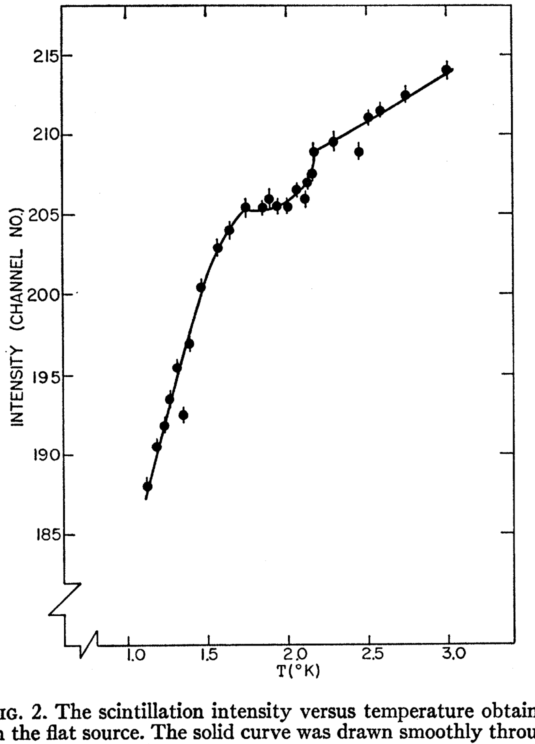

FIG. 2. The scintillation intensity versus temperature obtained with the flat source. The solid curve was drawn smoothly through the experimental points.

The decrease at the lambda point, which occurs for beta-produced scintillations also,[2] is probably related to the cessation of internal boiling and may not relate in any fundamental way to superfluidity. The steady decrease below 1.75°K, however, which is not observed in beta-produced scintillations,[2] appears to derive from the superfluidity of He II and the greater excitation and ionization density in the alpha tracks.

The "break" at 1.75°K and that observed previously in the electric-field-produced ion current (and the corresponding decrease in scintillation intensity)[4] strongly suggest the onset at that temperature of some ion trapping mechanism which reduces the recombination rate. Some such process might inhibit both the recombination of ions and their collection in the presence of an electric field. Ion trapping by vortex lines and rings in He II is known to occur, and the possible role of this process in the scintillation mechanism deserves further attention. It is conceivable that such vorticity could be produced by a given alpha particle rapidly enough to trap ions, or that the entire alpha track region could contain a high density of vorticity (of relatively long life), which could trap ions.

The need for observation of the effect of additional, externally produced vorticity on the scintillation intensity is obvious. In spite of the fact that the vortex density achievable by rotation of the helium bath appears too small to produce observable effects (see below), the distinctly speculative nature of the foregoing discussion and the general lack of detailed knowledge of He II vortex phenomena render further experimental study in this connection desirable.

## EFFECT OF ROTATION

Accordingly, we have observed the temperature dependence of the scintillation intensity in the presence of rotation-induced vortex lines below the lambda point. The scintillation chamber was set in rotation at a temperature of 4.2°K and the temperature of the fluid was lowered below the lambda point. The scintillation intensity was observed at various temperatures, thus providing a measurement of the temperature effect in the presence of vortex lines.

Since light collection efficiency and amplifier gain varied slightly from one set of observations to another, comparison of the scintillation inhibition effect in stationary and rotating He II required normalization of the intensity at a single temperature. This normalization was made just below the lambda point, where fluctuations in internal boiling and turbulence due to rotation of the chamber should not occur. In Fig. 3, experimental points obtained with the flat source at an angular velocity of 2 rad/sec are compared to the curve drawn smoothly through the points in Fig. 2. The results show no rotation-induced effect outside of the experimental error.

With the $Po^{210}$ source deposited on the axial wire, additional measurements were performed at 0, 2, and 11 rad/sec. These results, shown in Fig. 4, again indicate no change in scintillation intensity as a result of rotation.

## DISCUSSION

If one estimates the fraction of ions produced by an alpha particle which might be captured by rotation-induced vortex lines, the null result described in the preceding section is easy to understand. The density of vortex lines is given by[8]

$$n(\omega)\approx 2\times 10^3\omega \text{ lines/cm}^2,$$

or

$$n(2 \text{ rad/sec})\approx 4\times 10^3 \text{ lines/cm}^2.$$

For the case of the wire source, the annular cross-sectional area of the region containing the alpha tracks is

$$A=\pi(R_w+R_\alpha)^2-\pi R_w{}^2\approx 10^{-2} \text{ cm}^2,$$

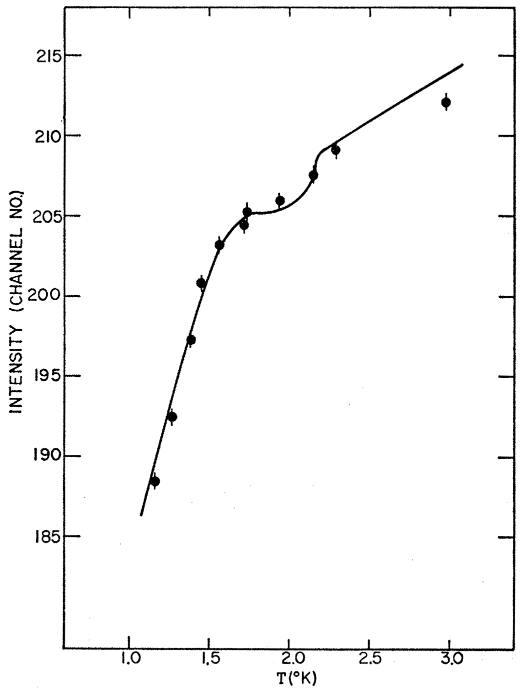

FIG. 3. The scintillation intensity versus temperature with the flat source at an angular velocity of 2 rad/sec compared to the curve in Fig. 2.

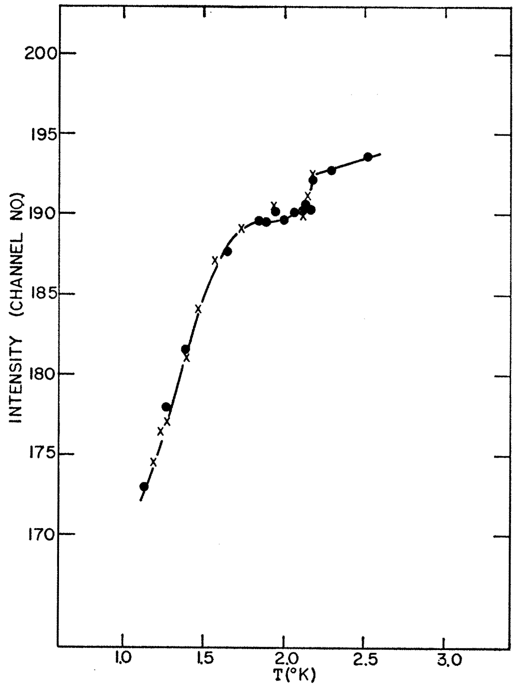

FIG. 4. The scintillation intensity versus temperature with the axial source at 2 (closed circle) and 11 (cross) rad/sec. The solid curve represents the experimental points (not shown) obtained in stationary He II. Probable errors are of the same magnitude as in Figs. 2 and 3.

where $R_w$ and $R_\alpha$ are, respectively, the radius of the wire and the range of the alphas (approximately 0.025 cm). Hence, at 2 rad/sec only about 40 vortex lines intersect the region occupied by the alpha tracks.

The "width" of a line for ion capture at low electric field strengths is approximately $10^{-3}$ cm at the most.[6,7] Consequently, the fractional, cross-sectional area of the alpha track region which is available for ion capture is

$$F\approx 6\times 10^{-4}.$$

Thus, the fraction of ions captured by vortex lines and any resulting reduction in scintillation intensity should be negligibly small, as observed.

It does not necessarily follow from this result that ion capture by vortex rings plays no role in the scintillation mechanism. The question as to whether the alpha particles themselves produce some equilibrium density of vorticity in the region near the source, which is large enough to trap an appreciable fraction of the ions produced, cannot be answered at the present time. Such understanding as exists of vortex ring production[9] is limited to instances in which an external electric field supplies the energy required for an ion to generate a ring. If ion capture by rings does limit the scintillation intensity (by inhibiting recombination), then the simple

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[8] R. P. Feynman, in *Progress in Low Temperature Physics*, edited by C. J. Gorter (North-Holland Publishing Company, Amsterdam, 1955), Vol. 1, Chap. II.

[9] Kerson Huang and A. Cesar Olinto, Phys. Rev. **139**, A1441 (1965); C. DiCastro, Nuovo Cimento **42**, 251 (1966).

interpretation of our earlier experiments reported in a previous paper[4] must be discarded.

Further experiments are planned at lower temperatures in the presence of electric fields to explore the He II scintillation process further. With the more detailed information which these and other experiments should provide, an understanding of the temperature dependence exhibited in Figs. 2–4 may be achieved.

## ACKNOWLEDGMENTS

We wish to thank Professor Kerson Huang of the Massachusetts Institute of Technology for helpful comments relating to ion-vortex ring interactions. We wish, also, to acknowledge the contributions of Dr. Frank E. Moss in connection with the design of the rotating vacuum seal and other equipment which was used.

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# Lambda Transformation of Liquid $He^4$ at High Pressures*

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Measurements are reported of the pressure coefficient $\beta_V=(\partial P/\partial T)_V$ of $He^4$ I and $He^4$ II along the isochore which crosses the λ line at $T_\lambda=1.7683°K$ and $P_\lambda=29.56$ atm, and of the compressibility $\rho\kappa_T=(\partial\rho/\partial P)_T$ along the isotherm $T=1.7683°K$, the closest points being 2.5 μdeg, 50 μatm, and $10^{-7}$ g/cm$^3$ from the lambda line in temperature, pressure, and density, respectively. The data are well represented by the equations:

$$\begin{array}{lll}
\text{He II:} & \beta_V=-14.22+3.54\log_{10}(T_\lambda-T), & 2.4\times10^{-6}\leq T_\lambda-T\leq3\times10^{-3} \\
\text{He I:} & \beta_V=9.00+7.50\log_{10}(T-T_\lambda), & 2.5\times10^{-6}\leq T-T_\lambda\leq6\times10^{-3} \\
\text{He II:} & (\rho\kappa_T)^{-1}=1000.4+78.9\log_{10}(\rho_\lambda-\rho), & 10^{-7}\leq\rho_\lambda-\rho\leq10^{-5} \\
\text{He I:} & (\rho\kappa_T)^{-1}=1675.0+167.2\log_{10}(\rho-\rho_\lambda), & 10^{-7}\leq\rho-\rho_\lambda\leq10^{-5},
\end{array}$$

where $T$ is in °K, $\rho$ in g/cm$^3$, $\beta_V$ in atm/°K, and $\rho\kappa_T$ in g cm$^{-3}$/atm. Although these measurements have been extended by a factor of 10 closer to the λ line than ever before, they continue to agree with a logarithmic form which cannot be correct at the λ line.

## INTRODUCTION

THE thermodynamic properties of liquid $He^4$ change very rapidly close to the lambda transformation. Consequently, in order to investigate the nature of the transformation, it is necessary to make measurements extremely close to the lambda line. Since the anomalous behavior is spread out over a larger temperature interval at high pressures, it is most advantageous to work near the upper lambda point $(T_{\lambda'},P_{\lambda'})$, where the lambda curve meets the melting curve.

Our earlier measurements[1] of the pressure coefficient, $\beta_V=(\partial P/\partial T)_V$, were made along that isochore which passes through the upper lambda point, and, therefore, could be made only in He I (above the lambda temperature), since the isochore is in the solid region of the phase diagram below the lambda temperature. In this paper, we present measurements of the pressure coefficient and of the compressibility, $\rho\kappa_T=(\partial\rho/\partial P)_T$, of both He I and He II near the point $T_\lambda=1.7683°K$, $P_\lambda=29.56$ atm, which is on the lambda curve 5.0 mdeg above the upper lambda point. The closest points were 2.5 μdeg, 50 μatm, and $10^{-7}$ g/cm$^3$ from the lambda line in temperature, pressure, and density, respectively. Thus, our measurements of the pressure coefficient and of the compressibility were an order of magnitude closer to the lambda point than were those of Lounasmaa,[2] whose measurements, in turn, were two orders of magnitude closer than the best previous measurements.[3,4] The resolution of the apparatus was about 0.5 μdeg in temperature, 1 μatm in pressure, and $10^{-9}$ g/cm$^3$ in density $(\Delta\rho/\rho=5\times10^{-9})$.

## EXPERIMENTAL

The apparatus used in these experiments is similar to that used previously.[1,5] It is shown schematically in Fig. 1.

Helium gas was purified in a trap (not shown) immersed in liquid helium and was condensed into the sample compartment G through the low-temperature valve A, which was kept closed during measurements. G was isolated from the liquid-helium bath by the vacuum case B. Its temperature was controlled by the heater F and by pumping on liquid helium in E.

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* Based on work performed under the auspices of the U. S. Atomic Energy Commission.

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