Recombination Luminescence in the Scintillation of Normal and Superfluid Liquid Helium*

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The alpha-particle-induced scintillation of liquid helium has been studied experimentally in the temperature range 1.23 to 4.2°K with an electric field (9 to 43 kV/cm) applied in the region of the alpha tracks. Simultaneously with observation of the scintillation intensity, the ion current extracted from the alpha tracks by the field was measured. The results indicate that recombination luminescence accounts for approximately 60% of the total scintillation intensity (with zero electric field) and that this component of the intensity is temperature-independent. However, the ion current extracted by the field and the corresponding reduction in scintillation intensity both have temperature dependences which exhibit anomalous behavior in the He II region.

I. INTRODUCTION

THE scintillation of superfluid helium produced by the passage of fast alpha particles through the fluid exhibits a number of unexpected and unusual characteristics which have been the subject of several recent investigations. The fact that the superfluidity of He II affects its scintillation properties first became apparent in an earlier experiment in which the authors[1] observed a continuous decrease in the scintillation intensity as the temperature of the liquid was reduced below the λ point.

This effect was subsequently confirmed in independent work by Kane, Siegel, and Suzuki,[2] who demonstrated further that the inhibition of scintillation in the He II region does not occur when scintillations are produced by beta particles, although a very sharp decrease of a few percent appears precisely at the λ point. Jortner *et al.*[3] also confirmed the decrease in intensity in the case of alpha-produced scintillation and showed that the excitation energy transfers readily to nitrogen and oxygen when these atoms are introduced into the liquid helium as contaminants.

In an effort to determine the degree to which ions participate in the scintillation process, the authors[4] investigated the effect of a strong electric field (10 to 40 kV/cm) applied in the vicinity of the alpha tracks and found that the field reduces the intensity by several percent in both normal and superfluid liquid helium. This observation was interpreted as indicating that ionic recombination luminescence plays a significant role in the scintillation mechanism.

More recently, experiments have been performed in this laboratory[5] in which the influence of a heat current introduced in the alpha-track region was studied. In these investigations an electric field was also applied, and the scintillation intensity and collected ion current were observed simultaneously at various values of the heat-current density. In the He II region, no effects were observed at low heat currents, but at certain (temperature-dependent) critical values of heat current, sharp increases in scintillation intensity and decreases in collected ion current occurred simultaneously. A strong hysteresis effect was observed as the temperature was cycled above and below the critical heat current. These observations demonstrated that a pronounced enhancement of recombination luminescence accompanies the establishment of a supercritical phase of heat conductivity in He II.

Although several suggestions have been made in efforts to correlate these anomalous phenomena with the known properties of superfluid helium, no adequate model of the liquid-helium scintillation process has been set forth. Moreover, some of the effects are difficult to reconcile with previous observations relating to the behavior of ions in He II. For example, the experiments[4] on the inhibition of scintillation by an electric field indicated that the field-induced decrease in intensity at 1.35°K is approximately 50% greater than at 2.18°K. On the other hand, previous measurements[6] of the ion current extracted from alpha tracks by a high electric field showed no temperature dependence. It is evident that a field-induced decrease in recombination luminescence which is not accompanied by an increase in collected ion current is difficult to understand.

The experiments described below were undertaken in an effort to determine the role of recombination in the scintillation mechanism and to resolve the apparent discrepancy between the scintillation data and the measurements of collected ion current. The results

* Supported by the U. S. Army Research Office.
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[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] Joshua Jortner, Lothar Meyer, Stuart A. Rice, and E. G. Wilson, Phys. Rev. Letters 12, 415 (1964).
[4] Frank E. Moss and Frank L. Hereford, in *Proceedings of the Ninth International Conference on Low Temperature Physics, Columbus, Ohio, 1964,* edited by J. G. Daunt, D. V. Edwards, F. J. Milford, and M. Yagub (Plenum Press, Inc., New York, 1965).
[5] Frank E. Moss, Frank L. Hereford, Forrest J. Agee, and James S. Vinson, Phys. Rev. Letters **14**, 813 (1965).
[6] A. N. Gerritsen, Physica **14**, 407 (1948); R. L. Williams and F. D. Stacy, Can. J. Phys. **35**, 928 (1957).

indicate that roughly 60% of the intensity derives from recombination luminescence and that this component of the intensity is temperature-independent. The data demonstrate further that the ion current collected in the presence of an electric field does increase below the λ point by an amount proportional to the decrease in scintillation intensity.

II. EXPERIMENTAL PROCEDURE

The experiments were performed in a 1-in.-diam by 1-in. cylindrical scintillation chamber (Fig. 1) attached to the lower end of a 1-in.-diam by 17-in. Lucite light pipe to which a RCA 6810 was optically coupled at the upper end. The scintillation chamber remained immersed in liquid helium throughout the course of the measurements.

The inner wall of the chamber was coated with an evaporated layer of POPOP for the purpose of shifting the He radiation, which is known to be in the extreme ultraviolet (below 1000 Å),[7] into the visible region. Alpha particles were provided by a small quantity of Po^{210} which was electroplated onto a 1-cm segment of 0.127-mm-diam silver wire which was located on the axis of a gold-plated cylindrical grid of 1 cm diam. With 1200 V applied between wire and grid, the electric field strength varied from 43 kV/cm at the surface of the source to 8.7 kV/cm at the end of a radially directed alpha track (approximately 0.25 mm from the surface). The average field strength along the alpha tracks was estimated by rough geometrical considerations. Reversal of the field produced no effect in the results to be described.

At various applied voltages (and average field strengths E), the scintillation pulse-height spectrum and the ion current collected at the source and grid were observed simultaneously for temperatures between 1.23 and 4.2°K. Pulse-height spectra were recorded with a multichannel analyzer, and Gaussian curves were fitted to the observed peaks by means of an iterative process with a Burroughs B5000 Computer. This analysis yielded: (1) the position of the peak $C(T,E)$ in channel number (proportional to photons per alpha and called the "intensity" hereafter); (2) the statistical error in $C(T,E)$; (3) the height of the peak; and (4)

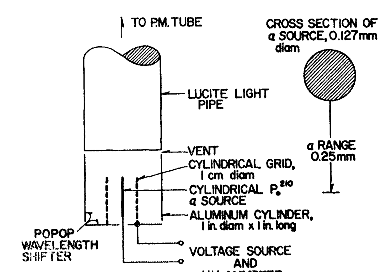

FIG. 1. The experimental arrangement.

[7] J. E. Simmons and R. B. Perkins, Rev. Sci. Instr. 32, 1173 (1961).

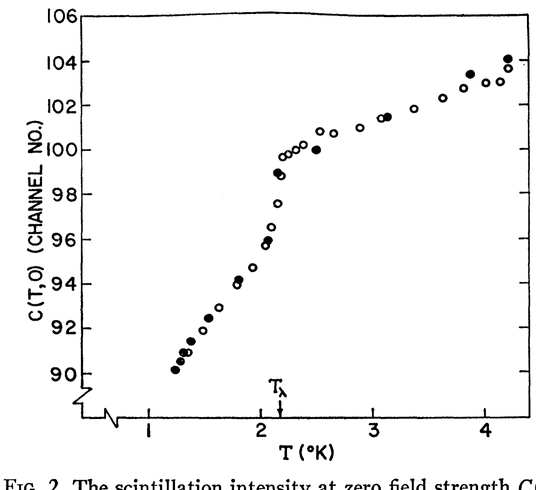

FIG. 2. The scintillation intensity at zero field strength $C(T,0)$ versus temperature. Open points show results of Kane *et al.* (Ref. 2); solid points show results of the authors.

the width of the fitted Gaussian distribution. The latter two quantities yielded the area under the peak in alpha particles per minute from which the number of ion pairs produced per second I_0 could be computed, as described below.

III. RESULTS

The scintillation intensity at zero field $C(T,O)$ is shown in Fig. 2, exhibiting the temperature effect between 1.23 and 4.2°K, and the results are compared with those of Kane *et al.*[2] With the electric field applied, two sets of measurements were made. First, at temperatures of 1.31, 2.17, and 4.2°K, $C(T,E)$ was measured with varying field strength E. Simultaneously, the collected ion current I_c was measured. The field in all cases produced a decrease in intensity, $\Delta C=C(T,O)-C(T,E)$, and a measurable collected ion current I_c. The fractional decrease in intensity $\Delta C/C(T,O)$ and the collected current I_c are shown versus applied voltage (and an estimated average field strength) in Fig. 3 for each of the three temperatures at which observations were made.

The simultaneous decrease in intensity and increase in collected ion current indicate that an appreciable fraction of intensity derives from recombination luminescence. Assuming that the scintillation intensity consists of a field-dependent recombination component, proportional to the total number of uncollected ions per second, and a component C_I independent of the collected ion current, one can write,

$$C(T,O)=\gamma I_0+C_I, \quad (1)$$

$$C(T,E)=\gamma(I_0-I_c)+C_I, \quad (2)$$

where I_0 and I_c are the total and collected numbers of ion pairs per second. Since the collection of one ion pair will cause the flow of one unit of charge through the voltage supply circuit (Fig. 1), it is convenient to

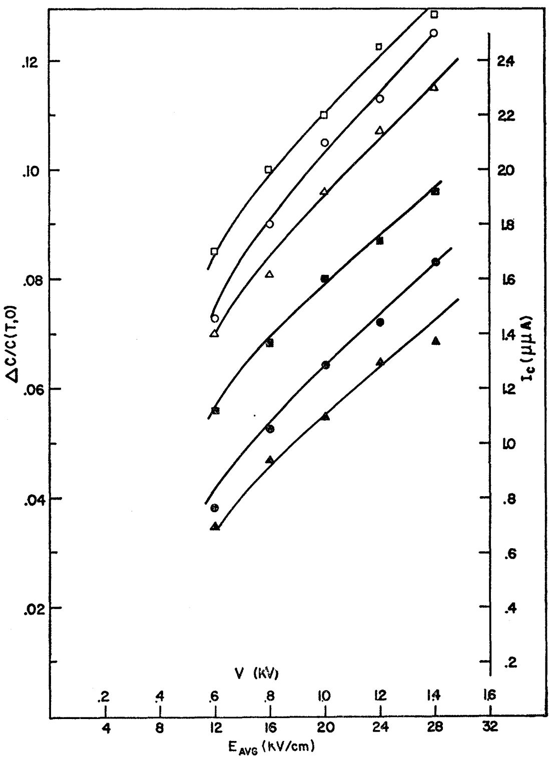

FIG. 3. The field-induced decrease in scintillation intensity (solid points, left scale) and the collected ion current (open points, right scale) versus applied voltage and estimated average field strength for 1.31°K (■,□), 2.17°K (▲,△), and 4.2°K (•,○).

express I_0 and I_c in units of current ($\mu\mu$A). The difference between Eqs. (1) and (2) yields the decrease in intensity ΔC (in channel number) produced by the field,

$$(\Delta C)_{T,E}=\gamma I_c. \tag{3}$$

Thus, if the experimental values of ΔC are plotted versus I_c, then the slope γ gives the efficiency of production of detectable photons per ion. Any possible temperature dependence of γ, which could account for the anomalous decrease in intensity below T_λ, should be apparent.

Figure 4 shows the data plotted in this fashion with a straight line fitted to the points corresponding to temperatures of 4.2 and 1.31°K. It is clear that the slope γ is the same within a few percent for these two temperatures. Hence, if I_0 is assumed to be constant, the origin of the temperature effect, which amounts to about 14% between these temperatures, must be sought in the scintillation component C_I in Eq. (1). For the moment the fact that the straight line of slope γ fails to intersect the origin has been neglected (but is discussed below). In Fig. 4 data are also shown for 2.17°K where fluctuations in the measurements were greater than at the first two temperatures. The fluctuations are attributed to the fact that the rate of change of intensity with respect to temperature is greater just below T_λ (Fig. 2) and to fluctuations due to the manual pumping speed adjustments which were more critical just below the λ point. However, even with greater experimental error, the points fit the straight line quite well.

It should be pointed out that γ presumably contains a factor $(1-F)$, where F is the fraction of ions that undergoes nonradiative recombination. For example, recombination could result in the dissociation of an ionic molecule with one of the product atoms in an excited state. Its de-excitation would yield resonance radiation which should be imprisoned and should not contribute to the very fast scintillation pulse.

The data shown in Fig. 4 yield a value for γ of 4.32 (channels per $\mu\mu$A). If one assumes that 30 eV are required to produce an ion pair, then the total number of ion pairs per second I_0 can be computed from the number of alphas per second (the area under the Gaussian curves fitted to the pulse-height spectra). One obtains the value 14.1 $\mu\mu$A, yielding for the recombination component γI_0 the constant value 60.9 channels (approximately 60% of the total intensity).

In a second set of measurements, the field-induced decrease in intensity ΔC and the ion current I_c were observed for a fixed applied voltage of 1200 V at a number of temperatures between 1.23 and 4.2°K. These results are shown in Fig. 5. They indicate a definite variation in the effectiveness of the field in extracting ions from

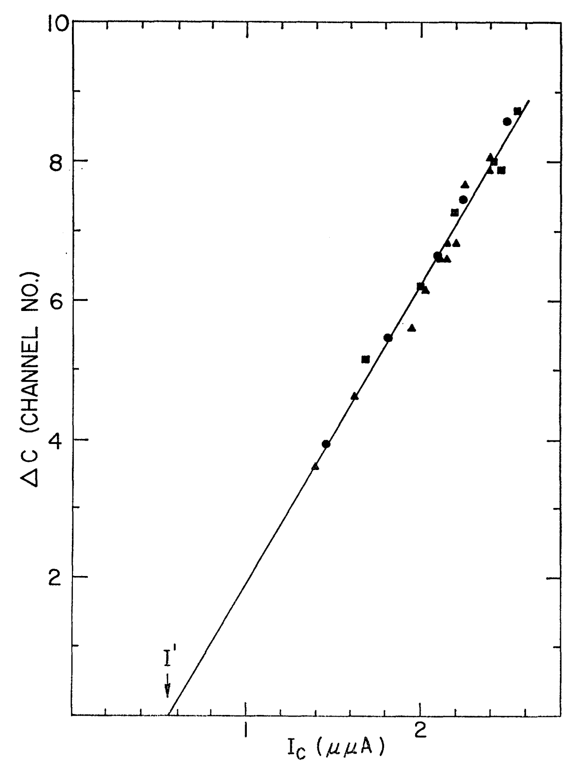

FIG. 4. The field-induced decrease in intensity versus the collected ion current at 1.31°K (■), 2.17°K (▲), and 4.2°K (•).

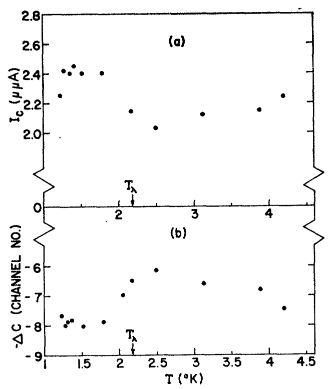

FIG. 5. (a) the collected ion current I_c, and (b) the field-induced change in intensity $(-\Delta C)$, versus temperature T for an applied voltage of 1200 V.

the column and thereby reducing the scintillation intensity. Both ΔC and I_c decrease as the temperature is lowered from 4.2°K to the λ point and then increase to what appear to be constant or maximum values at about 1.5°K.

The variation of ion current with temperature is in disagreement with previous results obtained by other workers[6] using a uniform electric field rather than a radial field. It appears likely that the current measurement in the previous experiments was not sufficiently accurate to exhibit the temperature dependence shown in Fig. 5.

IV. DISCUSSION

The results clearly establish the fact that recombination contributes substantially to the scintillation intensity. The value of 60.9 channels obtained above for the recombination component was determined on the assumption that 30 eV are required to create an ion pair. This figure is known to depend on the purity of the helium and is 46 eV for highly purified helium, but 30 eV in the presence of trace contaminants.[8] If the helium employed in these experiments were sufficiently pure, then the value of 46 eV/(ion pair) yields 39.8 channels for the recombination intensity. Since no special precautions were followed with regard to purity, it appears more likely that the larger value is correct. In any case, the results show that this component of the intensity is not temperature-dependent.

It appears likely that all recombination radiation is emitted during the fast pulse, which is known to have a temperature-independent decay time less than 10 nsec.[9] The recent work of Esterling and Lipman[10] indicates a recombination time of about 100 nsec in He gas at 15 atm. Assuming the recombination time to vary inversely with density, one expects it to be about 2 nsec for liquid helium. Since in the experiments reported here, the collection time was much longer (approximately 1000 nsec), the observation of a constant recombination component (at zero field) in the scintillation intensity is reasonable.

In the light of the above conclusions, the previous observation[5] of an increase in recombination luminescence when a supercritical phase of heat conduction is established is difficult to understand. Such an increase could only be the result of the recombination of some fraction of the ions which fails to recombine in the absence of a supercritical heat current.

The presence of such a fractional current is suggested in Fig. 4 by the existence of the intercept I' (0.55 $\mu\mu$A). One can modify Eqs. (1), (2), and (3) as follows:

$$C(T,O)=\gamma(I_0-I')+C_I(T), \quad (4)$$

$$C(T,E)=\gamma(I_0-I_c)+C_I(T), \quad (5)$$

to yield upon subtraction

$$(\Delta C)_{T,E}=\gamma(I_c-I'). \quad (6)$$

Thus, the intercept I' represents a current of ions which does not contribute to the fast recombination component and which is totally collected at the field strengths which were employed. In the presence of a supercritical heat current, either all or some substantial fraction of I' must recombine. In the experiment[5] in which an electric field was applied, the recombination of I' in the supercritical region could be responsible for the observed decrease in collected ion current. Thus, one is led to seek some process whereby several percent of the ions normally experience a very small radiative recombination rate, but recombine readily when the critical heat current is exceeded.

In this interpretation an apparent discrepancy exists between the magnitude of I', which represents an intensity change $\Delta C/C(T,O)$ of approximately 0.02, and the supercritical increase in intensity of about 0.09.[5] The fact that I' accounts for only part of the supercritical increase suggests that the field-independent component C_I also increases or that I' is only a fraction of the ions which normally do not yield recombination luminescence.

However, comparison of the two experimental results may not be very meaningful. In addition to differences in source and collector configurations in the two experiments, it is believed that a radial supercritical heat current produces quite violent changes in the region of the alpha tracks. Specifically, the experimental results of Strelkov[11] indicate that a cylindrical vapor bubble is created around the source wire. The presence of a vapor-liquid interface is known to significantly impede the passage of ions from the fluid to the vapor. Also, in the presence of an electric field a low-density bubble would shift the region of high ion density outward from the source where the field strength would be reduced. It is clear that further experimental work is required to

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[8] T. E. Bortner and G. S. Hurst, Phys. Rev. **93**, 1236 (1954).
[9] J. R. Kane and R. T. Siegel, Bull. Am. Phys. Soc. **10**, 515 (1965).
[10] Robert J. Esterling and Norman H. Lipman, Rev. Sci. Instr. **36**, 493 (1965).
[11] P. G. Strelkov, J. Phys. (USSR) **3**, 175 (1940).

determine what mechanisms are operative both in the scintillation process and in the supercritical phase of heat conduction.

The above interpretation of the significance of the intercept I' leads to a small adjustment in the magnitude of the recombination intensity as estimated above. The recombination component is now $\gamma(I_0-I')$ which yields 58.5 channels, if 30 eV per ion pair is assumed, and 37.6 channels, if 46 eV per ion pair is assumed.

With regard to the results shown in Fig. 5, it is clear that the effectiveness of an electric field in extracting ions from the alpha tracks varys significantly with temperature. This variation presumably reflects the complicated and anomalous behavior of ions in superfluid helium which has been the subject of a number of recent investigations.[12] Further experiments are in progress in an effort to extend observations to lower temperatures and a wider range of field strengths.

Finally, it should be noted that the experiments reported here do not disclose the origin of the scintillation temperature effect (Fig. 2), but they do indicate that the temperature dependence must be sought in the component C_I rather than the recombination component. This conclusion, of course, hinges upon the validity of the simple model embodied in Eqs. (4), (5), and (6).

[12] Kerson Huang and A. Cesar Olinto, Phys. Rev. **139**, A1441 (1965). These authors review experimental data on ion behavior and propose a phenomenological theory of the interaction between ions and quantized vortex rings.

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Growth of Pinned Quantized Vortex Lines in Helium II

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A model is proposed for the onset of instability of superflow in a narrow tube assuming growth of a primordial vortex pinned to irregularities on the wall. A description of subcritical and supercritical flow is obtained closely paralleling that proposed by Donnelly on a phase-slip argument. The critical velocity corresponds to the minimum radius of curvature of the pinned vortex line. The operation of a quantized-vortex-ring mill is described.

1. INTRODUCTION

It has been suggested by Feynman[1] that vortices in helium II flowing through a narrow tube might be generated by means of an initial vortex line attached to the walls of the tube. This paper describes a mechanism for the stretching of the pinned vortex line and the generation of vortex rings in pure superflow. We demonstrate that the effects on the flow are analogous to those described by Donnelly[2] on the basis of a phase-slip argument. A critical condition is found corresponding to the minimum radius of curvature of the vortex line. Above the critical velocity, the vortex line may be generated at a rate determined only by the available energy which must be supplied by a potential difference between the ends of the channel.

Our purpose here is to describe a mechanism of vortex generation which has not heretofore been discussed and which may play a role in narrow channel experiments. We deal only with the initiation of vortex growth: the process of amplification in the presence of a tangle of vortex line has been discussed by Hall.[3] The present discussion is restricted to tubes which are narrow in the sense that the normal fluid is effectively clamped by viscosity.

[1] R. P. Feynman, in *Progress in Low Temperature Physics*, edited by C. J. Gorter (North Holland Publishing Company, Amsterdam, 1955), Vol. 1, Chap. II, p. 17.
[2] R. J. Donnelly, Phys. Rev. Letters **14**, 939 (1965).
[3] H. E. Hall, Advan. Phys. **9**, 89 (1960).

2. THE PRIMORDIAL VORTEX LINE

Suppose there is present in a narrow tube a primordial vortex line which was created by some nonequilibrium process, perhaps during the formation of the initial flow. Suppose further that the primordial line is pinned to the walls in the orientation indicated in Fig. 1(a). Under these circumstances, the fluid flow in the channel will produce a lift (Magnus) force away from the nearest wall. This force is given by the relation

$$\mathbf{G}=\rho_s\mathbf{v}_s\times\boldsymbol{\kappa}, \tag{1}$$

where $\kappa(=h/m)$ is the strength of the vortex. The vortex is pictured as being attached to spike-like protuberances in the wall long enough to prevent image forces from drawing the vortex line into contact with the wall, beginning at the points of attachment. Without protuberances, the vortex line would end normally on the wall, and the point of contact would slide under the influence of vortex line tension. Ordinary surfaces should have sufficient roughness to provide sites for vortex pinning.