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[17]The critical parameters associated with the velocity minimum are $T_c = 5.1883 \pm 0.0005$°K and P_c 1706.6 ±0.4 Torr.
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ULTRAVIOLET EMISSION SPECTRUM OF ELECTRON-BOMBARDED SUPERFLUID HELIUM*

M. Stockton, J. W. Keto, and W. A. Fitzsimmons
University of Wisconsin, Madison, Wisconsin 53706
(Received 19 January 1970)

The emission spectrum of electron-bombarded superfluid helium has been measured as a function of wavelength between 550 and 2500 Å. The spectrum is characterized by a very intense asymmetric band of continuous emission peaking at approximately 800 Å with half-width of roughly 150 Å, along with a series of less intense bands between the wavelengths of 620 and 710 Å. This continuum is due to the radiative dissociation of neutral He_2 molecules in the reaction $A^1\Sigma_u^+ \rightarrow X^1\Sigma_g^+$.

Recent experiments have established that electronically excited states of the neutral He_2 molecule are well-defined local excitations in electron-bombarded liquid helium.[1,2] In particular, these experiments have shown that the lowest bound states of He_2, $A^1\Sigma_u^+$, and $a^3\Sigma_u^+$, are populated at a rapid rate. These observations suggest that the $a^3\Sigma_u^+$ metastable state of He_2 is probably the long-lived neutral excitation that has been reported by Surko and Reif.[3] In this Letter we report the vacuum-ultraviolet emission spectrum of electron-bombarded superfluid helium.[4] It is found that the spectrum consists of a very intense broad band of continuous emission between the wavelengths of 620 and 1100 Å. This continuum is interpreted in terms of the radiative dissociation of He_2 molecules in the reaction $A^1\Sigma_u^+ \rightarrow X^1\Sigma_g^+$.[5,6] The overall light intensity of this source corresponds to approximately 4×10^{15} photons/(sec μA) of 160-keV electron-beam excitation. Of all the fluorescence emitted by electron-excited liquid helium, the emission in the vacuum ultraviolet is by far the most intense. The intensity is, in fact, large enough that this could prove to be a feasible technique for obtaining a useful source of ultraviolet radiation.

The experimental arrangement is shown in Fig. 1. Due to the particular geometrical configuration of the present experiment, the vacuum-ultraviolet spectrograph was designed and built in this laboratory in order that it would be compatible with the existing helium cryostat and electron accelerator. A gold replica grating, having

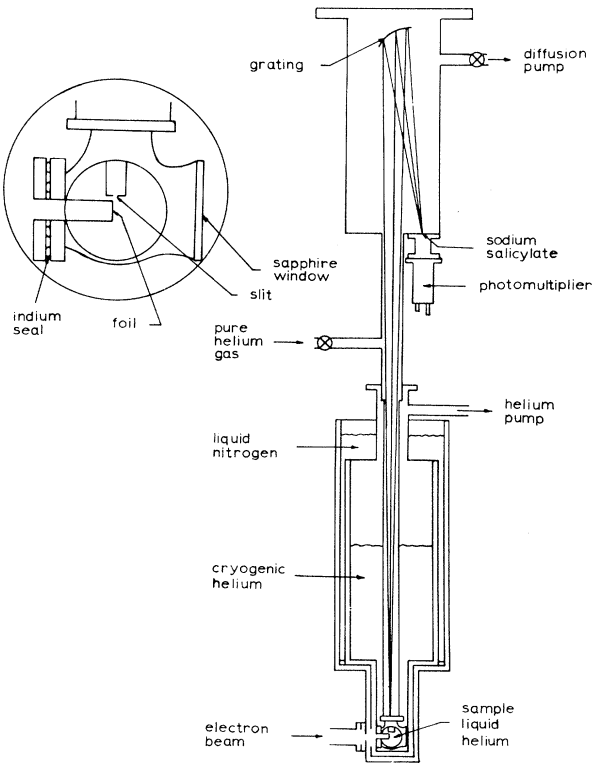

FIG. 1. Experimental apparatus.

a 1-m radius of curvature and blazed at 750 Å, is used in near-normal incidence with an object distance of 2 m and an image distance of approximately $\frac{2}{3}$ m. With this particular grating mount, a simple rotation of the grating about its center suffices to scan the spectrum in such a way that the diffracted light between 500 and 1700 Å is focused on a curve that is never more than 1 mm from the position of the exit slit. The instrument has a 1-Å bandpass with entrance- and exit-slit widths of 240 and 80 μ, respectively. A detailed description of this spectrometer will be published elsewhere. The optical signal is detected by observing the secondary fluorescence from a window which is coated with sodium salicylate and which forms the vacuum seal directly behind the exit slit.[7] The secondary fluorescence signal is detected with an EMI 6256 photomultiplier, amplified by a Keithley 610B electrometer having a 1-sec time constant, and plotted on a strip-chart recorder.

The entrance slit of the spectrograph is built into the top of the copper sample chamber in such a way that the spectrograph and the sample chamber form a completely isolated vacuum system which can be evacuated to 10^{-6} Torr. At the beginning of each experiment, the liquid sample is obtained by condensing purified helium gas into the copper chamber. The gas is purified by passage through a liquid-nitrogen–cooled charcoal trap and then through a liquid-helium–cooled copper-foil trap. The sample must be pure liquid helium in order to avoid the relatively intense emission of O_2 and N_2 impurities.[8] The copper walls of the container thermally connect the liquid sample to a separate liquid-helium bath. The temperature is controlled by pumping on the cryogenic liquid helium and regulating its vapor pressure. The electron beam, with nominal energy of 160 KeV, is stopped in the liquid sample after passing through a thin (0.000125 in.) metal foil which separates the liquid sample from the common vacuum of the accelerator and helium cryostat.[9] The diameter of the electron beam at the position of the foil is approximately 3 mm.

The experiment is carried out at temperatures below the λ-transition temperature of liquid helium in order to take advantage of the anomalously large thermal conductivity of superfluid helium which prevents the liquid from boiling. It has been shown,[1] and confirmed in this laboratory, that under the present experimental conditions the energy dissipated by the incident electrons does not cause the liquid to boil, and thus the physical observations are indeed characteristic of the liquid.

The spectrum of electron-excited superfluid helium is shown in Fig. 2(a). Curves 1 and 2 are tracings of the spectra with 1 μA of electron beam excitation at the temperatures of 2.1 and 1.4°K, respectively. The arrows indicate the estimated positions of the band maxima which are 621, 627, 637, 648, 665, 686, 707, and 783 Å, respectively. Figure 2(b) is a rescaled tracing of the spectrum emitted by a high-pressure helium discharge lamp that was used to calibrate the spectrograph.[10] The lines labeled neon in Fig. 2(b) are the 736- and 744-Å resonance emission lines of the neon impurity in the lamp, and they indicate the resolution of the spectrograph.

The overall intensity of the ultraviolet light emitted by the liquid helium is estimated to be 4×10^{15} photons/(sec μA) of 160-keV electron-beam excitation. This measurement was made by placing a small sodium salicylate screen in front of the sapphire window opposite the beam

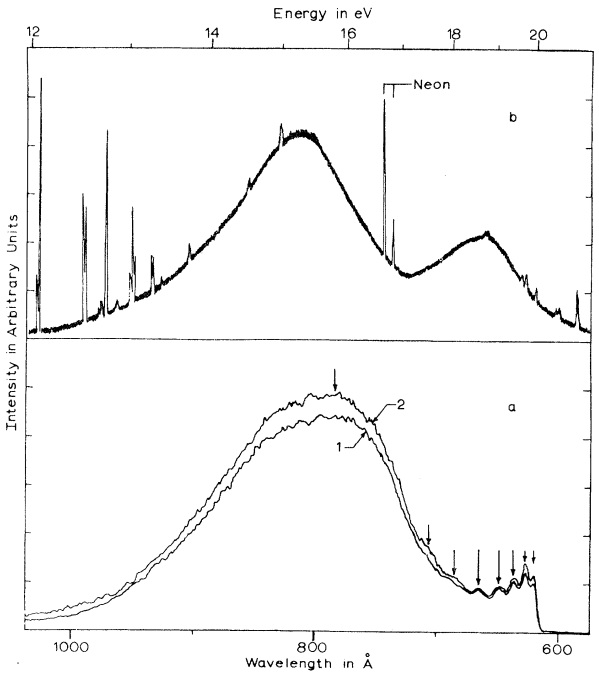

FIG. 2. (a) Ultraviolet emission spectrum of electron-bombarded superfluid helium. Curves 1 and 2 are for 1 μA of electron excitation at the temperatures of 2.1 and 1.4°K, respectively. (b) Ultraviolet emission spectrum of a high-pressure helium discharge lamp. The lines labeled neon are the 736 and 744-Å resonance lines of the neon impurity in the lamp and they indicate the resolution of the spectrograph that was used in this experiment.

foil and measuring the intensity of the secondary fluorescence. The distance between the salicylate screen and the beam foil was about 35 mm. The photoconversion efficiency of the sodium salicylate was shown to be the same at helium temperatures as at room temperature by observing the secondary fluorescence induced by the 2537-Å line of a mercury lamp. After correcting for solid-angle factors, the source intensity was determined on the basis of the photomultiplier sensitivity as specified by the manufacturer and the conservative assumption that the photon conversion efficiency of the sodium salicylate is 100%, independent of wavelength.[7] A second estimate based on the light reflected in zeroth order from the grating gave a similar result.

The intensity of the continuum increases linearly with beam current at all wavelengths, to within an estimated ±5% experimental uncertainty, for beam currents between 0.1 and 5.0 μA. The intensity is greatest with the entrance slit of the spectrograph placed as close as possible to the plane of the beam foil. A displacement of the entrance slit by roughly 1 mm away from the plane of the foil resulted in a 50% decrease of intensity. This is consistent with an estimated range of 3 mm for 160-keV electrons in liquid helium.

As indicated in Fig. 2(a) the shape of the continuum does not exhibit any significant dependence upon temperature, although the intensity increases by roughly 10% as the temperature is reduced from 2.1 to 1.4°K.[11] The liquid level in the sample chamber was varied between the various different experimental runs from 1 to 2 cm above the entrance slit to an estimated height of 10 to 15 cm. (Direct observation of the liquid level was not possible and these estimates are based on the time duration of the distillation process.) There was no noticeable difference in the intensity or shape of the spectrum for the different levels, indicating little self-absorption in the liquid.[12]

The prominent feature of the uv continuum emitted by liquid helium is very similar to the major peak in the spectrum of a high-pressure helium discharge and it is characteristic of radiative dissociation from the ground-vibrational level of the $A^1\Sigma_u^+$ state of He_2. The bands in the liquid spectrum between 620 and 710 Å are part of a well-known series of bands involving the higher vibrational levels of the $A^1\Sigma_u^+$ state.[5,6] The liquid-helium spectrum differs from the spectrum of an uncondensed helium discharge in that, for the gas, the series of bands at the short wavelengths extends down to about 600 Å, whereas, in the present case, they are not evident at wavelengths less than 620 Å.[13] This is probably due to the fact that the short-wavelength bands occurring in the uncondensed discharge are at least partially (and perhaps entirely) due to continuum-continuum dissociation of the $A^1\Sigma_u^+$ state. This is in contrast to the present case where the observed bands are due most likely to bound-state–continuum dissociation. Our interpretation is supported by the previously reported infrared emission spectrum of liquid helium which shows that at least the first four vibrational levels of the $A^1\Sigma_u^+$ state are populated.[1] In addition, a preliminary analysis that emphasizes dissociation at the classical turning points of the upper state is consistent with the observed spectrum. Thus, it may be expected that an accurate quantum mechanical analysis would yield relatively precise information about the forms of the two potential curves involved. The present authors intend to measure the transmission characteristics of the spectrograph used in this experiment in order that an accurate intensity profile of the spectrum will be available.

The following additional observations are recorded: In the present experiment, the electron beam can be pulsed (rise and fall times of the order of 10^{-7} sec) and thus the transient behavior of the fluorescence can be studied. Preliminary measurements of both the ultraviolet and infrared molecular emissions indicate that there are at least two different mechanisms populating the excited molecular states during the afterglow period. In the late afterglow the molecular fluorescence decays exponentially with time ($\tau \approx 300$ μsec) with no significant dependence upon beam current or temperature. The early afterglow period is characterized by a nonexponential decay with a decay rate that increases with increasing level of excitation and increases as the temperature is reduced. It is expected that the transient behavior of the molecular fluorescence will yield additional information concerning the microscopic nature of superfluid helium.

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SPECTROSCOPIC STUDY OF THE LUMINESCENCE OF LIQUID HELIUM IN THE VACUUM ULTRAVIOLET*

C. M. Surko,† R. E. Packard, G. J. Dick,‡ and F. Reif
Department of Physics, University of California, Berkeley, California 94720
(Received 19 January 1970)

The spectral distribution of luminescence excited in liquid helium by fast electrons was measured in the region between 500 and 3000 Å. The spectrum shows transitions of the He_2 molecule and is sensitive to the presence of impurities such as N_2.

The luminescence produced in liquid helium by energetic charged particles has been the subject of several experimental investigations.[1-5] These have provided evidence for the existence of metastable states in the liquid and have given information about optical transitions between excited states of the liquid. An investigation of the direct luminescent decay of the liquid to the ground state is more difficult since it requires measurements in the vacuum ultraviolet. We have undertaken such an investigation by studying the luminescent spectrum in the wavelength range between 500 and 3000 Å.

In our experimental arrangement the liquid helium (condensed after passing through a liquid-N_2-cooled charcoal trap) is excited by a 1-Ci tritiated-titanium β emitter immersed approximately 1 cm below the surface of the liquid. (In the liquid, the β particles have a range less than 0.05 mm.) The light produced in the region near the source travels vertically upward, passes through a monochromator,[6] and then impinges on a sodium salycilate converter. To prevent absorption of the uv radiation, no windows are used between the liquid and converter. The visible and near-ultraviolet light produced at the converter is detected by a cooled EMI 9514X photomultiplier tube. The output of the photomultiplier tube is fed into a discriminator (to discriminate against low-level noise and spurious large pulses due to cosmic rays) followed by either a scaler for a digital output, or an integrator for an analog output. Most data were taken digitally, setting the grating for a particular wavelength and pulse counting for up to four minutes.

The luminescence from the liquid is shown in Fig. 1(a) (solid circles) in the region between 580 and 1080 Å.[7] The spectrum is characterized by a broad peak near 780 Å and by a narrower peak near 600 Å. No luminescence is observed at wavelengths between 1200 and 3000 Å, or below 600 Å. (No intensity should be observable below 500 Å since the He vapor above the liquid absorbs strongly in this region.) The spectral distribution is independent of temperature between 2.7 and 1.2°K, while the intensity increases by about 10% when the temperature is lowered from 2.7 to 1.2°K. (No sudden change is observed as the temperature is varied through the lambda transition at 2.2°K.) As shown in Fig. 1(b), the leading edge of the spectral distribution near 600 Å varies with liquid level, indicating that the liquid absorbs the radiation in this region.

In order to examine the behavior of a potentially simpler system, we measured the luminescence from He gas at 4.2°K at pressures between