is 1.1×10^{-18} cm^2.[7] Thus the photoionization cross section for the $n=2$ transition is $(9\pm2)\times10^{-20}$ cm^2. The calculated value for the $(1s^2)$-$(2s,\epsilon p)$ transition given by Salpeter and Zaidi is 8.4×10^{-20} cm^2. Dalgarno and Stewart simply quote the ratio of the cross sections calculated at the respective spectral heads, namely, 1:0.0618. On taking the ratio of the experimental cross section for the $n=1$ transition at its spectral head[8] to that of the present experimental cross section for the $n=2$ transition a value of 1:0.012 is obtained.

It is expected that the absorption of radiation by helium of wavelengths shorter than 189 Å will populate the radiative $2p\,^2P_{3/2}$ and $^2P_{1/2}$ states of the ion (a) by direct absorption to those states and (b) by absorption into the metastable $2s\,^2S_{1/2}$ state with subsequent quenching caused by collisional processes. The energy radiated is the important 303.781 and 303.786-Å He II resonance radiation. In the upper atmosphere helium is one of the major constituents. Thus, the helium can act as a continuous absorber of radiation of wavelength less than 189 Å and re-emit this integrated energy into the 303.78-Å line.

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ULTRASONIC ATTENUATION IN LIQUID HELIUM AT 1 GHz †

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The attenuation of first sound in liquid helium was measured with an acoustical interferometer. Two results are of particular interest: the temperature dependence of the attenuation in the critical behavior region near the lambda point, and contrary to recent Brillouin scattering measurements, agreement with a theory of Khalatnikov and Chernikova in the region below about 2 K.

The purpose of this Letter is to present the results of an investigation of ultrasonic attenuation in liquid helium which is unique in two experimental aspects.[1] Firstly, the frequency is the highest used in helium measurements—Woolf, Platzman, and Cohen[2] obtained results at 0.56 and 0.72×10^9 Hz using a Brillouin-scattering technique, and more recently Heinicke, Winterling, and Dransfeld,[3] at 0.65×10^9 Hz, also using a Brillouin-scattering technique. Secondly, the attenuation is absolutely determined by obtaining the exponential decrease in amplitude as the distance between the source and receiver transducers is increased. The central experimental problem stems from the fact that the acoustic wavelength is only approximately 2000 Å, and accuracy of alignment usually associated with optical, rather than acoustical, interferometry must be maintained throughout the experiment. But it is the results of the measurements which are of primary interest and it will be shown that, among other things, at this elevated frequency the critical region around the lambda transition is delineated in a way not possible at much lower frequencies.[4,5] Further, our measurements yield greater detail and accuracy than has been previously reported.

The measurements are made with a pulse two-transducer (cadmium-sulfide thin film on a quartz substrate) acoustic interferometer of variable path length. The primary purpose of pulsing is to reduce the duty cycle to the point

where the integrated power input produces negligible heating. A gated sampling technique selects a part of the pulse which is free of transients. The attenuation is sufficiently high and the transducer spacing sufficiently large so that standing waves are not produced. Two signal paths are provided: the acoustic signal path yielding a signal of amplitude V_A and an electrical reference path yielding a signal of amplitude V_E. The sum of these signals, depending on their relative phase, has a value which lies between a maximum of $|V_A+V_E|$ and a minimum of $|V_A-V_E|$. As the acoustical signal path is increased, the amplitude alternates between these limits with a space period of an acoustic wavelength, and an exponential decrease in V_A is reflected in an exponentially decreasing envelope as shown in Fig. 1. Distance is obtained by counting wavelengths and using the known velocity of sound to obtain the wavelength.[6]

The attenuation coefficient as a function of temperature is shown in Fig. 2. The results can best be described in terms of three temperature regions: a classical normal-fluid region at temperatures above about 2.3 K, a critical region near the lambda transition, and a superfluid region below about 2 K.

Normal fluid region ($T \gtrsim 2.3$ K).—In the normal fluid region the attenuation is due to shear viscosity and thermal conductivity and is described by the Stokes-Kirchhoff equation. The measurements in this region were made by cooling to the working temperature, then pressurizing the Dewar a few millimeters of Hg in excess of the vapor pressure to suppress bubbling. Our results give good agreement, except for a gradually increasing surplus as T approaches T_λ, when compared with the theoretical Stokes-Kirchhoff attenuation curve, based on the most recent experimental measurements of the thermodynamic and transport properties. Our results also give good agreement when scaled by the square of the frequency with lower frequency measurements.[7]

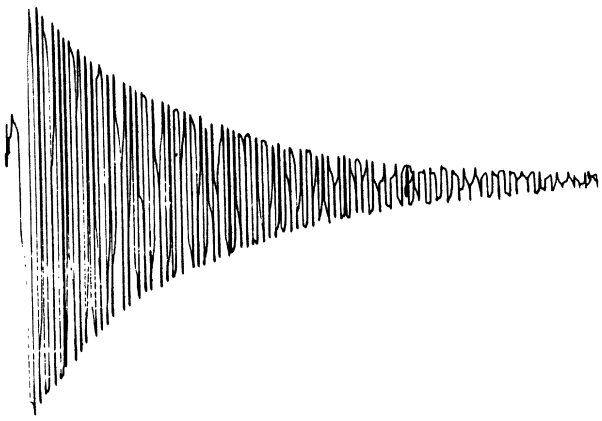

FIG. 1. Received signal amplitude versus distance in liquid helium at 1 GHz. Each cycle represents a change in spacing between the transducers of 1 acoustical wavelength, or about 2000 Å. The irregularities are mainly due to friction in the mechanism which varies the transducer spacing.

Critical region (2.0 to 2.3 K).—Although not apparent at first glance, the results in the critical region differ in a fundamental way from those found at lower frequencies. A sharp peak is also found at lower frequencies (22 kHz and 1 MHz),[5,4] and the attenuation on the low-temperature side of the peak has been attributed to an order parameter relaxation process described by Landau and Khalatnikov.[8] This relaxation time, τ, and attenuation coefficient, α, are given by

$$\tau = D/(T_\lambda - T),$$

$$\alpha = \frac{U_\infty - U_0}{U_\infty U_0}\,\frac{\omega^2\tau}{1+\omega^2\tau^2},$$

where $D = 1.5\times10^{-11}$ sec K and $(U_\infty - U_0)/U_\infty U_0 = 5.9$

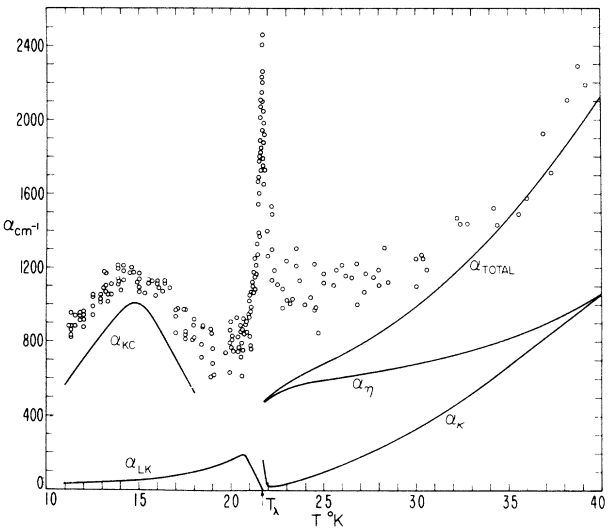

FIG. 2. Attenuation of first sound in liquid helium at 1 GHz. Each point represents one record of the type shown in Fig. 1. Some points have been deleted for clarity, but the scatter is representative. Solid curves: α_n, the attenuation due to shear viscosity; α_K, the attenuation due to thermal conductivity; $\alpha_{tot}=\alpha_n+\alpha_K$, total classical Stokes-Kirchhoff attenuation (the singular behavior of the thermal conductivity in the critical region has been excluded); α_{LK}, the order parameter relaxation theory of Landau and Khalatnikov; and α_{KC}, the elementary excitation theory of Khalatnikov and Chernikova.

$\times 10^{-8}$ sec/cm.[5] The peak occurs when $\omega\tau = 1$, and at 10^9 Hz the peak height is 185 cm^{-1} and occurs at 94 mK below T_λ (see Fig. 2). The Landau-Khalatnikov mechanism clearly contributes insignificantly to the observed peak.

By measuring the amplitude of the received signal using a fixed path length and drifting in temperature (the electrical reference path being disconnected), the relative attenuation was obtained. These measurements fill in the gaps, so to speak, for the point-by-point data plotted in Fig. 2. These measurements were made in an open bath and are thus inherently incapable of the submillidegree accuracy desirable for an investigation of detailed temperature dependences.[9] However, in view of the current interest in the nature of the temperature dependence of the attenuation in the critical region,[10] an attempt was made to obtain data as accurate and detailed as possible.

There is no singularity in the immediate vicinity of the λ point and the attenuation peak consistently appears 3 to 4 mdeg below T_λ. This apparent temperature offset should be regarded as provisional for the following reason. At the peak, the attenuation coefficient is very large, ~2000 cm^{-1}, and as a result the gap between the transducers never exceeds 2×10^{-3} cm. The temperature quoted is that of the bath and there remains the possibility that the temperature in the gap exceeds that in the bath by a few millidegrees. Acoustical heating has been shown to be negligible by varying both the amplitude and the repetition rate of the exciting signal and noting no change in the location of the attenuation peak.

In order to examine separately the large peak in attenuation associated with the critical behavior alone, the classical contribution due to shear viscosity and thermal conductivity was subtracted from the total attenuation. The remaining critical-behavior attenuation peak is shown in Fig. 3. On the high- and low-temperature slopes of the critical-region peak, the temperature dependence can be approximated by $\alpha = A/|T_\lambda - T|^n$. The values of n for six experimental runs above T_λ and six below T_λ are listed:

$T > T_\lambda$	$T < T_\lambda$
0.46 ± 0.03	0.47 ± 0.01
0.43 ± 0.02	0.55 ± 0.01
0.41 ± 0.02	0.50 ± 0.01
0.44 ± 0.01	0.58 ± 0.02
0.34 ± 0.02	0.57 ± 0.02
0.38 ± 0.02	0.47 ± 0.03

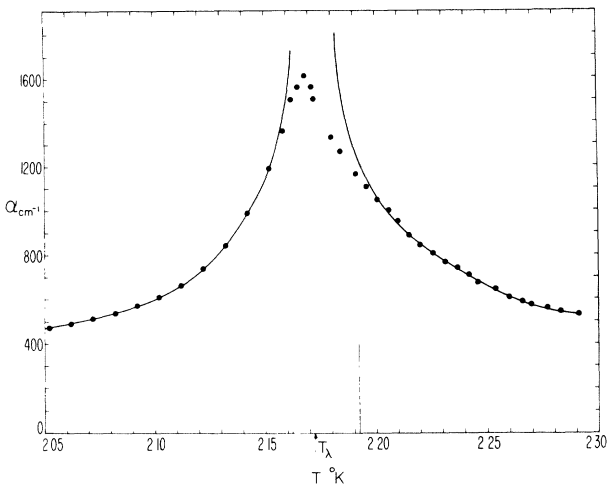

FIG. 3. Attenuation in the critical region. The points were obtained by fitting a continuous relative attenuation record obtained from a temperature drift with fixed transducer spacing to the point-by-point absolute attenuation data of Fig. 2. The classical Stokes-Kirchhoff contribution to the attenuation has been subtracted; so the remaining peak is expected to be characteristic of critical behavior. In the immediate vicinity of the λ point the attenuation departs from a singular behavior. This vicinity is denoted by the vertical bars which represent the inner limits to which the data were least-squares fitted with a power law of the form $\alpha = A/|T_\lambda - T|^n$ (solid lines). For $T > T_\lambda$, $A = 2.4 \times 10^2$ K^n/cm, $\bar{n} = 0.41$, and for $T < T_\lambda$, $A = 1.5\times 10^2$ K^n/cm, $\bar{n} = 0.52$.

The average values are $\bar{n} = 0.41$ and $A = 2.4\times 10^2$ K^n/cm for $T > T_\lambda$ and $\bar{n} = 0.52$ and $A = 1.5\times 10^2$ K^n/cm for $T < T_\lambda$. (Using T_p instead of T_λ in the expression for α, where T_p is the temperature of the attenuation maximum, the values of n for $T < T_\lambda$ are slightly higher, $\bar{n} = 0.46$, and for $T < T_\lambda$, slightly lower, $n = 0.48$.)

At lower frequencies, Chase[4] and Barmatz and Rudnick[5] find $n = 1$ on the low-temperature side (due to the Landau-Khalatnikov process) and $n = \frac{1}{2}$ on the high-temperature side. It is thus seen that a result of using high frequencies is to deemphasize the Landau-Khalatnikov process and establish a greater symmetry about the absorption peak, although the relative inaccuracy of determination of the exponent n does not allow a clear conclusion that it is exactly the same on both sides of the peak. Swift and Kadanoff[11] have recently emphasized that the exponent must be the same on both sides.

Theoretical treatments[10-12] cite exponents ranging from $\frac{1}{3}$ to 1. A basic assumption in obtaining these results is that the specific heat, C_p, is in the region of convergence, where its

temperature dependence can be ignored. This region does not correspond to the region in which our attenuation measurements fit a power law $\alpha = A/|T_\lambda - T|^n$. In fact, if C_p is approximated by a power law $|T_\lambda - T|^{-m}$ in the temperature region for which the critical behavior of the attenuation was determined, then $m \simeq 0.25$ for $0.01\ \text{K} < T - T_\lambda < 0.1$ K. It thus seems improper to compare the exponents obtained from our measurements with those cited in the literature.

Superfluid region ($T < 2.0$ K).—In the superfluid region, the attenuation is described in a theory by Khalatnikov and Chernikova.[13] Dissipative terms include a contribution associated with the relaxation times for the several processes involved in establishing equilibrium in the gas of elementary excitations. At higher temperatures these relaxation times are short compared with the acoustic period (hydrodynamic regime) and long at lower temperatures (collisionless regime). A peak in attenuation separates the two regimes. The measurements are seen to be in good agreement with the attenuation calculated[14] from this theory. In particular there is clear evidence of a maximum in attenuation at 1.5 K. We do not find any evidence that the theory may require modifications at high frequencies as indicated by measurements of Woolf, Platzman, and Cohen and Heinicke, Winterling, and Dransfeld.

This work was initiated with Professor R. W. Leonard, now deceased, who conceived the interferometer system in its present form.

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[14]We are indebted to Dr. W. M. Whitney for providing us with the computed curve shown in Fig. 2.

FERROELASTICITY OF NIOBIUM DUE TO HYDROGEN AS A LATTICE GAS

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We have measured the elastic response of niobium in the region of the critical point of hydrogen in niobium. The elastic susceptibility exceeds commonly observed values by two or three orders of magnitude and follows a Curie-Weiss relation over the temperature range investigated. The diffusion coefficient of hydrogen shows "critical slowing down" behavior but no anomaly in the transport coefficient.

It has been pointed out[1] that interstitially dissolved hydrogen in metals like Nb, Ta, V, Pd, etc., can, to a first-order approximation, be considered as an example for the theoretically well-explored lattice gas.[2] The characteristic feature common to the phase diagrams for hydrogen in these metals is a miscibility gap whose boundary can be interpreted as the coexistence curve for the lattice gas and lattice liquid. The van der Waals isotherms of the lattice gas can be deduced from solubility measurements. These isotherms have topologically the same appearance as the van der Waals isotherm of a free real gas, including a critical temperature below