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in curve 2 as compared to those in curve 1. The A peak decreases from $\simeq 1 \times 10^{-2}$ in curve 1 to $\simeq 0{\cdot}65 \times 10^{-2}$ in curve 2 and the B peak decreases from $0{\cdot}25 \times 10^{-2}$ in curve 1 to 0·20 in curve 2. The irradiation-produced decrease in the heights of the A and B peaks is about 25%, which will correspond to a reduction of $\simeq 3$ ppm in the number of dipoles. If the dipole moment of the S centre (responsible for the S loss peak, in Figure 1) is assumed to be equal to that of a divalent cation impurity associated with a nearest neighbour vacancy, the number of S dipoles calculated from the observed height of the S loss peak is about 20 ppm. We therefore conclude that the dipole moment of the S centres is very large. Similar results have been reported in additively coloured crystals (Krasnopevtsev 1963).

On thermally bleaching the x-irradiated crystals at $\simeq 200$°C, the S loss peak disappears and the heights of the A and B loss peaks and dc conductivity are partially restored to their original values (curve 3).

Optical and epr absorption studies of x-irradiated crystals have shown that the S centres give an optical absorption band at 210 nm and an EPR line of g-value 2·049 and halfwidth 62 gauss (Jain and Lal 1969a). The observed results can be qualitatively explained by assuming S centres to be $Co^{+}\boxed{+}\boxed{-}$. Here $\boxed{+}$ and $\boxed{-}$ are the cation and anion vacancies, respectively. The results will be discussed in detail in a separate paper (Jain and Lal 1969b).

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Brillouin scattering from superfluid ^{4}He

Abstract. Brillouin scattering at 90° from thermally excited first sound in superfluid ^{4}He has been measured with a Fabry–Perot etalon and digital scanning. The line shifts confirm that there is no dispersion compared with low frequency orthodox measurements over the range of temperature 1·25K to 2·15K.

In this letter we report some detailed measurements on the spectrum of light scattered from superfluid ^{4}He. They are consistent with the theoretical prediction (Ginsburg 1943) that the spectrum should contain only one doublet, due to Brillouin scattering from thermally excited first sound (phonons), no scattering being present at the incident frequency, and scattering due to second sound being too weak to be detected. An observation of Brillouin scattering from superfluid ^{4}He has already been mentioned briefly by T. J. Greytak, R. L. St Peters and G. B. Benedek in the Bulletin of the American Physical Society (see also St Peters 1969), but to our knowledge there has been no publication. In addition, light scattering from sound waves generated by a transducer in helium has been observed by Woolf *et al.* (1966), and *stimulated* Brillouin scattering has been observed by Heinicke *et al.* (1969). It should be emphasized, however, that in contrast to these two observations our own refer to a situation where the helium is disturbed to a negligible extent from its state of thermal equilibrium. Both the present work and some closely associated work on

Brillouin scattering from second sound in a ^{3}He–^{4}He mixture (Pike *et al.* 1969) are preliminary to a detailed study of scattering in the critical region near the λ line.

Our measurements on the scattered light were made with a plane Fabry–Perot etalon of 50 mm diameter and 662 mm spacing, using a digital scanning method (Jackson and Pike 1968, Jackson *et al.* 1969). The etalon length was accurately matched to the cavity length of a Ferranti–SERL argon laser operating at 0·4880 μm. This technique of matching the laser modes to the etalon pass bands obviates the need to operate the laser in a single longitudinal mode (Gilson 1967, Searby and Series 1969). The helium to be examined was passed, as a gas, through a cooled charcoal trap and a millipore filter, and then condensed into a small cell. The cell was constructed in a high-conductivity copper block which formed the base of a cryostat. Silica windows were sealed to the cell with indium rings. The scattered light was collected from the cell within a solid angle of 8×10^{-3} sr centred on a scattering angle of 90°, and was detected by a cooled ITT FW 130 photomultiplier of dark count 0·45 electrons per second. The etalon plates were scanned at 6 Hz with piezoelectric transducers, and the resultant counts from the photomultiplier were registered in approximately 60 channels per order.

Recordings of scattered light at six temperatures are shown in figure 1. The input power was about 300 mW and the count rate was a few photoelectrons per second. The recordings have about 100 counts per channel in the peaks and were built up over periods of about 30 min. The relative intensities of light scattering at the different temperatures were measured and are shown in figure 2.

In order to find and maximize the signal, precise alignment of the optics was essential. By slight misalignment of the collimating lens to the etalon, so that the interferometer viewed an area just to the side of the laser beam, it was possible to show that the count rate arising from spurious unshifted light due to flare was negligible in comparison with the dark count rate; that is that it contributed less than 5% of the total counts. An accurate spectrum of light scattered at the lowest temperature, where the doublet is well resolved, was built up by recording for a total of 3 hours. Analysis of the shape of this spectrum, according to the criterion that the two line profiles should each be symmetrical, shows that the total unshifted light, whether spurious or genuinely scattered from the ^{4}He, also constitutes less than 5% of the total scattering at the low temperature.

The Brillouin lines that we have studied have a minimum width of about 35 MHz, determined by the range of $\boldsymbol{k}$ vector observed within the light acceptance angle of the etalon. The instrumental width was about 15 MHz and was determined by the vibration-limited finesse of the etalon–laser system. There is clear indication that at our lowest temperature the lines are additionally broadened by attenuation of the scattering sound waves, the extent of the broadening being consistent with the attenuations measured at comparable frequencies by Woolf *et al.* (1966), Heinicke *et al.* (1969) and Imai and Rudnick (1969).

The components of a Brillouin doublet are shifted in frequency by an amount that is related to the velocity of sound. As we see from figure 1, the frequency shifts at higher temperatures are such that there is serious overlapping of Brillouin components from different orders. In these cases the shifts have been determined as follows. At a temperature of 1·91K the overlapping appears to be exact, and we assume that a trace at this temperature gives us the correct line shape for a single Brillouin component. At other high temperatures we have used this line shape to carry out a graphical reconstruction to fit the observed total profile and have then extracted the shift from this reconstruction. It should be added that we were not free to change the etalon spacing to avoid overlapping because of the need to match this spacing to the length of the laser cavity.

Velocities of first sound derived from the shift measurements are shown in figure 3. The solid curve deviates by less than $\frac{1}{2}$% from the data of Chase (1958) and of Whitney and Chase (1962) obtained at frequencies in the range of 1–10 MHz, thus confirming the observation of Woolf *et al.* (1966) that there is no significant dispersion up to frequencies of order 680 MHz.

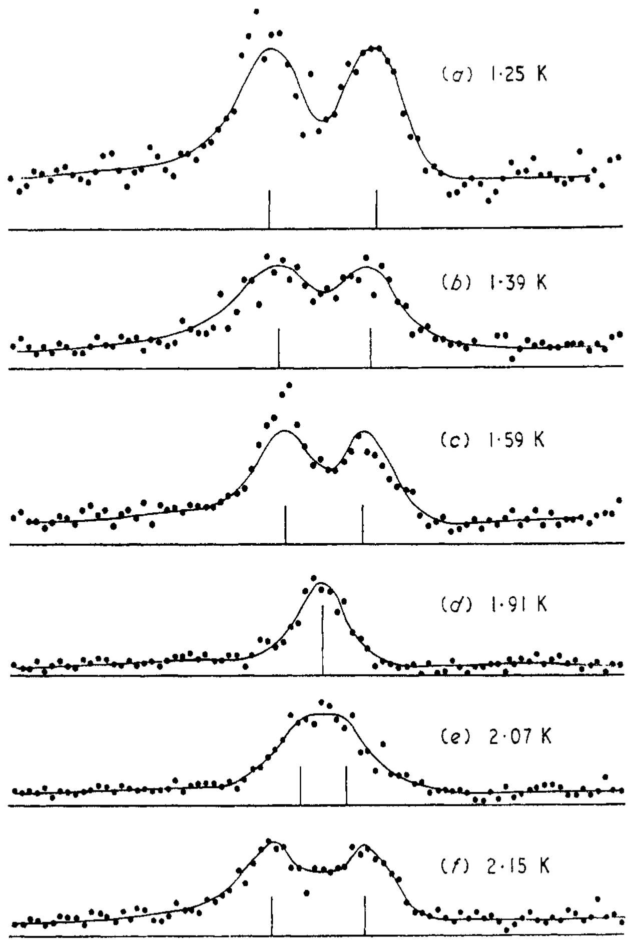

Figure 1. Spectra of first sound scattering from ^{4}He. One channel equals 3·71 MHz. The Brillouin lines are shifted approximately 3 orders of the etalon and range from ±3·11 orders (1·25K) to ±2·90 orders (2·15K). The estimated error limits are ±0·016 orders (±1 channel) for the resolved lines and ±0·025 orders for the two unresolved peaks.

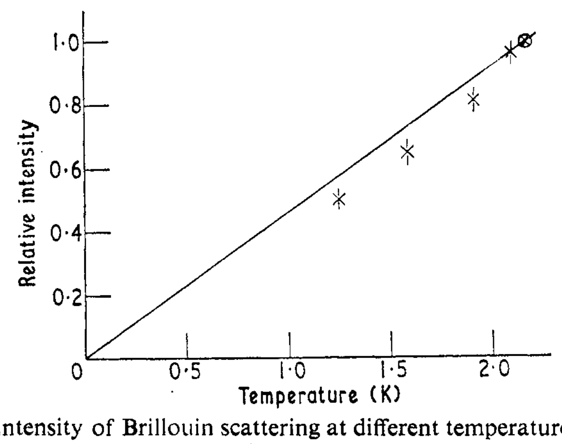

Figure 2. The intensity of Brillouin scattering at different temperatures, relative to the scattering at 2·15K.

The intensity of the Brillouin doublet should theoretically be proportional to temperature. There is slight evidence from the data of figure 2 that the observed intensity varied more rapidly with temperature, and we propose to investigate this point again.

Our failure to detect any unshifted component in the light scattered from pure ^4He is encouraging, but it should be remembered that even if helium were an ordinary liquid the

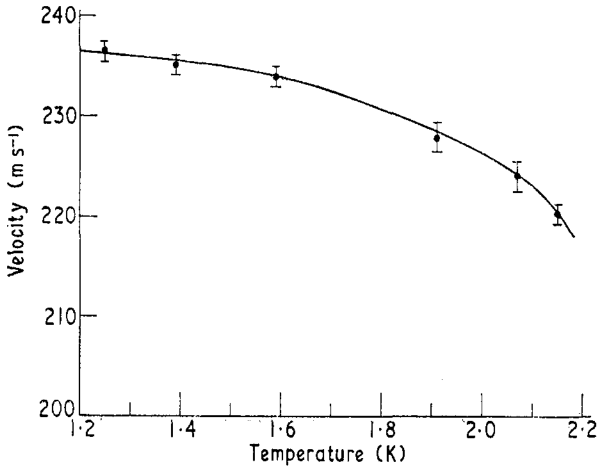

Figure 3. The velocity of first sound in the region of 670 MHz calculated from the Brillouin shifts measured off figure 1. The smooth curve drawn through the points deviates by less than 0·5% from data obtained by orthodox techniques at low frequency.

intensity of this component would be very small owing to the fact that (C_p/C_v) is so close to unity (Landau and Placzek 1934).

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