(1969)] is in all cases smaller than our random error (e.g., less than 0.2% for frequency shifts greater than 12 K), and we have therefore neglected this factor.

[9]G. A. Herzlinger and J. G. King, Phys. Lett. 40A, 65 (1972).

[10]H. T. Tan and C.-W. Woo, Phys. Rev. Lett. 30, 365 (1973).

[11]The theories of Refs. 4 and 5 do not predict Raman spectra, but only the dynamic structure factor $S(k,\omega)$. We have assumed that the changes in S will lead to modification of the Raman spectra. The authors of Ref. 1 point out that their assumption of the validity of quantum hydrodynamics is untested. The failure of this assumption could be the origin of the discrepancy between theory and experiment.

[12]The Raman data for both Δ and Γ are in reasonable agreement with very recent theoretical estimates by A. Bagchi and J. Ruvalds, to be published.

[13]R. L. Woerner, D. A. Rockwell, and T. J. Greytak, following Letter [Phys. Rev. Lett. 30, 1114 (1973)].

Measurement of Roton Energies and Linewidths in He^3-He^4 Solutions*

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Using Raman scattering from rotons in liquid He^3-He^4 solutions for He^3 concentrations $0 \leq X \leq 0.11$ at $T = 0.60$°K, we have measured the two-roton energy and linewidth. Our measurements indicate no change in the single-roton energy as a function of concentration, whereas the single-roton linewidth increases nonlinearly with X.

Although neutron scattering has provided detailed information on the elementary excitations in pure liquid He^4,[1] this technique has not been applied to solutions of He^3 in He^4 because of the very strong absorption of neutrons by the He^3 atoms. Therefore, only indirect information has been available about the influence of the He^3 atoms on one of the most interesting excitations in the pure He^4, the roton. Measurements of fourth-sound velocity,[2] ion mobility,[3] and normal-fluid fraction[4] in the solutions all infer that the roton energy $\Delta(T,X)$ first decreases rapidly with increasing He^3 molar concentration X ($\Delta^{-1} d\Delta/dX \sim -3$ near $X = 0$) and then levels out at concentrations $X \sim 0.2$. From values of the He^3-roton scattering cross section σ obtained from measurements of the diffusion of He^3 atoms in the solutions,[5] estimates of the concentration dependence of the roton linewidth $\Gamma(T,X)$ can be made. We report here direct measurements by Raman scattering of the energy and linewidths of zero-momentum pairs of rotons at a temperature of 0.60 °K and concentrations $0 \leq X \leq 0.11$. In contrast with previous results, we find that Δ is essentially independent of concentration in this region. The linewidth we measure is consistent with simple order-of-magnitude estimates based on σ. In addition, our measurements indicate a nonlinear dependence of Γ on X.

The experimental apparatus is the same as that used in earlier experiments[6,7] except that the liquid-helium sample is now cooled by a continuous He^3 refrigerator. The spectrometer is a pressure-swept flat Fabry-Perot type with a free spectral range of 48.6°K and an instrumental full width of 0.70°K (1°K = 0.6952 cm^{-1}). The mixtures were prepared in gaseous form at room temperature and then condensed into the scattering cell at a temperature below 0.30°K. The cell was sealed for an experimental run during which the solution was at saturated vapor pressure. As a check for heat flush, the 5145-Å incident laser power was varied between 300 and 750 mW. No changes in the measured spectrum were observed.

The most prominent feature in the spectrum of Raman scattering from pure liquid He^4 is a peak corresponding to the creation of a pair of rotons with zero total momentum.[6] The location and width of this peak are related to the energy and linewidth of the pair state. Figure 1 shows typical experimental spectra in the vicinity of the two-roton peak at 0.6°K for three different concentrations. Note that the position of the two-roton peak is essentially unchanged by the addition of He^3, whereas the broadening of this peak is quite evident.

Quantitative values for the changes in the energy and linewidth of the two-roton state were obtained as follows.[7] An experimental trace tak-

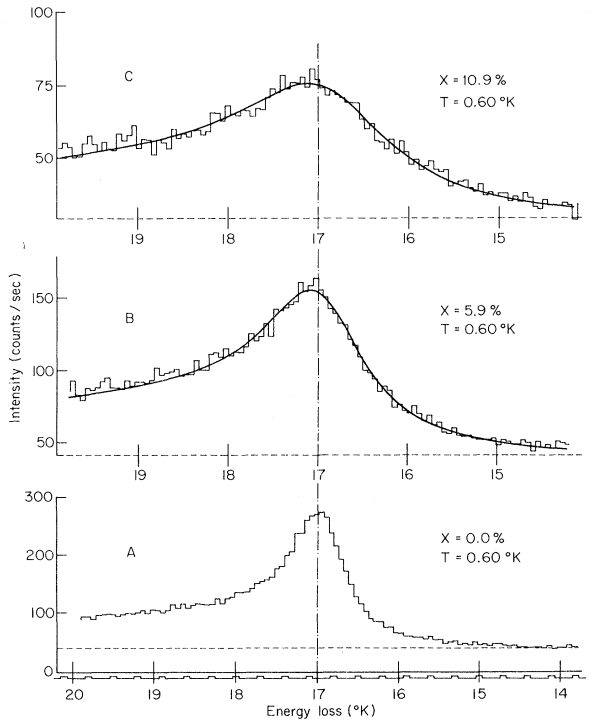

FIG. 1. Raman spectrum of liquid He^3-He^4 solutions for various He^3 concentrations at $T = 0.60$°K. The instrumental width is 0.70°K. The periodic pulses below the baseline of (a) are interferometrically generated frequency markers. Dashed curves, background due to Brillouin scattering from the phonons. The smooth curves in (b) and (c) have been calculated by convolving the $X = 0$ trace with Lorentzian line shapes.

en at $X = 0$ and $T = 0.60$°K was convolved by computer with a Lorentzian line of half width at half-height β, and the resulting spectrum shifted in energy by an amount α. α and β were chosen by a least-mean-square procedure to give the best fit to the measured traces taken at higher X. α is then interpreted as the decrease in energy and β as the increase in linewidth of the two-roton state due to the influence of the He^3 atoms. The smooth curves in Figs. 1(b) and 1(c) were generated by this procedure, and it can be seen that they represent the measured traces within the noise. This procedure was carried out for several sets of traces at each concentration. The results are summarized in Fig. 2 where the error bars represent the maximum spread in the fitted parameters. It can be seen that to within the error, no shift of the two-roton energy is required to fit the data. The small shifts in the location of the maxima of the spectra at finite concentrations observable in Fig. 1 are due to the broadening of the asymmetric $X = 0$ spectrum.[8]

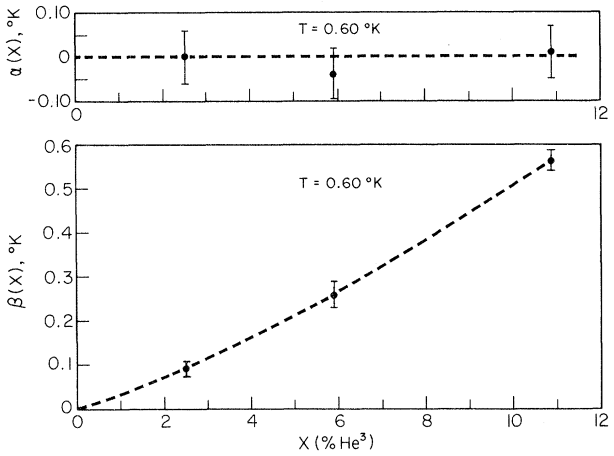

FIG. 2. α and β as functions of X. α is the decrease in the two-roton energy from its value at zero concentration of He^3. β is the increase in the half width at half-height of the pair state. The dashed lines simply provide smooth curves through the data.

When final-state interactions can be neglected (that is, when the rotons making up the pair do not interact with each other), α and β are simply twice the change in the energy Δ and the linewidth (half width at half-height) Γ of a single roton. For the more realistic case of interacting roton pairs in pure He^4 within the framework of a simple theoretical model[9] for the interaction, β is again simply twice Γ. α is then twice the change in Δ, neglecting changes in the small binding energy (0.37°K)[10] of the roton pair. We therefore make the plausible assumption that this relationship between the results of a convolution analysis of the measured traces and the single-roton parameters also holds true in the solutions.

As a result we conclude that in the range $0 \leq X \leq 0.11$ at $T = 0.60$°K there is no change in the single-roton energy to within ±0.03°K. This is inconsistent with previous experimental[2-4] and theoretical[11] results. In view of the large discrepancy in these results, we believe that neutron-scattering experiments from dilute solutions of He^3 would be very valuable.

Our values for Γ are obtained from Fig. 2 by dividing the values of β by 2. These data indicate that Γ increases nonlinearly with X with an initial slope $d\Gamma/dX = 1.8$°K. A recent theory of the He^3-roton interaction by Bagchi and Ruvalds[12] predicts a departure from linearity of the linewidth in this region. The relationship between Γ and the He^3-roton scattering cross section σ is complicated for many reasons, including the strong energy dependence of σ.[13] However, we

can make an *order-of-magnitude* estimate of Γ using a classical hard-sphere model for the collisions where the rotons are assumed to be stationary, and the He^3 quasiparticles move with a mean speed $\langle v\rangle = (3kT/m_3{}^*)^{1/2}$. Then

$$\Gamma(^\circ\mathrm{K}) = \hbar/2k\tau = (\hbar/k)\sigma n\langle v\rangle(2/3\pi)^{1/2}X,$$

where τ^{-1} is the mean collision frequency, n is the number density of atoms, and $m_3{}^* \approx 2.3m_3$ is the effective mass of the He^3 quasiparticle. Using a value of $\sigma = 1.6\times10^{-14}$ cm^2 measured by Herzlinger and King,[5] this expression becomes $\Gamma(^\circ\mathrm{K}) = 5.7X$, in satisfactory agreement with our results.

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[7]This technique was used previously to measure the temperature dependence of the roton linewidth in pure He^4: T. J. Greytak and J. Yan, in *Proceedings of the Twelfth International Conference on Low Temperature Physics, Kyoto, 1970* (Academic of Japan, Tokyo, 1971). Analysis of $X = 0$ traces between $T = 0.6$ and 1.2° K in the present experiment are in good agreement with these earlier results. It should be noted that, in general, one would not expect all of the excitations to be broadened by the same Lorenztian, but that our results indicate this is a good approximation.

[8]The Boltzman factor which skews the line shapes of the neutron-scattering results of Dietrich *et al.* (Ref. 1) differs from 1 by $\sim 10^{-6}$ for $T = 0.6$°K and $\hbar\omega/k_B = 8.7$°K, and therefore has a negligible effect on these results.

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Neutron Emission from Laser-Produced Plasmas*

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Neutron emission from laser-produced plasmas is shown, experimentally, to be adequately explained by electron heating and electrostatic ion acceleration. The absence of anomalous ion-heating mechanisms is not proved, but these mechanisms, if they exist, may be unimportant in reported experiments. It is concluded that no neutrons of thermonuclear origin are necessary to explain the results obtained thus far.

Because of the possible application of lasers for the production of thermonuclear fusion, much attention has focused on the generation of neutrons in laser-produced plasmas of deuterium or deuterated polyethylene (CD_2). Inverse bremsstrahlung and other mechanisms which selectively heat only electrons are discounted as ways of heating ions to thermonuclear temperatures because of the long electron-ion equilibration time in these plasmas.[1-4] Various anomalous ion-heating mechanisms are invoked to explain the neutron emission.[5-8] In the work described below, we show that anomalous ion heating is unnecessary and possibly incorrect as a description of the neutron-generation mechanism.

It is well known that neutrons are observed in plasmas heated with 2- to 10-nsec pulse lengths,[9-12] but not to any great extent in plasmas heated with picosecond pulses.[10,13,14] We have investigated the problem experimentally using a mode-locked Nd:YAlG (yttrium aluminum garnet), Nd:glass laser capable of delivering up to 17 J, in a bandwidth-limited pulse approximately 25 psec in length, to a solid target. These experiments em-