FIG. 3. X-ray intensity ratio between MO tail beyond the united-atom energy and S K line, as a function of sulfur projectile energy. Contributions from spontaneous (sp) and induced (ind) transitions and the sum of both (solid line) are indicated as calculated from Eqs. (4) and (5).

portant. From experiments with gas targets we have attained enlightening results on this very important question; these will be communicated elsewhere.

[1]F. W. Saris, W. F. van der Weg, H. Tawara, and R. Laubert, Phys. Rev. Lett. 28, 717 (1972).

[2]H.-D. Betz, in *Proceedings of the Heavy-Ion Summer Study, Oak Ridge, Tennessee, 1972,* edited by S. T. Thornton, CONF-720669 (Oak Ridge National Laboratory, Oak Ridge, Tenn., 1972), p. 545 ff; H. W. Schnopper, H.-D. Betz, J. P. Delvaille, K. Kalata, A. R. Sohval, K. W. Jones, and H. E. Wegner, Phys. Rev. Lett. 29, 898 (1972).

[3]H.-D. Betz and H. W. Schnopper, J. Phys. (Paris) 33, Colloq. No. 5, Vol. II, p. 116 (1972); H.-D. Betz, in Gesellschaft für Schwerionenforschung Report No. 73-11 (unpublished), p. 160.

[4]J. H. Macek and J. S. Briggs, J. Phys. B: Proc. Phys. Soc., London 7, 1312 (1974).

[5]B. Müller and W. Greiner, Phys. Rev. Lett. 33, 469 (1974).

[6]H.-D. Betz, F. Bell, and M. Kleber, to be published.

[7]P. Kienle, M. Kleber, B. Povh, R. M. Diamond, F. S. Stephens, E. Grosse, M. R. Maier, and D. Proetel, Phys. Rev. Lett. 31, 1099 (1973).

[8]M. Kleber and D. Jakubassa, to be published.

[9]W. E. Meyerhof, T. K. Saylor, S. M. Lazarus, W. A. Little, B. B. Triplett, and L. F. Chase, Phys. Rev. Lett. 30, 1279 (1973).

[10]M. Abramowitz and I. A. Stegun, *Handbook of Mathematical Functions* (Dover, New York, 1965), p. 300.

[11]J. S. Greenberg, C. K. Davis, and P. Vincent, Phys. Rev. Lett. 33, 473 (1974).

[12]G. Kraft, P. H. Mokler, and H. J. Stein, Phys. Rev. Lett. 33, 476 (1974).

Light Scattering through the Isotropic-Cholesteric Phase Transition of a Cholesteric Liquid Crystal

T. Harada and P. P. Crooker
Department of Physics and Astronomy, University of Hawaii, Honolulu, Hawaii 96822
(Received 12 February 1975)

We have measured the Rayleigh intensity and linewidth in cholesteryl oleyl carbonate continuously through the cholesteric-isotropic phase transition. Above the phase transition the intensity data do not agree with the theory of de Gennes; we also do not observe the instability of the isotropic phase predicted by de Gennes. At the phase transition we observe *two* exponentials simultaneously which we associate with order-parameter and director fluctuations.

Despite extensive measurements on director fluctuations in nematic phases[1,2] and order-parameter fluctuations in isotropic phases[3-7] of liquid crystals, it has so far been impossible to observe the passage from one type of fluctuation to the other because of the presence of a weak first-order transition separating the two phases. Indeed, de Gennes[8] has recommended looking for liquid crystals with "metastable phases" for just this purpose.

In this Letter we report measurements of the Rayleigh intensity and linewidth of cholesteryl oleyl carbonate (COC), a cholesteric liquid crystal which appears to have the metastable state mentioned by de Gennes. We summarize our observations as follows:

(1) The optical properties of COC change *continuously* upon cooling from the isotropic phase to the cholesteric phase without a detectable first-order phase transition.

(2) In the isotropic region, the reciprocal intensity of the scattered light increases linearly with temperature; however, the polarized and depolarized components have a ratio larger than the $\frac{4}{3}$ predicted by the de Gennes theory.

(3) In the isotropic region, the Rayleigh linewidths increase linearly with temperature, but the polarized and depolarized linewidths are different because of a small velocity coupling.

(4) In the region of the phase transition the Rayleigh linewidth consists of two Lorentzians associated with order-parameter and director fluctuations, respectively.

(5) Near the transition, we do not observe the instability of the isotropic phase predicted by de Gennes,[8] nor do we observe any detectable non-Lorentzian behavior of the lines.

Our COC, purchased from Eastman Kodak, was first filtered through a 500-Å filter, degassed for 3 h in the isotropic phase under a 10^{-4}-Torr vacuum, and then sealed in flat glass cells of various thicknesses. Tests for purity using thin-layer chromatography showed the presence of $\lesssim 1\%$ impurity, and separately prepared samples showed a range of clearing temperatures ranging from 30 to 32.5°C. As has been reported by others,[5,7] sets of data from different samples were identical when shifted on the temperature axis; we therefore believe that the presence of small amounts of impurity is not critical to our results.

Observation of our samples by use of a polarizing microscope shows that on heating, COC exhibits the cholesteric texture below about T_c = 31°C, at which point it undergoes a first-order phase transition into the textureless isotropic phase. When cooled, however, the sample remains continuously isotropic through T_c, with tiny cholesteric domains first becoming visible at about 28.5°C. The intermediate region between 28.5 and 31°C, which we associate with the "metastable phases" of de Gennes,[8] is quite stable and reproducible; isotropic samples in this region show no tendency to revert to the cholesteric phase over periods of many hours. Similar behavior has been reported for the well known α-β transition of quartz.[9]

For our light-scattering measurements, the angle between the incident and scattered light was 28.1°, with the sample oriented perpendicular to the scattered light. Polarization of the incident beam was perpendicular to the scattering plane while the scattered light was polarized either in the scattering plane (VH orientation), or perpendicular to the scattering plane (VV orienta-

tion). Glan-Thompson prisms (extinction ratio $\leqslant 10^{-5}$) were used to define the polarizations. We found it necessary to use samples 254 μm thick in order to reduce multiple-scattering effects, and sample temperature was controlled to ± 0.01 °C. The light source was a 488-nm-wavelength argon laser operated at $\leqslant 40$ mW. Laser power was carefully monitored during the measurements and no sample-heating effects were detected when the intensity was reduced. Light detection was accomplished by use of a cooled photomultiplier (dark count of 1 count/sec) and photon-counting electronics. For the linewidth measurements, a Saicor SAI-43A digitial autocorrelator was used.

In Fig. 1, we show the Rayleigh linewidths of the polarized (Γ_{VV}) and depolarized (Γ_{VH}) components of the scattered light as a function of temperature. In the isotropic phase, the experimental correlation functions are well fitted by a single exponential, with Γ_{VV} and Γ_{VH} converging to the same temperature, 31.49 ± 0.05°C, when extrapolated. According to the theory of de Gennes[8] in the approximation of Yang,[7] $\Gamma_{VV} = [a(T - T^*) + L_1 q^2]/\nu$. Here a and L_1 are constants, q is the wave vector of the order-parameter fluctuation, and ν is a viscosity taken by Yang to be constant. The depolarized linewidth Γ_{VH} is larger than Γ_{VV} because of coupling with shear velocities; for the case where the intrinsic width of the velocity shear mode is much larger than that of the order-parameter fluctuation, $\Gamma_{VH} = \Gamma_{VV}/(1 - 2\mu^2/\eta\nu)$. Here η is the shear viscosity and μ is a constant having the units of viscosity. From our data, we obtain $a/\nu = 35.1 \pm 1.2$ kHz/°C, and $\mu^2/\eta\nu = 0.094 \pm 0.003$. The latter value compares favorably with the same value in p-methoxybenzylidene-p-n-butylaniline (MBBA)[4] and as for MBBA our value remains constant to within 1°C of T^*.[10]

Below 32.5°C the linewidths no longer vary linearly with temperature; nevertheless, the line shape is still fitted by a single exponential down to 31°C, well below T^*. Below 31°C a second exponential component appears in the spectrum, growing in intensity until it completely dominates the spectrum below 28.3°C. In Fig. 2 we show the raw data in this intermediate region along with our best fit to a double exponential. The mode persisting into the isotropic phase we associate with order-parameter fluctuations while the mode persisting into the cholesteric phase is identifiable with director fluctuations. To the best of our knowledge the simultaneous observation of both types of fluctuations has not been ob-
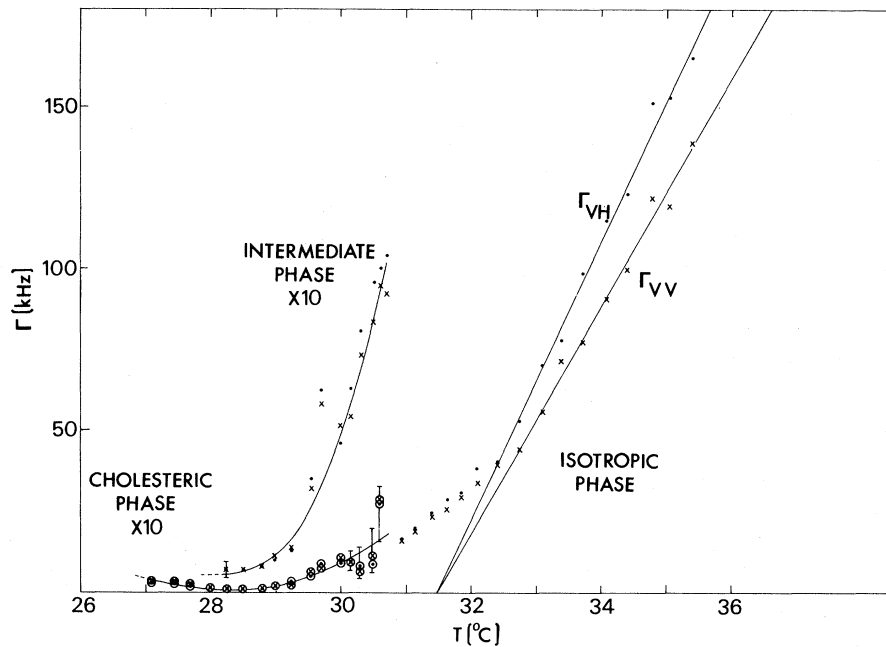
FIG. 1. Rayleight linewidth versus temperature for polarized (VV) and depolarized (VH) scattering. Straight lines are least-squares fits to the data.

served before.

Below 28.3°C long-range order has been established and the sample consists of randomly oriented cholesteric domains. Nevertheless, the linewidth rises with decreasing temperature, an effect we qualitatively associate with the "hardening" of the curvature elastic constants reported elsewhere.[11]

In Fig. 3 we show the dependence of the polarized (I_{VV}^{-1}) and the depolarized (I_{VH}^{-1}) compo-

nents of the reciprocal intensity versus temperature. The significant feature of these data is that, unlike measurements in MBBA,[3,6] the ratio of the slopes is $(\partial I_{VH}^{-1}/\partial T)/(\partial I_{VV}^{-1}/\partial T) = 1.448 \pm 0.014$. We have repeated these measurements
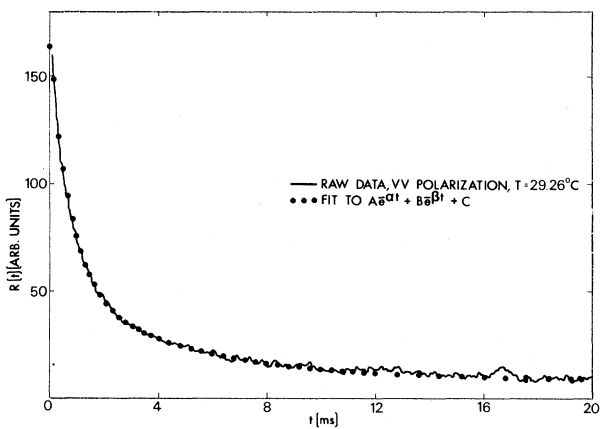

FIG. 2. Typical autocorrelation function in the double exponential region. Solid line is raw data; plotted points are empirical fit by two exponentials.
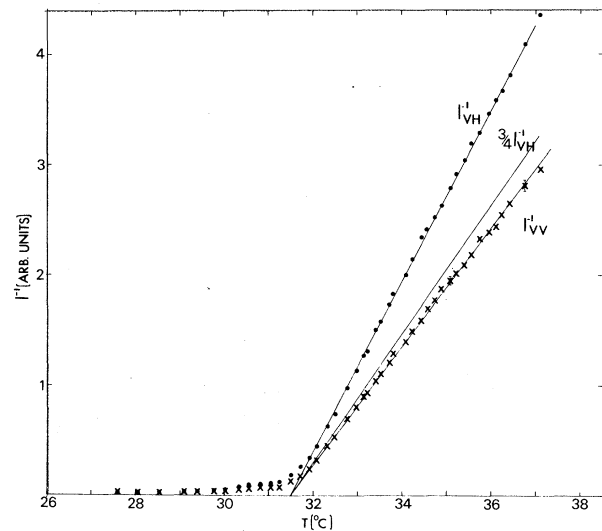

FIG. 3. Reciprocal of light scattering intensity versus temperature for polarized (VV) and depolarized (VH) scattering. Straight lines are least-squares fits to the data. Lines labeled I_{VH}^{-1} and $\frac{3}{4}I_{VH}^{-1}$ have the slope ratio predicted by theory.

at other angles, including 90° scattering from thick samples, and the ratio of slopes has consistently turned out to be close to 1.45. By use of the theory of de Gennes[8] with the approximations mentioned previously,[6,7,12] $I_{VV}^{-1} \propto a(T - T^*) + L_1 q^2$ and $I_{VH}^{-1} \propto \frac{4}{3} I_{VV}^{-1}$. Although the observed linear behavior of the reciprocal intensities is consistent with the theory, the theory predicts that $(\partial I_{VH}^{-1}/\partial T)/(\partial I_{VV}^{-1}/\partial T) = \frac{4}{3}$ in disagreement with our data.

We have investigated the effect of a background contribution to the polarized component of the scattered light, either from impurities or from stray scattered light.[5] Such a contribution would have an intensity and spectral line shape that would be essentially temperature independent. Although this would cause the I_{VV}^{-1} data to bend away from the $\frac{3}{4} I_{VH}^{-1}$ line in Fig. 3, attempts to fit the data with such an assumption do not produce a better fit than the straight line in Fig. 3 labeled I_{VV}^{-1}. Furthermore, the effect would produce a second component in our line shapes which we do not see.

[1]Orsay Liquid Crystal Group, Phys. Rev. Lett. 22, 1361 (1969).

[2]P. G. de Gennes, Mol. Cryst. Liquid Cryst. 7, 325 (1969); Groupe d'Etude des Cristeaux Liquides (Orsay), J. Chem. Phys. 51, 816 (1969).

[3]T. W. Stinson and J. D. Litster, Phys. Rev. Lett. 25, 503 (1970).

[4]T. W. Stinson, J. D. Litster, and N. A. Clark, J. Phys. (Paris), Colloq. 33, C1-69 (1972).

[5]T. W. Stinson and J. D. Litster, Phys. Rev. Lett. 30, 688 (1973).

[6]B. Chu, C. S. Bak, and F. L. Lin, Phys. Rev. Lett. 28, 1111 (1972).

[7]C. C. Yang, Phys. Rev. Lett. 28, 955 (1972).

[8]P. G. de Gennes, Phys. Lett. 30A, 454 (1969), and Mol. Cryst. Liquid Cryst. 12, 193 (1971).

[9]S. M. Shapiro and H. Z. Cummins, Light Scattering Spectra of Solids, edited by G. B. Wright (Springer, Berlin, 1969), p. 705.

[10]N. A. Clark, Phys. Lett. 46A, 171 (1973); J. D. Litster, private communication.

[11]I. Haller and J. D. Litster, Phys. Rev. Lett. 25, 1550 (1970).

[12]The details of these calculations, which follow the approach of Ref. 8, will be given elsewhere. See also Ref. 4.

Two-Dimensional Calculation of Electron-Beam–Target Interaction

Z. Zinamon, E. Nardi,* and E. Peleg
The Weizmann Institute of Science, Rehovot, Israel
(Received 10 February 1975)

The interaction of a pinched relativistic electron beam with a solid target is calculated by use of the Monte Carlo method for energy deposition and two-dimensional particle-in-cell (PIC) hydrodynamics to take into account the full effect of target expansion. Bremsstrahlung emission is also evaluated through the use of the Monte Carlo method. Self-magnetic-field effects are neglected. It is found that target expansion can considerably reduce the efficiency of energy deposition in the focal region.

The use of relativistic electron beams for an inertially confined controlled thermonuclear reaction involves obtaining high energy densities in solid targets by pinched-beam energy deposition.[1-4] Considerable effort is devoted to obtaining highly pinched electron beams.[5-10] The process of energy deposition in the high-current, high-energy-density regime differs from the classical cold-target process in a number of ways. One of these is the effect of target expansion due to the high pressures which develop during the energy-deposition process. In cold high-density targets the penetration depth of a typical beam (say, 500 keV) is much smaller than a typi-

cal obtainable pinch radius. Therefore, in a cold dense target, an electron which is scattered sideways during the process of slowing down still has a good chance to deposit its energy in the focal region. Later in the pulse, matter initially in the focal region expands and the expanding column is much more "transparent" to electrons in the lateral direction. Therefore, an electron entering the expanded target material has a better chance to escape without depositing its energy if it is scattered sideways. This effect is expected to be important whenever

$$\bar{\rho} R < \rho_0 d \quad \text{or} \quad l + d > R, \tag{1}$$