

the WKB approximation for linear waves. In contrast with the linear case, the amplitude estimated this way remains finite at the turning point, and is indicated on Fig. 2 for a few incident fields.

Figure 4 shows the ion density at the turning point as a function of *incident* field strength, from (13). The corresponding ion density versus the maximum field *at the turning point*  $F_T = 2(\alpha^2 - \alpha)^{1/2}$  is also shown. This curve may be compared with the condition of Akhiezer and Polovin<sup>1,2</sup> for the existence of circularly polarized traveling waves in a uniform overdense medium,  $F \geq (\alpha^2 - 1)^{1/2}$ . A more interesting condition,  $F_0 \geq (\alpha/Z)^{1/2}$  derived by Max and Perkins<sup>3</sup> for propagation of very strong waves in a nonuniform medium, depends on the scale length of the plasma  $Z = (d \ln \alpha / d \xi)^{-1} \equiv \omega L / c$ , and could therefore be plotted on Fig. 4 only for a definite choice of scale length. In any case, this condition applies to fields  $F_0 \gg 1$  for which (13) must be altered because of depletion effects near the turning point.

At the field strengths we have been considering, thermal effects are negligible unless the electron thermal velocity  $v_i$  approaches the speed of light.

A value of  $v_i$  typically employed in laser-induced-plasma simulations<sup>4</sup> is  $c/10$ . Much more serious than neglecting the temperature is our assumption of fixed ions. The ion density is known to bunch at the nodes of the field after the standing wave is formed. The extent to which the transient evolution of these striations alters our predictions of penetration depth cannot be investigated in the context of our solutions.

<sup>1</sup>A. I. Akhiezer and R. V. Polovin, Zh. Eksp. Teor. Fiz. **30**, 915 (1956) [Sov. Phys. JETP **3**, 696 (1956)].

<sup>2</sup>P. Kaw and J. Dawson, Phys. Fluids **13**, 472 (1970).

<sup>3</sup>C. Max and F. Perkins, Phys. Rev. Lett. **27**, 1342 (1971).

<sup>4</sup>E. J. Valeo and K. G. Estabrook, Phys. Rev. Lett. **34**, 1008 (1975).

<sup>5</sup>P. Kaw, G. Schmidt, and T. Wilcox, Phys. Fluids **16**, 1522 (1973).

<sup>6</sup>L. D. Landau and E. M. Lifshitz, *Mechanics*, translated by D. B. Sykes and J. S. Bell (Addison-Wesley, Reading, Mass., 1960).

## Intensity and Linewidth of Rayleigh Scattering near the Double Plait Point of the System Ne-Kr†

R. J. Tufeu,\* P. H. Keyes,‡ and W. B. Daniels

*Department of Physics, University of Delaware, Newark, Delaware 19711*

(Received 21 July 1975)

From the intensity and Rayleigh linewidth of light scattered by the system Ne-Kr near the temperature minimum of the critical line (double plait point), we have verified the phenomenological rule that, for constant overall composition, the critical exponents are independent of the path of approach to the critical line, except along a path which is asymptotically parallel to the critical line where they assume twice their usual values.

Phase diagrams of binary systems show a variety of behavior.<sup>1</sup> Among them, fluid-fluid equilibria of the second type are of special interest: Their critical line passes through a temperature minimum as a function of pressure (or composition) at the so-called "double plait point."

As discussed by Griffiths and Wheeler,<sup>2</sup> the critical divergence for a given quantity must be independent of the path of approach to a point of the critical line at constant overall composition except when approaching the critical line tangentially. In this latter case, it is predicted that the critical exponents will differ from their con-

ventional values. Figure 1 shows several possible paths of approach to the critical line in the  $P$ - $T$  plane.

The purpose of this experimental investigation was (1) to verify that the critical exponents for a given quantity, in a region where  $P_c$  varies smoothly with temperature, should be the same whether the variable is taken to be  $P - P_c$  or  $T - T_c$ , the composition  $x_c$  being held constant (this prediction follows from the fact that in either case the path followed is parallel to the coexistence surface in the "field" representation introduced by Griffiths and Wheeler<sup>2</sup>); and (2) to

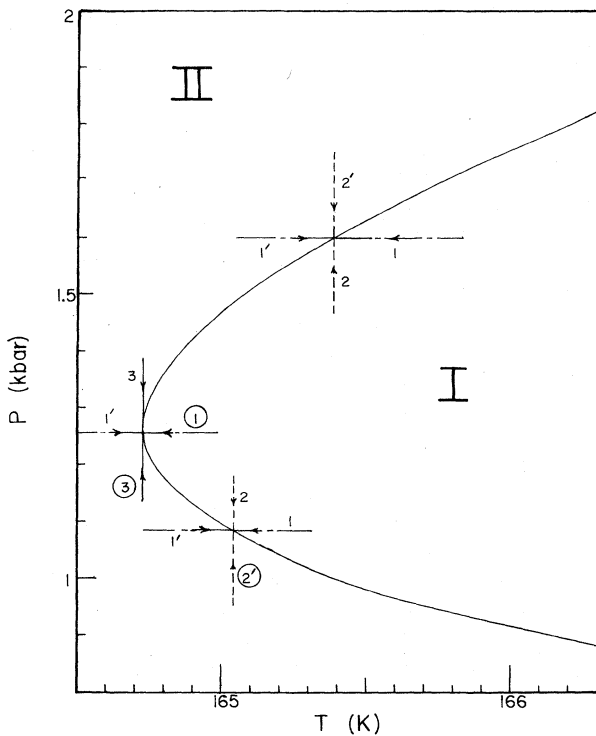


FIG. 1. The  $P$ - $T$  projection of the critical line of the system Ne-Kr in the vicinity of the double plait point. I is the one-phase region and II is the two-phase region. The critical exponents should be the same for all paths illustrated except for path 3. The circled numbers indicate the paths chosen in our experiment.

compare these exponents to those obtained along a special path parallel to the critical line, which in the system Ne-Kr is most conveniently taken to be the path along the coexistence curve at the double-plait-point temperature  $T_D$ .

From measurements of the intensity of the scattered light in the hydrodynamic regime (i.e., where the product of the momentum transfer  $k$  and the long-range correlation length  $\xi$  is much less than unity), one can get the exponent  $\gamma$  governing the divergence of the susceptibility. From the linewidth of the Rayleigh component, in the same hydrodynamic limit, one gets the critical exponent for the diffusion coefficient  $D$ , which is the same as the exponent  $\nu$  for the inverse correlation length  $\xi^{-1}$ , according to the Kadanoff and Swift theory.<sup>3</sup>

The phase diagram of the system Ne-Kr has been determined very accurately by Schouten.<sup>4</sup> From high-purity Ne and Kr, we prepared a mixture having the double-plait-point composition (37.5% Kr) with an estimated accuracy of  $\pm 0.2\%$ .

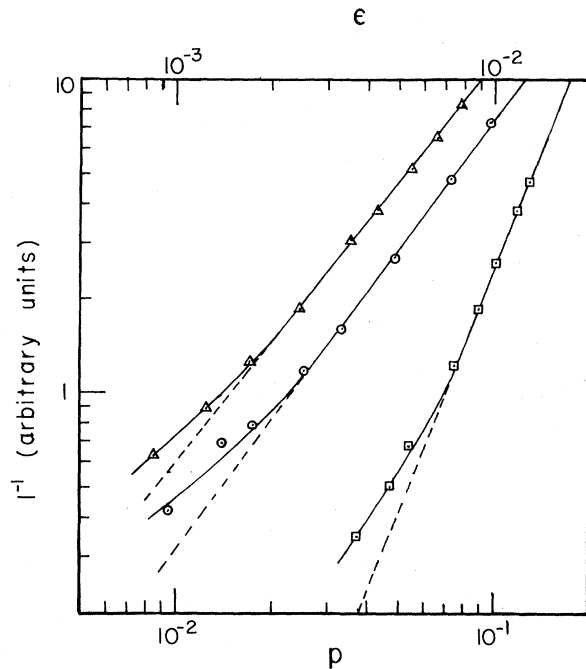


FIG. 2. The inverse scattered intensity.  $\Delta$ , path 1,  $I^{-1}$  versus  $\epsilon$ ;  $\circ$ , path 2,  $I^{-1}$  versus  $p$ ;  $\square$ , path 3,  $I^{-1}$  versus  $p$ .

The transition temperature of this mixture at the double-plait-point pressure ( $P_D = 1256$  bar) was found to be 164.716 K in good agreement with the value given by Schouten ( $164.72 \pm 0.02$  K). Furthermore, the lower transition pressure at  $T = 165.036$  K  $= T_D + 0.320$  K was found to be 1080 bar, also in agreement with Schouten's data.

The sample was confined in a variable-volume, high-pressure optical cell allowing  $90^\circ$  observation. An RCA model LD2186 helium-cadmium laser ( $\lambda = 441.6$  nm) was used as the light source. The signal was analyzed by a Saicor 51B real-time spectrum analyzer.

The approach to the transition surface was performed along three selected paths (see also Fig. 1): (1) Varying the temperature at  $P_D = 1256$  bar in the one-phase region. (2) Varying the pressure at  $T = T_D + 0.320$  K in the lower two-phase region, this observation being done in the upper phase. (Since the composition is fixed in our experiment, the transition does not take place at the critical pressure corresponding to this temperature, but at a pressure approximately 1 bar lower. This difference should be unimportant in the hydrodynamic regime which is characterized by  $P_c - P > 25$  bar.) (3) Varying the pressure at  $T = T_D - 0.002$  K in the lower two-phase region,

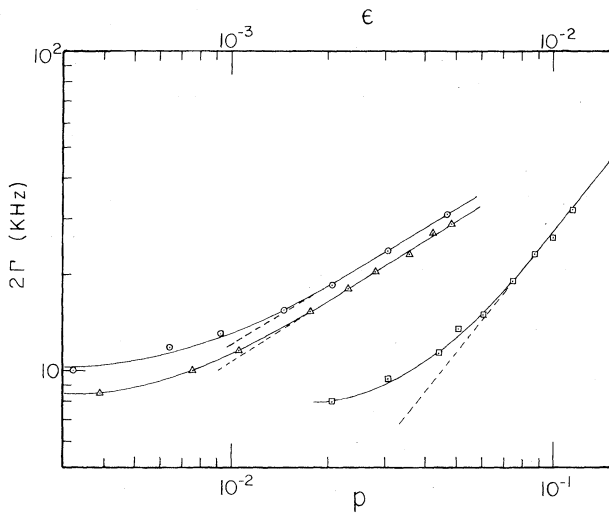


FIG. 3. The Rayleigh linewidth  $\Gamma$ .  $\Delta$ , path 1,  $\Gamma$  versus  $\epsilon$ ;  $\circ$  path 2,  $\Gamma$  versus  $p$ ;  $\square$ , path 3,  $\Gamma$  versus  $p$ .

the observation being done in the upper phase.

Figures 2 and 3 are log-log plots of the inverse intensity and linewidth in terms of  $\epsilon \equiv |T - T_c|/T_c$  or  $p \equiv |P - P_c|/P_c$ . Deviations from linearity for small values of  $\epsilon$  and  $p$  reflect the changeover from the hydrodynamic ( $k\xi \ll 1$ ) to the critical ( $k\xi \gg 1$ ) regime. Because of experimental limitations the accessible hydrodynamic regime is not very extended. However, for the intensity measurements, the precision is good enough to allow a determination of the slopes with an acceptable precision. For paths 1 and 2, one gets  $\gamma = 1.24 \pm 0.05$  and  $1.30 \pm 0.05$ , respectively. For path 3 we find  $\gamma' = 2.45 \pm 0.05$ . The straight lines in Fig. 2 have been drawn with these slopes. In Fig. 3, in the hydrodynamic regime, we have fitted the linewidth data, which were determined with less precision, by straight lines having slopes of  $\nu = \gamma_{ave}/2$  and  $\nu' = \gamma'/2$ .

The first point to note is that the exponents  $\gamma$  and  $\nu$  are in good agreement with results obtained for binary liquids, as, for example, 3-methylpentane-nitroethane.<sup>5</sup> Also, as in the case of a binary liquid, it does not seem to be necessary to correct the Ne-Kr linewidth data for the effects of a background "concentration conductivity." In other words, the system Ne-Kr, near the double plait point, resembles a liquid-liquid system more than it does a liquid-vapor system.

The second and most interesting point is that our results are consistent with the phenomenological rules devised by Griffiths and Wheeler re-

called in the introduction of this paper: (1) In a region where  $P_c$  is a smoothly varying function of temperature, there is no preferred direction in the  $P$ - $T$  plane as far as the critical behavior is concerned; (2) the approach tangent to the critical line at the double plait point is fundamentally different.

The factor-of-2 increase for the exponents along path 3 can be understood by following a simple argument developed by Griffiths and discussed by Bartis and Hall.<sup>6</sup> Let us consider the behavior of the correlation length  $\xi$ , in terms of which both  $D$  and the susceptibility can be expressed. On the coexistence surface at temperature  $T_D$  and pressure  $P$ , one can write

$$\xi = \xi_0(P) \left( \frac{T_c(P) - T_D}{T_D} \right)^{-\nu},$$

where  $T_c(P)$  is the temperature of the critical line corresponding to the pressure  $P$ . Expanding  $T_c(P) - T_D$  in terms of  $P_D - P$ , keeping the first nonvanishing term (quadratic), and also assuming that  $\xi_0(P) = \xi_0(P_D)$ , one gets

$$\xi \propto (P_D - P)^{-2\nu},$$

i.e.,  $\nu' = 2\nu$ .

One of us (R.J.T.) would like to acknowledge a grant from the Centre National de la Recherche Scientifique which enabled him to spend a year in the Department of Physics of the University of Delaware.

†Work supported in part by the National Science Foundation under Grant No. GH32491X2, the Unidel Foundation, the University of Delaware Research Foundation, and the North Atlantic Treaty Organization through a Fellowship to R. J. Tufeu.

\*On leave of absence from Laboratoire Interactions Moléculaires Hautes Pressions, Centre National de la Recherche Scientifique, 92190-Meudon-Bellevue, France.

‡Present address: Department of Physics, University of Massachusetts, Boston, Mass. 02125.

<sup>1</sup>See, e.g., G. M. Schneider, Ber. Bunsenges. Phys. Chem. **76**, 325 (1972).

<sup>2</sup>R. B. Griffiths and J. C. Wheeler, Phys. Rev. A **2**, 1047 (1970).

<sup>3</sup>L. P. Kadanoff and J. Swift, Phys. Rev. **166**, 89 (1968).

<sup>4</sup>J. A. Schouten, thesis, Universiteit van Amsterdam, 1969 (unpublished). See also N. J. Trappeniers and J. A. Schouten, Phys. Lett. **27A**, 340 (1968).

<sup>5</sup>R. F. Chang, P. H. Keyes, J. V. Sengers, and C. O. Alley, Phys. Rev. Lett. **27**, 1706 (1971).

<sup>6</sup>J. T. Bartis and C. K. Hall, Physics (Utrecht) **78**, 1 (1974).