A BRIEF SURVEY OF THE EQUILIBRIUM AND TRANSPORT PROPERTIES OF CRITICAL FLUIDS AND THE DEGREE TO WHICH MICROGRAVITY IS REQUIRED FOR THEIR EXPERIMENTAL INVESTIGATION

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ABSTRACT

The modern theory of second order phase transitions is very successful in calculating the critical exponents as an asymptotic expansion in powers of $\varepsilon = 4 - D$, the deviation of $D = 3$, the spatial dimension of the actual physical system from that of the abstract four-dimensional reference model. This remarkable mathematical *tour de force* leaves unanswered, however, many fundamental questions concerning the exact nature of how the fluctuations interact. I discuss here some experiments which would help to further our understanding of the equilibrium critical properties. Especially promising would be a measurement of the temperature dependence of the turbidity very close to the critical point. This has the promise of determining the small and elusive but fundamentally important anomalous dimension exponent η. I also review various ways of measuring the critical transport coefficients and point out some cases where ground based experiments may usefully supplement flight experiments.

INTRODUCTION

Consistent with the brevity of the oral presentation of this paper, I am presenting it in an outline, and almost telegraphic style. Those who find this too cryptic and desire more details are invited to write to me. (I hesitate to violate the decorum of these conference proceedings by listing here my telephone number.)

I. EQUILIBRIUM PROPERTIES

The Fisher-Wilson ε-expansion is an effective technique for computing numerically the critical exponents, but a full fundamental understanding of second order phase transitions calls for a more thorough and probing investigation of how the fluctuations interact. To arrive at a more complete picture of what is happening in a fluid at thermal equilibrium when the temperature T is lowered toward the critical temperature T_c, we need to study, both theoretically and experimentally, the evolution of $P(\Psi)$, the probability distribution of the fluctuations in the variable

$$\Psi = \int_{\Omega=\ell^3} \psi(\underset{\sim}{x}) d^3x.$$

This integral of the order parameter $\psi(\underset{\sim}{x})$ is carried out over a small volume of linear dimensions ℓ. Far above the critical point, the correlation length, ξ, is much smaller than ℓ. As T is lowered, $P(\Psi)$ remains Gaussian but broadens. Upon further approach of T to T_c, ξ will grow and become comparable to ℓ. At this stage the broadening will cease, but the shape of $P(\Psi)$ will change and become flatter. For $T < T_c$, the distribution becomes bimodal and splits into two peaks, at positive and negative values of Ψ.

A. Direct Observation of the Fluctuations

Beysens has reported[1] on a straightforward approach, by means of microscopy, to the determination of $P(\Psi)$. A microscope is focused on a thin layer of fluid. A spot, of dimensions determined by the wavelength of the light and the resolving power of the microscope, is observed at many successive instants over a period that is much longer than the longest equilibration time of the fluid. For this type of experiment, a special fluid containing small polymer spheres is prepared so as to obtain a correlation length that is large enough to be comparable to the spot size, thereby making possible the observation of critical behavior.

B. Light Scattering

1. Turbidity

The suppression of the wings and the resulting flattening of the shape of $P(\Psi)$ is a consequence of the repulsive interaction of the order parameter fluctuations. This effect also shows up in the mean square of the fluctuation of wave number k, proportional to $k^{-2}\left(k / k_0\right)^{\eta}$, where k_0 is a crossover parameter and η is the small anomalous dimension critical exponent. This formula, valid for $\xi^{-1} << k << k_0$, describes a shrinkage, or decrease, in the amplitude of the fluctuations, by the factor $\left(k / k_0\right)^{\eta/2}$, and is an essential feature of critical phenomena. Both the ε-expansion computations and an independent approach based on a sum rule[2] predict $\eta \cong 0.04$. Light scattering measurements[3] have yielded $\eta = 0.03 \pm 0.03$. I have argued[4] that a preferred method of determining this important exponent is the measurement of the temperature dependence of the turbidity. This corresponds to integrating over all of the scattering angles and is largely free of the complication of double scattering. Some studies

have been carried out on the experimental feasibility of measuring η for a binary liquid in this way[5]. For the one-component fluid, the Zeno cell also suggests itself.

2. Cross Correlations

As noted by Korenman[6] the cross correlation of the signals in two separate photo-detectors, placed in two different directions relative to the incident laser beam, yields information on the interaction of the fluctuations. An advantage of this experimental method is that, by introducing a time delay between the two detectors, information can also be obtained regarding the critical dynamics of the fluid.

II. CRITICAL DYNAMICS

Dynamic scaling theory was first enunciated[7] for the divergence of the thermal conductivity at the lambda point of liquid ^{4}He, but was soon thereafter extended to the classical fluid.[8,9] Dynamic scaling has, furthermore, been extended to the critical behavior of the viscosity,[10,11,12,13] which can be regarded also as a transport coefficient—the transport of momentum through a fluid subjected to shear.

A. Thermal Conductivity by Electrostriction

Electrically charging a wire in a fluid causes an adiabatic temperature rise in the vicinity of the wire. Observing the thermal equilibration and the resulting density change, in a microgravity environment, might make possible a measurement of the thermal conductivity that is free of the usual boundary effects.

B. Critical Viscosity

A manifested flight experiment, CVX, promises[14] to yield a value for the critical exponent that is free of the complication of gravitational stratification. Nevertheless, it is useful to consider the possibility of a ground-based experiment in which stratification is minimized by using a very thin horizontal layer. Electrostriction, an effect demonstrated during the July, 1994 Columbia flight, could be used to drive the fluid against the opposing viscous force.[15]

C. Critical Ultrasonic Attenuation

Of all the critical fluid properties, ultrasonic attenuation exhibits the strongest, and perhaps the most dramatic dependence on the reduced temperature—roughly as the inverse square (along the critical isochore). Unfortunately, there are strong deviations from pure dynamic scaling[16] that result from the

large non-critical background contribution to the thermal conductivity (which determines the relaxation rate of the fluctuations). For this reason, a microgravity environment will be required to explore experimentally the true asymptotic scaling region.

III. ADIABATIC FAST EQUILIBRATION

A. Supercritical Fluid

The diverging thermal expansion coefficient endows a one-component fluid with some remarkable critical properties, such as adiabatic fast equilibration, the theory[17] of which predicts an inverse square root time dependence for the approach to equilibrium in the intermediate time regime. This adiabatic effect is important for CVX and also plays a dominant role in some of the density changes observed in Zeno.

B. Two-Phase Relaxation

The density changes in the coexisting liquid and vapor that have been observed in the liquid ^{3}He Duke experiments can be understood by means of a straightforward extension of the adiabatic theory. The temperature at the interface plays a dominant role in the analysis.

SUMMARY

Many good experiments that would clarify our picture of what is happening at the critical point are calling out to be performed. Especially important would be the measurement of η by turbidity. In the dynamics, much work also remains to be done. Dynamic scaling for the ultrasonic attenuation, for example, remains to be explored and would require microgravity. The theory of two-phase equilibration has only recently been completed and requires experimental testing. Throughout all of this work, there is basically no difference between the second order phase transitions at ambient temperature and at low temperature. A unified approach would, thus, seem to be highly desirable.

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