

Neutron Scattering Verifies Dynamic Scaling

A Brookhaven group has observed the time-dependent behavior of rubidium manganese fluoride near the critical point, and their results agree with dynamic-scaling predictions made by Bertrand Halperin and Pierre Hohenberg (Bell Telephone Laboratories); the agreement is the latest in a series of successes that scaling laws have achieved in predicting critical-point behavior.

Static scaling. When a substance changes from a disordered to an ordered state, for example, in magnetic systems, the susceptibility is infinite at the transition temperature. In a liquid in equilibrium with its vapor, as the temperature is raised the compressibility becomes infinite at the critical point. The spontaneous magnetization in a ferromagnet goes to zero as the temperature is raised to the transition point.

These qualitative properties are well described by the "classical theories" of van der Waals, Weiss and Landau. Recently, careful experiments have revealed quantitative discrepancies

with classical theories. In addition, as early as 1944, Lars Onsager's famous solution of the two-dimensional Ising model revealed behavior that differed markedly from that predicted classically. The hope has been to find an alternative phenomenological theory, which would be in better agreement with both the Onsager solution and experiments on real systems.

Initial attempts dealt with static properties, trying to understand temperature dependence. Benjamin Widom¹ (Cornell) and others introduced so-called "scaling laws," which were first applied to the dependence of thermodynamic parameters on temperature T and magnetization M . In the equation of state the magnetic field of a ferromagnet is a function of T and M . As M and $T - T_c$ approach zero, one approaches a very complicated singularity in the two variables.

If one makes the strong assumption that the equation of state can be written as a homogeneous function of $T - T_c$ and M^x where x is some exponent, one can obtain relations between the critical singularities in the variables T and M .

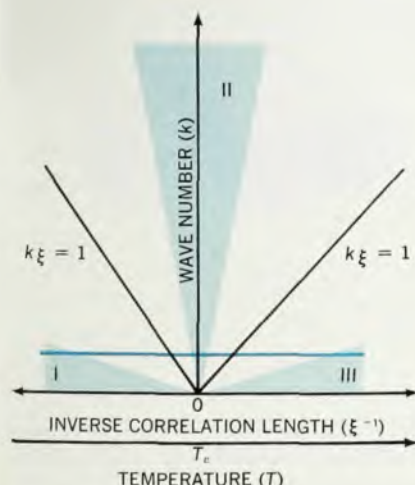
The next step was made by Leo Kadanoff² (Brown) and by A. Z. Patashinskii and V. L. Pokrovskii³ (Novosibirsk), who applied scaling not only to thermodynamic quantities, but also to static correlation functions. The spin correlation function, for example, is a function of T , M and r , the spatial separation of the two spins (or k , the wave number, if one takes the Fourier transform). In the small- k limit the correlation function becomes proportional to a thermodynamic derivative. (Correlations at small k , that is, at long wavelengths, are related to susceptibilities, for example.) Whatever behavior the correlation function has, it must reduce to the homogeneity that was assumed for thermodynamic quantities. Near the transition, large correlations exist, whose spatial range or correlation length ξ goes to infinity as T goes to T_c in zero magnetic field.

According to the scaling assumption, the correlation functions become homogeneous functions of r and ξ when both r and ξ are large, while ξ itself is

presumably a homogeneous function of M^x and $T - T_c$. The behavior of the Fourier-transformed correlation function then depends on the dimensionless parameter $k\xi$, essentially the ratio of ξ to the wavelength under consideration. For any fixed temperature, other than T_c itself, the parameter $k\xi$ becomes small compared to unity when the wavelength is sufficiently large; one is then in the "macroscopic region." If the wavelength is fixed and the temperature approaches T_c , $k\xi$ must eventually become large compared to unity, and one leaves the macroscopic domain. The scaling laws enable one to derive relations between the behaviors in the different regions.

Dynamic scaling. Could the static laws be extended to time-dependent properties? Richard A. Ferrell and his collaborators at the University of Virginia⁴ did such an extension, in studying the λ point of He^4 , by scaling the characteristic frequencies. They predicted an anomalous damping of second sound below T_λ and a singular thermal conductivity above T_λ . These properties were soon verified: J. Anthony Tyson⁵ (at the University of Chicago) reported anomalous damping of second sound that agreed well with prediction, and Guenther Ahlers⁶ (Bell Labs) observed the singular thermal conductivity.

Two years ago Halperin and Hohenberg⁷ applied scaling to dynamics of magnetic systems as well, talking about the characteristic frequency ω of spin fluctuations. Similar work was done independently by Kyozi Kawasaki⁸ (Kyushu University). At any value of k and any T (or ξ), you have a value for ω that is a function of k and ξ . Again one assumes that $k\xi$ is the relevant variable and looks at the behavior for large and small values of $k\xi$. Knowing the behavior in the macroscopic domain (when $k\xi$ is small), you can make predictions (dynamic scaling laws) about the behavior in the other domain, the critical domain, for which $k\xi$ is large. For example, at the Néel temperature of a Heisenberg antiferromagnet, dynamic scaling predicts that the characteristic frequency for fluctuations of the staggered magnetization



SCALING LAWS apply to correlation functions for small wave numbers k , when the temperature T is close to a critical point T_c . The correlation length ξ is a function of T that diverges at T_c . Regions I and III are the "macroscopic regions" below and above T_c respectively, where $k\xi \ll 1$. Region II is the extreme critical region where $k\xi \gg 1$. An experiment at constant k (solid color) will pass through all three regions as T is varied.

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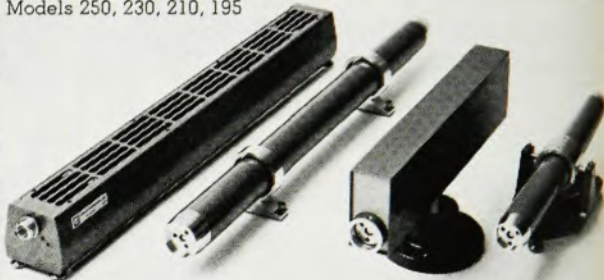
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should be proportional to $k^{3/2}$, because the spin-wave frequency is believed to vary as $\xi^{-1/2} k$ in the macroscopic region below T_c .

The Brookhaven experiment was done by H. Y. Lau, Lester Corliss, A. Delapalme, Julius Hastings, Robert Nathans and A. Tucciarone (*Phys. Rev. Lett.* **23**, 1225, 1969). The experimenters used a simple "fruit-fly" type of material, rubidium manganese fluoride: the manganese atoms sit on a simple cubic lattice; the exchange interaction is very closely of the form $S_1 \cdot S_2$, where S_1 and S_2 are atomic spins; the interactions lead to antiferromagnetic ordering at a temperature T_N of 83 K.

A beam of neutrons strikes the sample, and the experimenters measure the energy and momentum of the inelastic magnetically scattered neutrons. The momentum dependence yields information on the spatial extent of the correlated regions, and the en-

ergy dependence yields information on their time dependence.

The Brookhaven group was able to determine the characteristic frequency for k approximately equal to zero as a function of temperature (or ξ) and for $T = T_N$ ($\xi^{-1} = 0$) as a function of k . Comparing the behavior in these two regions, they find good quantitative agreement with the prediction of dynamic scaling. —GBL

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Panel Suggests New Uses for Accelerators of 6 MeV or Less

A National Academy of Sciences report, "New Uses for Low-Energy Accelerators," suggests a variety of experiments for nuclear astrophysicists, atomic and solid-state physicists. The 173-page report, prepared by an ad hoc panel chaired by William A. Fowler, discusses many uses for machines with energies of 6 MeV or less. Comments from the report include:

- Thermonuclear-reaction studies provide the most useful application of these accelerators to nuclear astrophysics. One can study nonresonant charged-particle, resonant and neutron-induced reactions and photonuclear rates.

- With beam-foil spectroscopy the atomic physicist can study the level structure of monatomic ions. The atomic lifetimes of the highly charged ions produced in the foil experiments are determined by measuring the decrease either in the transition rate or in the brightness of the emerging ions.

- Among the experiments of interest to solid-state physicists are those dealing with energy loss and with penetration of keV to MeV particles into amorphous and crystalline solids. Channeling (anisotropic-penetration) studies can be performed on crystals to locate foreign atoms, determine precise crystal orientation and study lattice damage. One can possibly tailor

solid-state materials by adding atoms dynamically (ion implantation) rather than by conventional doping techniques.

- Solid-state and nuclear physicists might profitably cooperate in studies of the interaction of nuclear moments with solid-state environments. Measurements of magnetic and electric fields in solids interacting with the magnetic and electric moments of the nuclei could be used to study either the fields or the moments.

Doppler Shift Is Used to Study Superfluid Currents

At the December APS meeting in Los Angeles, a group from UCLA reported on a new method of studying persistent currents in superfluid helium in which they observe the Doppler shift of a sound wave in the medium.¹ This method has also been used by a Texas A & M group.²

In the UCLA work, Isadore Rudnick, H. Kojima, Wolfgang Veith and Reynold S. Kagiwada place liquid helium in a container packed with powder of very fine (about 17 to 32.5 nanometers) grain size. They rotate the cylinder as it is cooled below the critical temperature and then stop the rotation. Because of the viscosity of the normal fluid, it is trapped by the

powder pores while the superfluid component is free to move.

When a resonant sound wave is induced in the cavity it propagates only in the superfluid, a mode of propagation known as "fourth sound". Because fourth sound faces infinite resistance in the normal fluid and zero resistance in the superfluid there is no power loss.

The motion of the superfluid causes the fourth-sound resonance to be split into a doublet whose frequency difference measures the angular momentum of the superfluid. The mean frequency is proportional to the superfluid density, and Rudnick believes that the constant of proportionality, which depends on a scattering correction for the grains of the powder, is empirically well determined. Other studies of persistent currents,^{3,4} which depend on the gyroscopic effects associated with the rotation, also measure the angular momentum but are able to determine only temperature dependence of superfluid density.

Rudnick and his colleagues plan to investigate not only the persistent-current velocity but also the superfluid density, which is a function of temperature, coherence length and pore size of the powder.⁵ Because the density goes to zero on the boundary of the pore, the average density is less than the density in the bulk, especially for small pore sizes. By comparing the measurements of the density of superfluids on the free surface of a film¹ to the UCLA measurements of the density on bound surfaces, one should obtain interesting information about the boundary conditions on superfluids.

So far the UCLA team has only preliminary data. They hope to obtain greater accuracy by replacing the present dipole-source transducer with one that will consist of n segments, each one $2\pi/n$ out of phase with its neighbor. For a given direction of phase difference this transducer would excite only one of the two resonant frequencies. —BGL

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