tinguished group of speakers and participants for the purpose of discussing a subject so germane to our function. We were happy also for the stimulus to our technical program which the conference provided through the activities of our staff as participants, speakers, and organizers. More than these, however, we were happy to have this important group of scientists in our midst so that we might learn from them about opportunities and needs to improve our services and they in turn might perhaps learn from us about those of our services and activities which might be of help to them.

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INTRODUCTION

As their temperature is raised, the properties of a liquid and of the vapor with which it is in equilibrium become more and more similar until, at a particular temperature, the difference disappears. The state of the fluid at this temperature is the critical point. At room temperature iron has the power to acquire a magnetic moment which remains even after the magnetic field is removed. As its temperature is raised this remanent magnetism diminishes until, at a temperature of some several hundred of degrees, it suddenly disappears. This state of iron is called the Curie point. Below the temperature of its critical point He^4 may exist in an ordinary liquid form which is qualitatively the same as liquids existing at room temperature. At a temperature several degrees below its critical point the ordinary liquid suddenly acquires new properties, especially those relating to flow, which are so extraordinary that the state has been called superfluid. The state at which this transition occurs is called the λ-point.

All these phenomena have in common that at a definite transition point a substance gains or loses all at once what another age would have called a *virtue*. In this they differ from first order phase transitions, melting, evaporation, sublimation, in which the physical change is not sudden, but takes place by a piecemeal transformation of small portions of the substance from one state to another. They differ also from first order phase transitions in that they seem to be the focus or source of anomalous behavior in a wide region of the surrounding thermodynamic phase plane. Critical points of liquid vapor transitions, consolute points in binary liquid mixtures, Curie and Néel points in magnetism, second order phase transition points in solids, λ-points in liquid helium together with the anomalous phenomena which occur in their neighborhood were the subject of the conference whose proceedings are reported in this volume.

That critical points in this general sense have much in common with each other is attested by the fact that they have been treated from the beginning by very similar models and theories. These models and theories are based on the idea that phase transitions and critical points are brought about through the mutual cooperative interaction of many particles. For this reason these phenomena are often called cooperative phenomena. The essential similarity of these early theories, the Van der Waals theory of the liquid-vapor critical point, Curie-Weiss theory of ferromagnetism, the Bragg-Williams and Bethe theory of order-disorder phenomena is emphasized in the introductory historical lecture of Uhlenbeck. They give, as Uhlenbeck pointed out, an excellent qualitative picture of critical phenomena, but fail more and more seriously in their quantitative predictions as the critical point is approached. Their ultimate inadequacy is demonstrated by their disagreement with Onsager's exact solution of the two-dimensional Ising model of ferromagnetism.

Several recent scientific developments, both experimental and theoretical, contributed to the feeling on the part of a number of scientists, and in particular, on the part of those who formed themselves into an *ad hoc* committee to organize it, that April 1965 was an appropriate moment for a conference on critical phenomena. Firstly, there was the theoretical prediction of non-classical critical behavior for three dimensional lattice models of gases and magnets based on the numerical generation and summation of a large number of terms of exact low and high temperature series expansions. A second recent development, in this case experimental, was the discovery that the specific heat at constant volume of a simple fluid near the critical point is apparently singular and very similar in its behavior to the λ-singularity in the specific heat of liquid helium. A third development was the confirmation through measurement of the internal magnetic field by nuclear magnetic resonance that the shape of the magnetization versus temperature curve of a ferro- or antiferromagnet is similar if not identical to the shape of the coexistence curve of the liquid-vapor phase transition and similar to the shape predicted by the series summation method.

A fourth development was the critique of the Ornstein-Zernike theory of critical opalescence and the experimental confirmation of deviations from this theory.

A common feature of these developments and of others not listed is that they point up a relationship between phenomena which are normally investigated by different institutional groupings of scientists using different experimental techniques who perhaps normally do not meet each other at scientific conferences. It was the purpose of the conference to present these recent developments, to provide an opportunity to assess their significance both individually and as a total picture, to bring together for mutual enlightenment scientists working in different specialities and disciplines, to provide a forum for theoretical speculations.

The program of the conference consisted primarily of papers reviewing the experimental situation for various important critical phenomena. In addition to these, each session contained a selection of shorter papers presenting new data, a novel experimental method, or new theoretical ideas. These proceedings contain the text of the papers substantially as presented except for the paper of Passell which is represented only as an abstract. Also included is a "dictionary" of corresponding parameters in various critical systems together with a tabulation of results on critical exponents prepared by Fisher.

An attempt was made by the session chairmen to elicit as much discussion as time permitted and this is included almost *verbatim* in these proceedings. Certain discussion remarks were in effect short papers. In some of these cases a manuscript was available and was included in the text. In other cases it was possible to make references to a recent or shortly to appear publication.

It will be noted that the bulk of the papers at the conference were experimental. This does not represent a bias towards empiricism on the part of the conference organizers but rather their feeling that the most appropriate way to further an eventual theoretical understanding of critical phenomena was by a complete and critical presentation of the experimental situation. However, in addition to the theoretical papers of Domb, Fisher, Buckingham, and Marshall which were presented in the main program, the last session of the conference was almost entirely devoted to short theoretical presentations. Not all of these are published here. This supplementary session also included the experimental paper of Lorentzen. Although not actually presented at the conference, a review article by I. M. Firth, a participant, of certain techniques of low temperature calorimetry was felt to be relevant and is included in this volume.

The contribution of a conference such as this one is to be judged not only on the questions it answers but also for the issues which it brings to clear statement. I close this introduction with my own opinion of what some of these outstanding issues are.

It may perhaps be regarded as established that the thermodynamic properties of substances near critical points are singular functions in the mathematical sense. A primary issue then is *what is the nature of these singularities?*

One of the ways of expressing these singularities is through critical exponents as defined in the paper by Fisher. The fact, coming out of the papers by Rowlinson, Domb, Benedek, and Fisher, that values of critical exponents predicted by the series summation method are in very good agreement with experiments both in fluids and in magnets is an important success of theory. Nevertheless, several questions remain.

The summation theory predicts different results for different physical models such as the Heisenberg and Ising models of ferromagnetism. *Can we exhibit these differences experimentally?* The paper of Wolf describes an experimental realization of an Ising ferromagnet. *What is the significance of the quantum effects on critical exponents pointed out in the papers of Sherman and M. H. Edwards?*

Another aspect of the nature of the critical singularity is the behavior of the specific heat. *Is the logarithmic specific heat singularity, so convincingly demonstrated for the λ-transition in liquid helium in the paper of Fairbank, a paradigm for the behavior of specific heat on all critical systems?* The paper of Moldover and Little reports experiments on this question for the liquid vapor critical point of helium while Yamamoto reviews the situation for some solid-state second order transitions. Teaney discusses the specific heat of some ferromagnetic and antiferromagnetic transitions from

this point of view, while Kierstead presents results on the singular behavior of the pressure coefficient near the λ-point.

A question which was not represented in the program but which was touched upon in the discussion is *what is the relation of the superconducting transition point to the λ-point and to the liquid vapor critical point?*

The paper of Chu and the earlier work of McIntyre referred to in the discussion indicate deviations from the classical, Ornstein-Zernike theory of critical fluctuations within a few hundredths of a degree Kelvin from the critical consolute point of a liquid mixture. An obvious experimental problem is to *confirm these deviations, to correlate the results of light and x-ray scattering and to make precise the nature of the critical singularity in these phenomena.* The present status of results on elastic light and x-ray scattering was reviewed by Brumberger while Dietrich and Als-Nielsen presented their results obtained by elastic neutron scattering on β-brass. A related question brought up in the discussion is *why do deviations from the classical theory of critical opalescence occur only within hundredths of a degree of the critical point while deviations in thermodynamic quantities show nonclassical behavior much farther away?*

Phenomenological theory predicts that magnetic fluctuations become slower and slower near the Curie point, and therefore that critical magnetic scattering should be elastic, while the experiments of Passell and Jacrot show a definite and unexpected amount of inelastic scattering. Although Marshall's paper suggests a possible and even likely solution, the question still remains *why is critical magnetic neutron scattering inelastic?*

The review of transport phenomena by Sengers indicates that the thermal conductivity of simple fluids exhibits a large anomaly near the critical point while the viscosity exhibits no such anomaly or a very minor one. The opposite seems to be the case for binary liquid mixtures. The question arises, *which transport coefficients are anomalous near critical points and why?*

Several new techniques or techniques newly applied to critical phenomena were presented at the conference. One of these was the inelastic scattering of laser light, which was represented in the papers of Alpert and of Ford and Benedek. Another was nuclear magnetic resonance whose application to fluids was given in the paper by Bloom and in a discussion remark of Trappeniers. The application of this method to antiferromagnetism was presented in the talk of Heller.

Not a new method but one which has not perhaps been fully exploited is the diagnosis, using a light probe, of the density gradients produced by gravity in a fluid near its critical point. The papers of Schmidt and Lorentzen present results obtained by this method. A somewhat related method was brought up by Webb in the discussion in which the meniscus, which becomes more and more diffuse as the critical point is approached, is probed by its reflectivity to light.

Results on ultrasonic propagation in fluids near critical points were reviewed by Sette while the application of this method to a solid state second order transition is given in the paper of Garland and Renard and to helium near its critical point by Chase and Williamson.

Perhaps the foregoing questions can be subsumed under two fundamental questions: the first question is *are all the phenomena considered in the conference under the rubric of critical phenomena truly analogous?* This question can be perhaps answered quickly and affirmatively when, say, the liquid-vapor transition is compared to the phase separation of a binary liquid mixture or even to order-disorder phenomena in solids. The analogies become less clear when these are compared to magnetic phenomena, superfluidity, and superconductivity.

When available in any given case, the best experimental and theoretical evidence seems to show that the singular behavior of analogous properties in different systems is very similar. Of course, the series summation method indicates small but definite differences between different systems. Without prejudging the significance of these differences, the similarity of behavior already suggests a common explanation.

A second question is then, *what is the common reason for the singular behavior of analogous properties?*

MELVILLE S. GREEN.