GENERAL PHYSICS

I. MOLECULAR BEAMS*

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RESEARCH OBJECTIVES AND SUMMARY OF RESEARCH

During the last decade, with the development of techniques of ultra-high vacuum and high purity materials, a new interdisciplinary research field called surface science has evolved. It has many applications in various fields of science and engineering. One need only recall the problems of friction and lubrication in mechanical engineering, catalysis and fluid purification in chemical engineering, effects of corrosion and surface treatment in metallurgy. There are also applications in medicine, biology, chemistry, and physics. New analytical tools have been developed to study these problems, such as Auger spectroscopy, low-energy electron diffraction, and electron-beam microprobes.

We are studying the surface of liquid helium, which should be as vital in understanding surfaces as atomic hydrogen was in learning about atoms in the past. At present, we are investigating the evaporation of helium atoms at low temperatures with molecular-beam techniques.

The following helium-beam experiments have been completed. Theses have been written and papers for publication are being prepared.

1. Measurement of the cross section of He^4 atoms for collision with He^4 at low temperatures. Extensive theoretical work has been done throughout the world in the last 40 years on this problem which should be amenable to exact calculation, but until very recently no experimental data have been available, especially at low temperatures. The results of this experiment attracted wide interest and attention because these are the first measurements carried out at sufficiently low temperatures, fully a factor of 10 lower than before, to exhibit the interesting effects of the scattering of identical bosons. Since the apparatus is working, D. E. Oates and S. A. Cohen are going to do He^3-He^3 scattering at low temperatures where the effects of Fermi statistics should be noticeable. Because our group is not primarily interested in atomic scattering we do not plan to extend this work very much, but we have obtained the necessary data for interpretation of our other experiments.

2. Measurement of the velocity distribution of atoms evaporating from He II at low temperatures. It has been found extremely difficult to maintain an open pot of liquid helium in the vacuum system without troublesome superfluid creep. Nonetheless, Dr. R. F. Tinker and Dr. J. W. McWane were able to obtain enough data in a long series of experiments to show that the velocity distribution from liquid He II, whether in bulk or in film, is characterized to the order of 10% by the temperature as measured by other methods such as vapor pressure, in contradiction of the earlier result of

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W. D. Johnston, Jr., and J. G. King, which seems to have arisen from excessive scattering near the source and the effects of the velocity-dependent cross section.

The following experiments are in progress. Some have already yielded preliminary results.

3. Studies of evaporated atoms resulting from heat pulses introduced into the liquid He II. W. B. Davis is preparing apparatus to perform this experiment, with particular attention being given to the control of the creeping superfluid film. The results of this experiment should give information concerning the free path of excitations and their conversion efficiency to evaporated atoms at the surface on a microscopic scale, at the same time that the techniques are developed one step further.

4. Studies of diffusion He^3 in He^4 by observation of evaporating atoms. The apparatus for this experiment is developed and much data have been obtained by G. A. Herzlinger. The results can essentially be interpreted as yet another measurement of the cross section of He^3 quasi-particles for scattering by excitations. At present, the measurements, which are far higher in resolution than those previously carried out, indicate an unexpected variation of the diffusion constant with temperature. It is possible that this may indicate that these cross sections long considered to be temperature-independent are actually exhibiting some variations with temperature.

5. An experiment to measure the vapor pressure of He^4 at lower temperatures than hitherto used has been undertaken by S. A. Cohen and Professor J. R. Clow. A preliminary result has been obtained.

6. We are planning a series of experiments designed to study the mobility and surface coverage properties of unsaturated helium films at low temperatures, a problem to which our methods are admirably suited and one that has recently become of considerable interest. S. A. Cohen has been preparing the necessary apparatus.

7. Lastly, although not related to liquid helium but nonetheless to low-temperature physics, the remarkable success of the experiment of Dr. T. R. Brown, in which the hitherto unmeasured velocity of the lattice of vortices in a current carrying type II superconductor has been determined by an atomic-beam method in which transitions are induced in the hyperfine structure of alkali atoms passing near the superconductor by the spatially periodic field therein. This field appears to the moving atoms as a time-variant field in such a way that when the vortices move a Doppler effect can be seen. Besides the scientific interest of this new development, there is a strong technical reason for understanding the motion of vortices in superconductors because that motion is responsible for the dissipation of energy when large currents are to be carried, as in the practical application of superconductors to power transmission and rotating machinery. Such applications are likely to have important applications in the power industry in the next two or three decades.

Further progress has been made recently and work will be continued with increasing vigor on three microscopy projects.

8. The research described above has stimulated the development of a new analytical instrument that will be of unique importance in surface studies, the molecular microscope. It makes possible the study at high resolution of evaporation from any surface. Our initial studies, undertaken in collaboration with Professor I. V. Yannas of the Department of Mechanical Engineering, M.I.T., will be of changes in various properties of collagen, which are connected with aging and fatigue in animals (man included), and the manufacture of artificial tissue. We are also planning a series of interdisciplinary studies with this new instrument such as the effects of lubricants on surface composition, material transfer in wearing surfaces, and surface properties of various kinds of membranes. Developmental problems with the apparatus have held up progress; we are beginning to get results now.

9. We are also collaborating with Dr. David Waugh of the Department of Biology, M.I.T., on an experiment in which neutral atoms will be observed coming from surfaces

as a result of the stimulation of the surface by a highly focussed beam of energetic electrons as used in scanning electron microscopes. In particular, we hope to examine the distribution of thrombin molecules on polyethylene surfaces as used in heart implants and thus eventually to discover some property of the polyethylene that may cause clotting and subsequent failure of the patient.

10. Dr. E. H. Jacobsen, assisted by Dr. M. G. R. Thomson, continues the development of the Auger electron microscope with its associated wide-angle electrostatic electron lenses in which the spherical aberration is corrected by the interposition of appropriately shaped conducting foils through which the electrons can pass. Computer analysis of the trajectories indicates that it should be possible by these methods to see individual low Z atoms, which do not scatter with sufficient strength to provide the contrast needed to make them visible.

J. G. King, J. R. Zacharias

A. DIFFUSION OF He^3 IN SUPERFLUID BACKGROUND

The purpose of this report is to present preliminary results of direct measurements of the diffusion He^3 in superfluid He^4. The measurements were performed between 1.32° and 1.75° at He^3 concentration of the order of 10^{-4}, so that according to current theory, the mean-free path of the He^3 "quasi particles" is limited by the presence of the roton excitations in the He II, and thus the diffusion constant provides a measure of the He^3-roton interaction. The experiment involves the application of a concentration gradient of He^3 in the solution, and directly observing the decay of the gradient by monitoring the He^3 concentration in the vapor just above liquid.

The diffusion occurs in a sample chamber that is thermally isolated from the He^4 bath, except for the copper block at the top of the level of the mixture (see Fig. I-1).

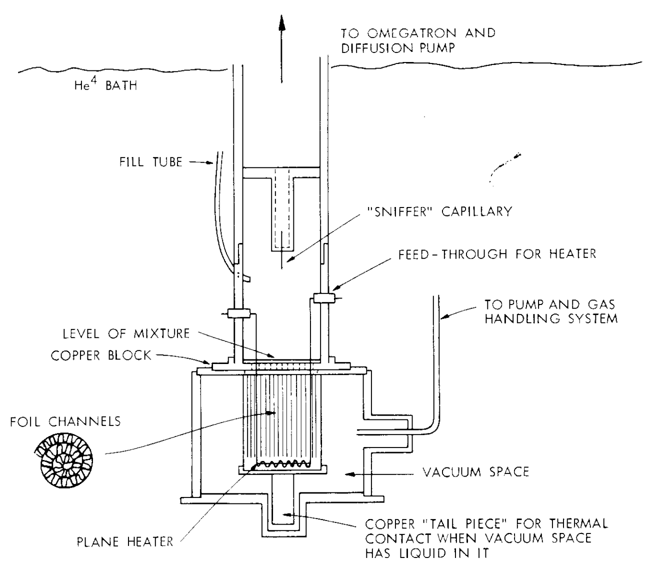

Fig. I-1. Diffusion chamber.

Heat is applied to the mixture by means of a plane heater at the bottom of the chamber. The only thermal path to the bath is through the mixture to the copper block at the top of the chamber. This results in a steady upward convective flow of He^4 excitations (normal fluid) which, in turn, forces He^3 atoms to the region near the top of the chamber, thereby producing a concentration gradient in the liquid. The vapor above the liquid (at pressures of a few Torr in the temperature range of this experiment) is sampled continuously by means of a 2-mil capillary, "sniffer," 1 in. long, which is connected to a high-vacuum system. At room temperature an omegatron mass spectrometer connected to the vacuum system continuously monitors the amount of He^3 in the vapor.

The experiment is kept one-dimensional by filling the diffusion chamber with corrugated and plane stainless-steel foil wound together to form small channels approximately 0.05 in. in diameter. The channels also serve to reduce any secondary convection that may be present.

In the presence of the thermal current the spatial distribution of the He^3 concentration is determined primarily by the balance between the flow of He^3 that is due to the thermal current (characterized by the normal fluid velocity v_n) and the back diffusion current that is due to the build-up of atoms at the top of the chamber:

$$D \frac{\partial n_3}{\partial z} = v_n n_3, \qquad n_3 \sim e^{v_n z/D}.$$

When the heat is turned off the gradient will decay into a constant distribution, determined by the diffusion equation

$$D \frac{\partial^2 n_3}{\partial z^2} = \frac{\partial n_3}{\partial t}.$$

For a given initial distribution $n_3 \sim e^{\alpha z}$ (no assumption on α made) in the presence of the boundary conditions of the experiment (He^3 current is zero at the bottom of the liquid chamber and approximately zero at the top), the solution to the diffusion equation is

$$n_3(z,t) - n_3(z,\infty) = \sum_{m=0}^{\infty} \frac{(-1)^{2m+1}}{(\alpha L)^2 + (2m+1)^2 \pi^2} \frac{\cos m\pi z}{L} e^{-(2m+1)^2 \frac{\pi^2 Dt}{L^2}}.$$

Putting in $Z = L$, and noting that the first term is dominant both in magnitude of the coefficient and in the fact that the other terms decay very quickly, we find (except near $t = 0$) that

$$n_3(Z=L,t) - n_3(Z=L,\infty) \sim e^{-\pi^2 Dt/L^2}.$$

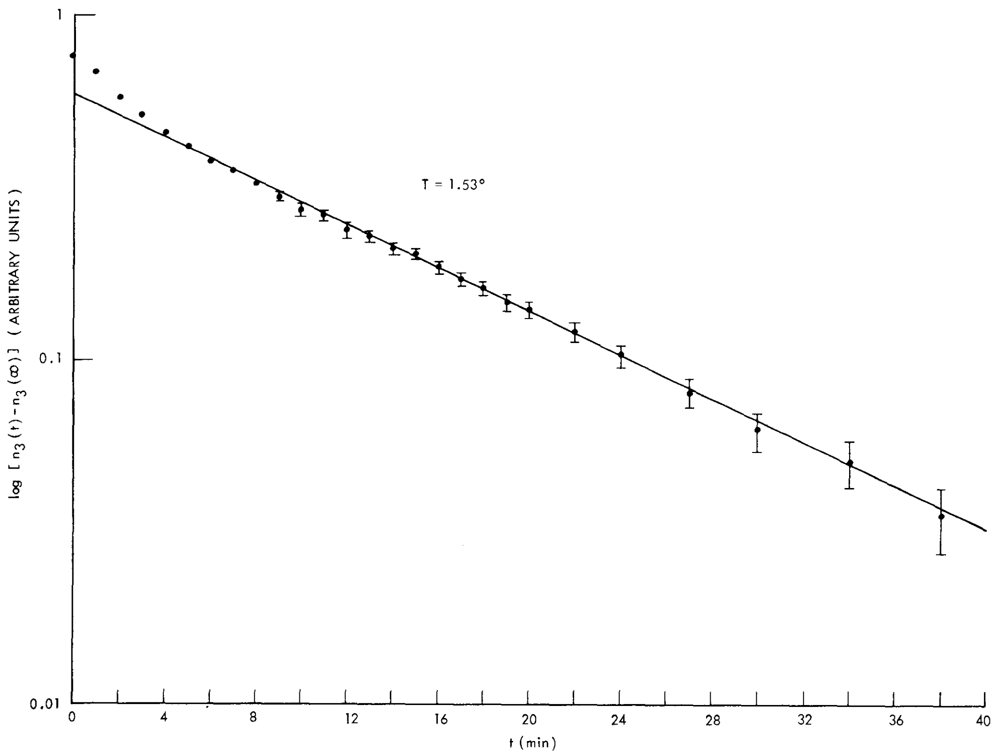

Fig. I-2. log $[n_3(t)-n_3(\infty)]$ vs t.

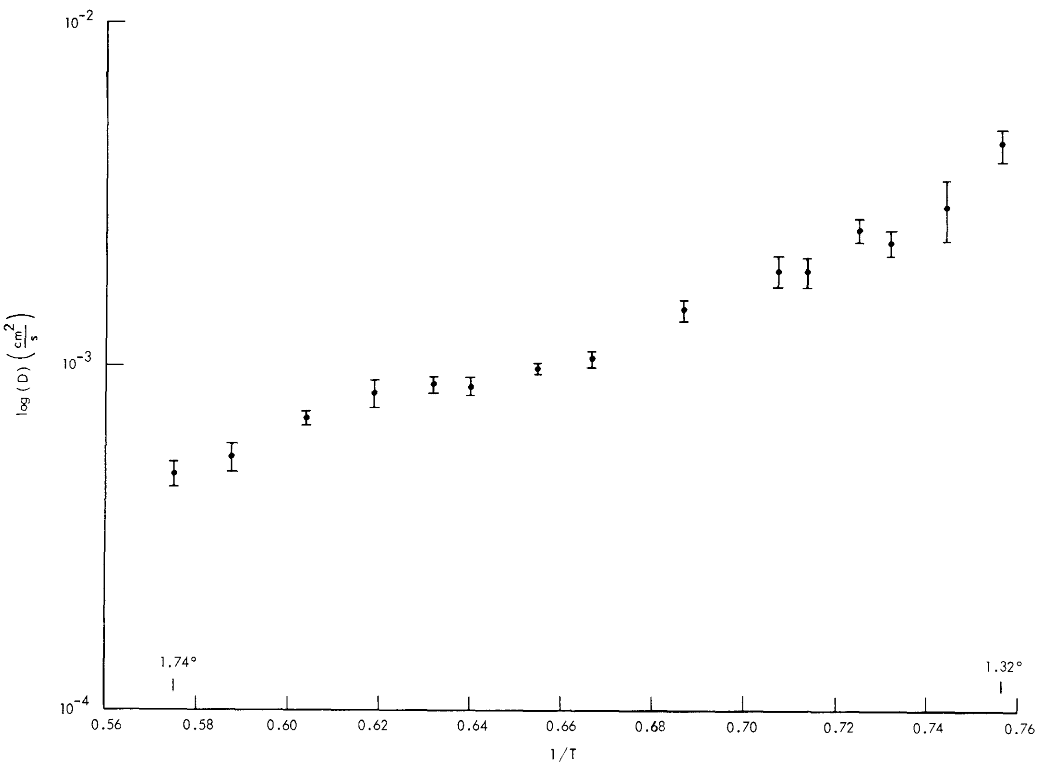

Fig. I-3. log (D) vs 1/T.

By plotting log $[n_3(t)-n_3(\infty)]$ against t, we get D from the slope of the straight line. A typical plot is shown in Fig. I-2. Data for D as a function temperature are also given (see Fig. I-3). Note three factors in the experiment.

1. The diffusion times through the vapor are negligible compared with those measured for the liquid.[1]

2. The concentration of He^3 in the vapor is proportional to that in the liquid at $C_L < .01$ (in this experiment $C_L \sim 10^{-4}$).[2]

3. The pumping effect of the "sniffer" is negligible, both in terms of depleting the liquid and in producing an unwanted thermal current.

As the data are still preliminary, only a few tentative conclusions can be drawn. Writing

$$D = \frac{kT}{m_3N_r} \frac{1}{\sigma^*_{3r}\bar{v}_3},$$

where

$$\sigma^*_{3r} = \frac{1}{2} \int \sigma_{3r}(1-\cos\theta)\ d(\cos\theta),$$

with θ the scattering angle, we see that the dominant temperature dependence is given by the roton density $N_r \sim T^{1/2} \exp(-\Delta/T)$ ($\Delta = 8.65°$) and any energy dependence of the roton-He^3 cross section. Khalatnikov and Zharkov[3] assume a δ-function interaction and predict an He^3-roton cross section which is independent of energy.

In the present experiment log (D) is plotted against 1/T, and although the general trend is a slope of approximately 9° (attributable to the roton density), there is also additional structure which indicates a temperature dependence to the He^3-roton cross section (the flattening between 1.5° and 1.6°).

The present measurements are the first direct (in the sense of observing a decaying spatial gradient) measurements of the diffusion constant of dilute He^3-He^4 solutions. The diffusion constant has been previously derived from thermal-conductivity measurements,[4] and from measurements of the decay of He^3 nuclear spin polarization in the presence of a magnetic field gradient using spin-echo techniques.[5,6] The spin-echo measurements were not taken at dilute enough solutions and on a fine enough scale to be comparable to the present data. The thermal-conductivity measurements of Ptuhka[4] were not taken on as fine a scale as the present measurements, but the one point in the 1.5°-1.6° region is lower than the rest of her curve, in agreement with the present results.

Further measurements covering a wider range of temperatures are proceeding, and we hope that they will lead to an understanding of the He^3-roton interaction, and to the nature of the roton itself.

G. A. Herzlinger, J. G. King

References

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B. FIELD-DISTRIBUTION MEASUREMENTS BY THE ATOMIC-BEAM METHOD

In view of the very successful preliminary experiments with this technique, a serious effort has been made to develop the instrument to the point where it can be used as a standard technique for observing magnetic periodicities of appropriate wavelengths.

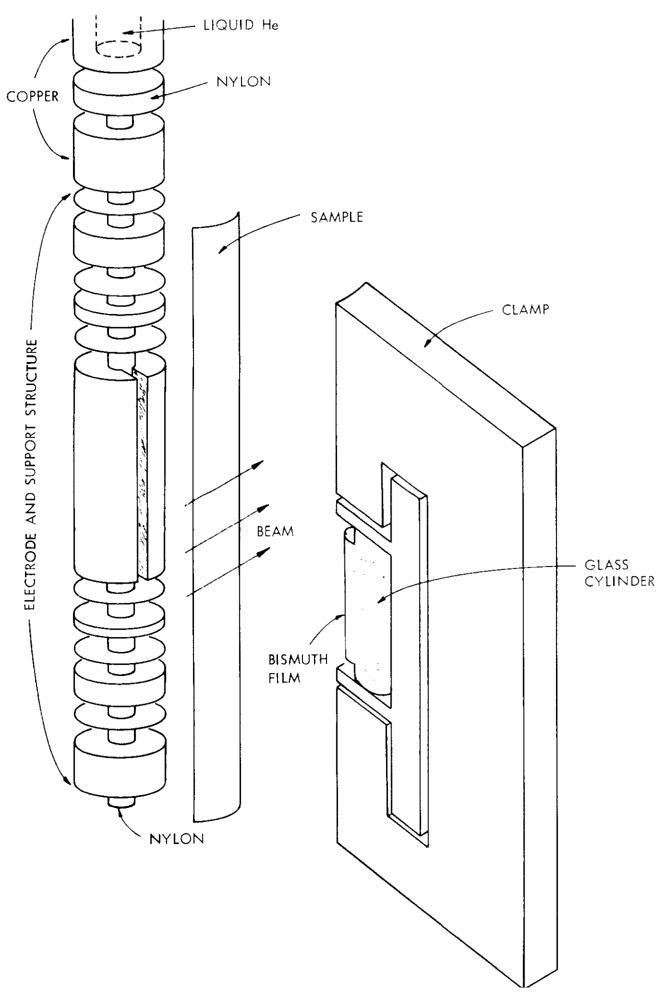

Fig. I-4.

Detail of sample holder. The electrode holder is alternating pieces of gold-plated copper and mica. The two outer electrodes serve as current leads, while the four inner electrodes are transverse and longitudinal voltage probes. The bismuth film measures the internal field of the sample.

Although the present improvements are designed to obtain data relevant to superconductors, we feel that further data from various samples obtained reliably and quickly will indicate that a general instrument will be worth designing.

The apparatus has been modified to produce a wider velocity distribution, a less hysteretic magnetic field in the C region, further auxiliary data from the superconducting sample and better temperature control of the sample. Modifications of the data analysis program are being considered which would allow on-line analysis.

In order to obtain detailed auxiliary data on our superconducting samples, the interaction region of the apparatus has been rebuilt to provide transverse and longitudinal voltage measurements. The value of internal magnetic field will be measured by a bismuth strip which is deposited on the collimating surface opposite the superconducting sample. In this way the internal field can be measured directly without correction for diamagnetism. Figure I-4 is a detailed drawing of the sample holder.

T. R. Brown, J. G. King