"Heat Flush" Method of He^3 Separation

CHARLES A. REYNOLDS,* HENRY A. FAIRBANK, AND C. T. LANE
*Sloane Physics Laboratory, Yale University,** New Haven, Connecticut*

AND

B. B. MCINTEER AND ALFRED O. NIER
*Department of Physics, University of Minnesota,*** Minneapolis, Minnesota*

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A further experimental study has been made of the efficiency of separation of He^3 from mixtures of He^3 and He^4 in a method making use of the "internal convection" process in superfluid liquid helium. It is shown that the method is capable of removing all the He^3 in mixtures with an original He^3/He^4 abundance of 10^{-2} percent in a period of about five minutes with a power input of 13 milliwatts. The efficiency of the method as a function of power input is also studied and comparison is made with Kapitza's measurements on the "latent heat" of superfluid atoms.

INTRODUCTION

IN a previous communication,[1] a method was described with which it was found possible to separate He^3 from a mixture of He^3 and He^4 by making use of the superfluid properties of liquid He^4. If such a gaseous mixture is condensed and brought below the λ-point and a small temperature gradient, resulting in a flow of heat, is produced in the liquid it was found that the He^3 atoms experienced a ponderamotive force, in the direction of the heat flow, causing a separation of the isotope.

In the work cited we were able to raise the He^3/He^4 concentration by a factor of about 130 using a mixture having an original He^3/He^4 abundance of about 1.3×10^{-6}. This at a working temperature of 2°K with about 17 milliwatts of power supplied for approximately 5 minutes. In the same experiment we also attempted to produce the same effect at 1.8°K but with a negative result. At the time we thought this failure to be due to the nature of the He^3-He^4 equilibrium below the λ-point which we had been studying concurrently with the above problem.[2] Later investigation, however, has shown that these equilibrium measurements are probably in error[3] and hence this explanation of our failure to produce the effect at 1.8°K is no longer tenable.

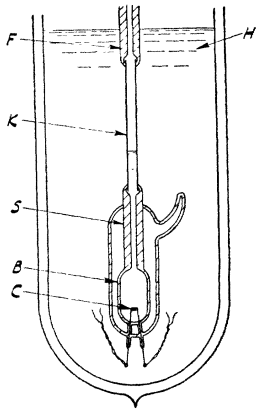

FIG. 1. Schematic diagram of the apparatus.

We are now of the opinion that the negative result at 1.8°K is due to either or both of the following reasons:

(1) The geometry of the apparatus used in the original heat flush experiment was rather poor, i.e., the heat current had no well defined path. In consequence the He^3 could not be localized in a small region as is desirable if high enrichments are to be achieved.

(2) The experiment at 1.8°K was performed in the same run as that at 2.0°K. In the successful experiment at 2.0°K we removed in our analysis sample approximately 50 percent of the He^3 present in the original gaseous mixture leaving the gas used for the lower temperature measurement greatly depleted of He^3. We were therefore dealing with different initial concentrations of He^3/He^4 in the two experiments, and this initial concentration may, and probably does, have a bearing on the degree of enrichment obtained.

Since the publication of these results we have continued our investigation of this method, using, however, gas with a higher initial He^3/He^4 abundance than that used in our prior work, the richer gas being produced by thermal diffusion separation.[4] With this richer source we made some preliminary runs with our original apparatus at various temperatures below the λ-point, and the same pattern of behavior as previously found was observed. Thus large enrichments were obtained at some temperatures and little or none at all at other temperatures.

Accordingly, we modified the equipment and technique to avoid the two objections mentioned above.

NEW MEASUREMENTS

Figure 1 is a diagrammatic sketch of the new apparatus. The gaseous mixture to be separated, usually around 2 liters S.T.P. with an He^3/He^4 abundance of about 10^{-2} percent, was condensed in the Pyrex bulb *B*, the glass capillary (diameter ~2 mm) *S* and part way

* Now at Rutgers University, New Brunswick, New Jersey.
** Assisted by ONR.
*** Assisted by the joint program of ONR and AEC.
[1] Lane, Fairbank, Aldrich, and Nier, Phys. Rev. **73**, 256 (1948).
[2] Fairbank, Lane, Aldrich, and Nier, Phys. Rev. **73**, 729 (1948).
[3] Lane, Fairbank, Aldrich, and Nier, Phys. Rev. **75**, 46 (1949).
[4] McInteer, Aldrich, and Nier, Phys. Rev. **72**, 510 (1947).

up the Kovar metal capillary K, the liquid level being as indicated. Sealed into bulb B is a small constantan heating coil C provided with both current and potential leads. Surrounding the bulb B and capillary S is a vacuum jacket as shown. The whole apparatus is immersed in a bath H of liquid helium whose temperature can be controlled by pumping in the usual way. A glass capillary F extends out of the cryostat to the gas handling and sampling equipment. The latter consisted essentially of a 2-liter Toepler pump, a small manometer, and a number of break-seal bulbs for collecting samples of the vapor in K.

Because of the vacuum jacket and geometry of the apparatus, the path of the heat flow from C to K (via the helium in B) and thence to the outer bath H is clearly defined and thus the objection raised in (1) above is largely met.

In order to overcome the second objection we proceeded in the present experiment as follows: The temperature of the outer bath, and hence the helium in B, was reduced to a low figure ($\sim$1.35°K). The vapor pressure at this temperature is about 2 mm Hg; hence most of the sample in B is in the liquid phase. The temperature was now allowed to rise to the desired value and a few milliwatts of power applied via C for a period of 5 minutes. With the heat still applied a sample of vapor from K was now obtained in the previously evacuated 2-liter Toepler. A fraction of this sample was now transferred to a break-seal bulb for analysis; this sample usually amounted to about 5 percent of the mass of gas taken into the Toepler. The remaining gas in the Toepler was now recondensed in B, the latter again reduced in temperature to about 1.35°K and the process repeated at another desired temperature. By this technique we depleted the He^3 content of B by not more than 5 percent per sample and in this way largely overcame the objection raised in (2) above.

We have investigated the effect at a number of different temperatures below the λ-point and, in addition, at one temperature (1.8°K) we have studied the effect as a function of the input wattage at C.

RESULTS AND DISCUSSION

With a heat input of 13 milliwatts and starting with a mixture of He^3/He^4 of about 10^{-4} we find that, within our experimental error, 100 percent of the He^3 originally present in the mixture is removed into the sampling Toepler at all temperatures below the λ-point. The concentration He^3/He^4 in any given analysis sample depends, of course, on the size of the latter which was variable. Our richest sample showed an He^3/He^4 concentration of 4 percent which represents an enrichment of about 400 times the original. Figure 2 shows the percent depletion of He^3 in the original mixture in B as a function of the power input to C at 1.8°K. As in the previous case, the wattage was applied for a period of 5 minutes plus the time required for sampling, this latter being of the order of $\frac{1}{2}$–1 minute.

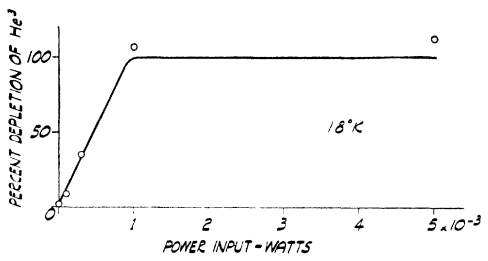

FIG. 2. The percent separation of He^3 in a given mixture as a function of the input power at 1.8°K.

In this experiment we are of the opinion that two effects are occurring simultaneously:

(a) Under the influence of the heat the He^3 atoms are flushed to or near the surface of the liquid in B.

(b) On sampling, we obtain gas evaporated from this surface plus the residual vapor in the connecting line from K. From our most recent measurements[3] we believe that the vapor in equilibrium with the liquid is probably richer in He^3 content than the parent liquid. The combination of these two processes lead, then, to the large enrichments which we observe.

The fundamental process behind this heat flush mechanism appears to be somewhat as follows. Superfluid helium atoms are continually flowing toward C, while the heat is applied, and are there raised in energy to the levels occupied by the normal fluid atoms in the energy spectrum of the liquid. A balancing flow of these latter atoms then flow toward the heat sink at K, where the reverse process takes place. In this internal convection the He^3 atoms appear to the cooperating superfluid He^4 stream as "foreigners," and are not permitted to take part in their activity, but no such discrimination is practiced by the normal fluid component. The net result is, therefore, to "flush" the He^3 atoms from C to K. In view of this it is of interest to compare the minimum energy which we found necessary for 100 percent depletion with the difference of heat content Q between superfluid helium and free helium II as measured by Kapitza.[5] The latter is the energy per gram necessary to change a stream of the superfluid helium into normal helium. We will mean by the energy necessary for *one complete heat flush*, the amount needed to convert into normal helium a quantity of superfluid helium equal to the mass of helium in B.

Thus if P is the power input to the heater in watts; t the length of time the power is applied in seconds, and m_0 the total mass of liquid helium in B in grams, then the number of heat flushes N due to a power P for a time t is given by

$$Nm_0Q=Pt$$

i.e., substituting the known values at 1.8°K,* we get

$$N=1000P.$$

Thus at 1 milliwatt power input there is one complete heat flush, and we note that at 1 milliwatt in Fig. 2 we

[5] P. L. Kapitza, J. Phys. U.S.S.R. 5, 59 (1941).

* $m_0=0.28$ g; $Q=0.26$ cal./g; $t=300$ sec.

begin to get 100 percent depletion. While our experimental accuracy is such that this agreement is somewhat fortuitous we may, however, conclude that the back diffusion of He^3 in the liquid during the heat flush is small.

It is also of interest to estimate the possible heat flush in a closed system produced by a creeping film. We will consider the simple case of a bulb filled with a sample of liquid helium, connected to a filling tube, the bulb being immersed in a bath of liquid helium, the whole forming an isolated system. The film creeps up the filling tube and evaporates[3] and, in the steady state condition, a mass of helium gas recondenses at the liquid surface equal to the mass flowing in the film. If we assume that all of the heat of condensation is transmitted to the liquid sample, and take Daunt and Mendelssohn's[6] value for the creep rate at 1.8°K and a tube diameter of 2 mm we obtain a power input to the surface of the liquid of 0.1 milliwatt. From Fig. 2 it may be seen that at 0.1 milliwatt power there is a finite heat flush. It is possible that the use of the Daunt and Mendelssohn creep rate may not be justified here. Later work[7] has given different results, indicating in some cases a much higher creep rate and this would, of course, lead to a larger heat flush. We believe in the particular apparatus used in the present experiment, the effect of creeping film heat flush is small. The surface of the liquid sample is in the Kovar section, and hence most of the creeping film heat would proceed directly out into the bath, passing through only that amount of the sample which is in the Kovar section.

The method appears to be a rapid and efficient way of concentrating He^3 possibly up to 100 percent purity. The process may, however, break down for concentrations much higher than our present record of 4 percent He^3 although we have, as yet, no indication that this is so.

Finally we are indebted to Mr. Ernest Lynton for his assistance with the low temperature phases of this work.

[6] J. G. Daunt and K. Mendelssohn, Proc. Roy. Soc. **A170**, 423 (1939); **170**, 439 (1939).

[7] K. R. Atkins, Nature **161**, 925 (1948).

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The Interaction Representation of the Proca Field

FREDERIK J. BELINFANTE
Department of Physics, Purdue University, Lafayette, Indiana
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The methods used by Schwinger in quantum electrodynamics can be generalized in such a way that they become applicable to meson theory. This is shown by an example. The method used seems slightly simpler than the method proposed by the Japanese school. It turns out that the covariant field variables in interaction representation are not simply the transformed of the covariant variables used in Heisenberg representation. Also it turns out to be necessary to confine the space-like surfaces used in many applications to flat surfaces perpendicular to the time direction. The direct interaction between two particles through the meson field is obtained by a canonical transformation similar to the first approximation Schwinger transformation in quantum electrodynamics.

The example of a neutral vector meson field discussed in the present paper has been chosen in such a way as to show the analogy to quantum electrodynamics. The interaction energy between particles obtained by Schwinger's relativistic treatment in meson theory (and also obtainable by the other usual perturbation methods) goes over into the Møller interaction for vanishing meson mass.

INTRODUCTION

In recent developments of quantum electrodynamics much use has been made of the so-called interaction representation, in which the q-numbers describing various fields of particles or quanta satisfy field equations of a form as if no interactions between these fields would exist, while the interaction is described by a generalized Schroedinger equation for the situation functional (Schroedinger state vector) Ψ. The theory of this interaction representation and its use in quantum electrodynamics have been developed here in America by Schwinger.[1] The basic ideas of this theory of the interaction representation had been developed independently and published earlier by Tomonaga[2] in Japan. As the theory may be considered as a generalization of the many-times theory of Dirac, Fock, and Podolsky,[3] the new theory was called by him the "super-many-time theory."[4]

If one tries to apply the super-many-time forma-

[1] J. Schwinger, Phys. Rev. **74**, 1439 (1948).

[2] S. Tomonaga, Bull. I.P.C.R. (Riken-iho) **22**, 545 (1943) (*in Japanese*); Prog. Theor. Phys. **1**, 27 (1946) and **2**, 101 (1947).

[3] Dirac, Fock and Podolsky, Physik. Zeits. Sowjetunion **2**, 468 (1932). See also Chapter 18 of G. Wentzel, *Einführung in die Quantentheorie der Wellenfelder* (F. Deuticke, Vienna, 1943; reprinted by Edwards Brothers, Inc., Ann Arbor, 1946).

[4] Compare for instance T. Miyazima, Prog. Theor. Phys. **2**, 94(A) (1947).