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Vapor Pressures of He^3-He^4 Mixtures*

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Vapor pressures, P_x, of He^3-He^4 mixtures ranging in liquid mole fraction, X, from 0.1 to 0.9 have been measured between 0.6° and 2.4°K versus the vapor pressure, P_3^0, of liquid He^3. Except for sharp breaks in the vicinity of the lambda and stratification temperatures of some of the mixtures, P_x/P_3^0 is found to vary slowly and smoothly with X and with temperature. Contrary to much of the work of other authors, there are no breaks at the He^4 lambda temperature.

A comprehensive smoothed table of P_x/P_3^0 is derived. Using this as a reference it is possible, for the first time, to intercompare all of the previously existing data on P_x. The data of some authors are in excellent agreement with our table but other data are in serious quantitative disagreement near 1.2°K and much previous data are in qualitative disagreement at the He^4 lambda temperature.

INTRODUCTION

Vapor pressures of He^3-He^4 mixtures have been reported by a number of workers. The most extensive series of measurements are those of Esel'son and Berezniak.[1] These workers and Sommers[2] discuss most of the early literature data.

An important practical use of such measurements is the correlation and smoothing of data into tables of vapor pressure, P_x, as a function of both X, the liquid mole fraction of He^3, and temperature, T. Using such tables, the unknown composition of a liquid mixture may be determined from a measurement of its vapor pressure and temperature. For example, Sommers gives a smoothed table of $\log P_x$ for X between 0.00 and 0.13 and T between 1.2 and 2.2°K. In the present work vapor pressures were measured for nine liquid concentrations ranging in steps of 0.1 from $X=0.1$ to 0.9. The temperature ranged from 0.6 to 2.4°K and was determined from P_3^0, the vapor pressure of pure He^3. The ratio, $R=1000P_x/P_3^0$, is found to be a slowly varying function of T and has been used to tabulate and graphically represent and analyze our data. A smoothed table of R as a function of X and T is presented and compared with results of other workers.

A second possible result of such measurements is the determination of the stratification temperature, $T_s(X)$, at which a liquid He^3-He^4 mixture first begins to separate into two layers having different compositions.[3] Since the phases are in thermodynamic equilibrium, their vapor pressures are necessarily identical. Weinstock, Osborne, and Abraham[4] applied this principle of coincidence of vapor pressures in an unsuccessful first attempt to demonstrate stratification, failing only because the theoretical prediction[5] on which they based their experiment gave a much too high value of T_s. Using a He^3 bath to reach considerably lower temperatures, we demonstrate here the validity of the method and find it possible to determine T_s with moderate precision except near the consolute temperature, where the precision is very poor. A more precise determination of $T_s(X)$ has been made by first sound measurements.[6,7]

A third result of careful measurements of P_x is the determination of the temperature, $T_\lambda(X)$, at which a He^3-He^4 mixture becomes superfluid by observing the temperature at which dP_x/dT is discontinuous.[8,9] References to theoretical papers on the lambda transition in mixtures are given by Esel'son, Kaganov, and Lifshitz[10] and by de Boer and Gorter.[11] In the present paper the determinations of $T_\lambda(X)$ from vapor pressure measurements are compared with and are shown to be in good agreement with most of the recent measurements of $T_\lambda(X)$ by other methods.[6,7,12,13]

By the use of vacuum-jacketed pressure-sensing tubes and He^3 vapor pressure thermometry it is felt that these measurements have minimized errors in X due to fractionation and errors in T due to He^4 film reflux. The existence of such errors in previous measurements is made clear by a careful analysis of data appearing in the literature. For example, several sets of mixture data have shown breaks or irregularities in the slope of

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P_x versus T at the He^4 lambda temperature.[1,14–16] No such effect is apparent in our own or certain other measurements.[4,17] Possible experimental causes of these inconsistencies are considered in the comparison of the various sets of data.

A fifth result of these measurements will be the subject of a separate paper. Wansink[18] has calculated vapor composition and various thermodynamic functions from vapor pressure and density data for liquid concentrations up to 7% He^3. Similar calculations are being performed for the entire range of compositions measured in the present experiments.

Finally, we may point to the fact that measurements of P_x have been of use[2,19] in the evaluation of the various solution theories. As more extensive measurements of P_x become available and are analyzed the more recent theories of Chester[20,21] and of Prigogine[22–27] will be subject to similar tests of applicability.

EXPERIMENTAL

Some details of the experimental apparatus have been described elsewhere.[28,29–31] We shall elaborate here only on those details which we believe pertinent to the accuracy of measurements of temperature and vapor pressure. Figure 1 is a schematic diagram of the interior of the Dewar. The chambers and tubes below the Dewar lid in the figure are surrounded by a vacuum. Thermal equilibrium is aided by putting the liquid He^3 coolant, the He^3 vapor pressure thermometer, and the mixture liquid, into a massive copper block having $\frac{1}{16}$-inch thick walls separating the three liquids from each other and from the vacuum space.

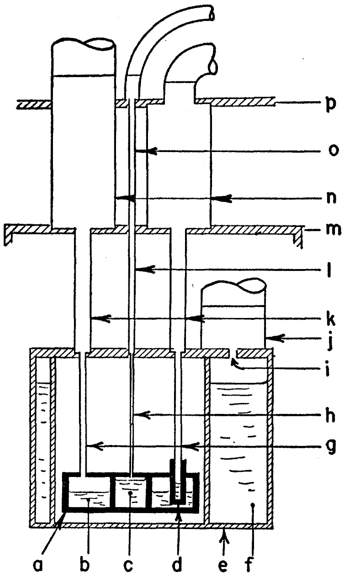

FIG. 1. He^3 Dewar. A copper block, *a*, is hollowed out to leave $\frac{1}{16}$-inch thick walls between a 15 cm^3 annular well for liquid He^3, *b*; a 1.9 cm^3 cell for mixture liquid, *c*; and a 0.1 cm^3 He^3 vapor pressure bulb, *d*. The block is suspended in a separate vacuum space surrounded by copper, *e*, maintained $\geqslant$ 1.1°K by liquid He^4, *f*, in an eccentric annulus of 5 liters capacity. A $\frac{3}{16}$-inch diameter constriction, *i*, minimizes film flow. The He^4 pumping line has a diameter of 1 inch at *j* and increases in steps (not shown) to 6 inch diameter enroute to a 10 horsepower fore pump in the basement beneath the laboratory. The pumping and pressure-sensing tubes for He^3, *g*, *k*, and *n*, have inside diameters of 2.7, 6.1, and 24.9 mm, respectively, in order that calculated pumping and thermomolecular pressure gradients be negligible in the lowest section and roughly the same in the middle and upper sections of each line. Each section is about 30 cm long. A liquid nitrogen pot (not shown) keeps radiation shield, *m*, at 75°K. The main vacuum jacket (not shown) is sealed to the Dewar lid, *p*, by means of *O* rings. Section *h* of the mixture pressure-sensing tube was 1.4-mm i.d. in all experiments. In series *A* experiments tubes *l* and *o* were the same, 2.7-mm i.d. In series *B* runs *l* and *o* were 6.1- and 24.9-mm i.d., respectively.

Not shown at the top and bottom of the mixture cell are horizontal quartz crystals[29] used in these experiments as a liquid level indicator. When the liquid level reached the upper crystal it became possible to transmit sound between the crystals. Except for $X=0.200$ data, pressure measurements were carried out only under these conditions, which corresponded to the cell being at least 84% full. The minimum liquid volume for sound signals was 1.6 cm^3.

For a number of reasons to be discussed later two sets of graduated pressure sensing tubes were used. Below the liquid He^4 heat sink both sets were the same, consisting of 0.145-cm i.d. tubing. Above this level set *A* had an inside diameter of 0.270 cm all the way to room temperature while set *B* was enlarged to 0.608-cm i.d. up to the liquid nitrogen level and to 2.490-cm i.d. above this level. Each of the three sections was approximately 30 cm long. The He^3 pressure-sensing tubing was identical in size with the set *B* mixture-sensing tubes.

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Vapor Pressure Measurement Details

The use of He^3 instead of He^4 vapor pressure thermometry eliminates the possibility of a pressure gradient due to return flow of a vaporized He II film to the mother liquid. Also, due to the much higher vapor pressures of He^3 and the large diameters of the pressure-sensing tubes the calculated[32] thermomolecular pressure ratio, $P_T/P_{300°\mathrm{K}}$ is nowhere less than 0.995 in the range of our measurements. The Weber-Schmidt thermomolecular pressure ratio equation has been found to fit within an accuracy of a fraction of a percent for experimental values as low as 0.500.[32,33] Had He^4 thermometry been used $P_{\mathrm{cold}}/P_{\mathrm{warm}}$ would have fallen below 0.5 at 0.8°K.

In the mixture pressure measurements, when using the set A, small bore tubes, $P_{\mathrm{cold}}/P_{\mathrm{warm}}$ was never less than 0.911, well above the experimentally proven range of the Weber-Schmidt equation. In further justification of the calculation of $P_{\mathrm{cold}}/P_{\mathrm{warm}}$, it was found that good agreement was obtained when using the large bore, set B, tubes.

Manometers and McLeod gauges used were similar to those described elsewhere,[31] except that the mixture oil manometer was of smaller bore, 7 mm, in order to reduce the noxious volume of the mixture system. The oil manometers were frequently calibrated against mercury, at about 90 mm Hg, and were in turn used to check the McLeod gauge calibration at 3 mm Hg (43-mm oil). Detailed calibration of the McLeod gauges was carried out down to 0.100 mm Hg, using a traveling microscope clamped to the case of the oil manometer to obtain an accuracy of 0.002 mm Hg. Readings of the manometers during the actual vapor pressure measurements were done using a level slide-rule hairline in front of the manometer and a mirrored scale behind. With this system independent scale readings of the same pressure by two observers usually agreed to within 0.1 mm which was two or three times less than the scatter of the data from run to run.

Errors Due to Film Reflux Etcetera

A pressure gradient associated with reflux of an evaporating mobile film is not a likely source of error in our experiments because the high concentration of He^3 in the vapor phase effectively prevents rapid diffusion toward the liquid surface of He^4 vaporized from the film.[30]

Actually a much more likely cause of serious error in pressure measurements involving He^4 or He^3-He^4 mixtures is seldom mentioned in the literature. We refer to the likelihood of an appreciable temperature difference between the liquid and the walls of its container, due to heat entering the liquid via condensation at its surface. For example, consider a cylindrical He^4 vapor pressure bulb of diameter, D, and height, h, connected to a vacuum jacketed pressure sensing tube of the same diameter. At 1°K, the total heat flux due to condensation of the refluxing film will be $0.7D$ milliwatt or greater, depending on the surface over which the film flows.[34,35] This heat must flow across a boundary separating the liquid from the rest of the apparatus, the area of the boundary being πDh if we neglect the area of the bottom of the bulb. The temperature drop across the liquid-solid boundary will therefore be[36]

$$\Delta T = Q/0.0222AT^2 = (0.010/h) \text{ degrees},$$

if h is in centimeters.

The results of this calculation were mentioned some time ago.[37] The above details are included here for the purpose of calling renewed attention to the importance of providing an adequately large refrigerated wall surface in a He^4 vapor pressure bulb.

The above calculation is also pertinent to the discussion of our measurements of P_x. For reasons not yet completely understood there was an appreciable heat influx to our mixture liquid beginning at pressures of the order of 3 mm Hg and increasing rapidly with decreasing pressure.[30] For a 40% He^3 liquid mixture this anomalous heat leak had risen to 0.076 milliwatt by 0.7° and 0.093 milliwatt by 0.6°K. Taking 8 cm^2 for the surface area of the sides and bottom of the mixture cell we estimate the temperature of this mixture to have been in excess of the He^3 thermometer by 0.0008° and 0.0014°K when at 0.7°K and 0.6°K, respectively. For $X>0.4$ the effect was less. For $X<0.4$ the anomalous heat leak was not measured.

Liquid Concentration

From time to time the ratio $X/(1-X)$ of He^3 to He^4 molar concentration of each of the nine stored mixtures was measured on a Nier-Consolidated mass spectrometer, to an accuracy of $\pm 1\%$. The accuracy of the measurement of X therefore varied linearly from $\pm 0.9\%$ at $X=0.1$ to $\pm 0.1\%$ at $X=0.9$.

Fractionation of a liquid He^3-He^4 mixture can cause its concentration to differ considerably from the known average concentration of the input gas. As an example, we note in the data of reference 1 that for $X=0.10$ the vapor concentration, X_v, will be 0.34 at 2.4°K and will rise to 0.80 at 1.4°K. If, as is usually the case, only the average concentration of the input gas is known, then X will be known exactly only if the mass and composition of the vapor in the system are known. To minimize the uncertainty in liquid concentration due to fractionation, we have chosen a Dewar design

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and operating procedure such that formation of He^3 rich vapor is kept to a minimum. As a check on the efficacy of these measures we have repeated many of the measurements with a much larger pressure-sensing tube and with differing volumes of vapor in the cell itself.

Evaporation of the mixture is prevented by following the procedure of starting a run by filling the cell at a high temperature and going, usually monotonically, to lower temperatures during the run. If a check point at a significantly higher temperature is needed the cell is emptied completely, the gas collected in the storage can is mixed thoroughly by pumping it at 8 liters/min for about half an hour out one port of a 12-liter storage can and into another port, and a new run is then started.

The procedure of progressively reducing temperature will not necessarily be sufficient to prevent appreciable vaporization of mixture liquid in an ordinary immersion-type Dewar. Some apparatus used elsewhere for mixture vapor pressure measurements has consisted of unjacketed pressure-sensing tubes immersed in liquid He^4. With such a Dewar the high efflux of vapor accompanying a reduction in temperature will cool the entire pressure sensing tube and may conceivably result in a transient increase in m_g, the mass of vapor present in the tubing. Ultimately a new and lower equilibrium value of m_g will exist because of the reduced pressure, but there will be an increase in the He^3 concentration of a large portion of the vapor mass every time the bath temperature is changed.

A second and possibly more serious cause of difficulty in measurements done with such an immersion-type He^4 Dewar is the increase in vapor volume which will occur when in the He II region when the temperature is reduced. At progressively lower temperatures the film will rise to that higher level on the outside of the pressure sensing tubing at which the increased conduction heat leak just balances the increase in film flow available for vaporization. Hence a net increase in m_g and resultant decrease in X may occur despite the decreased pressure. We shall see later that measurements done elsewhere with unjacketed mixture pressure-sensing tubes show peculiarities near the He^4 lambda temperature which can be interpreted as above in terms of the effect of the He II film on m_g and hence on the He^3 concentration in the liquid.

These difficulties cannot arise in the Dewar of Fig. 1 because the mixture pressure-sensing line is in a vacuum, it is surrounded by a constant temperature vacuum jacket and it makes thermal contact only with heat sinks held at fixed temperatures greater than the highest cell temperature during a run.

By the above described design and procedure, mixing of high He^3 content vapor and low He^3 content input gas is limited to that which can occur by the slow process of diffusion. There will be a tendency to counteract even this slow mixing process because of the condensation of vapor near the liquid surface which precedes each arrival at a new, lower pressure, data point. Direct experimental evidence for the effectiveness of these measures for avoiding errors in X will be given in the discussion of results.

RESULTS

Results of the measurements are given in Table I along with the deviation of each data point from a smoothed table (Table II) whose origin will be described later. In 20 of the runs the set A (small bore) sensing tubes were used. In later runs mixture pressures were transmitted to the gauges via the set B tubes.

Despite the order of magnitude enlargement of tubing cross sections after the first 20 runs it is seen that there is no systematic change in the fit of the data to the smoothed table. As further evidence for the avoidance of errors in X due to fractionation we call attention to the runs for $X=0.200$, in which the fraction of cell volume occupied by vapor was 16%, 18%, and 23%, respectively, in the three runs. We note that there is no systematic shift in the column of deviations, even for the higher pressures, where fractionation is most likely to have an effect on the liquid concentration.

Graphical representation of that portion of the data above T_s is given in Fig. 2 as a plot of $P_x/P_3{}^0$ versus T. This is seen to be a most satisfactory way of presenting such data because the ratio $P_x/P_3{}^0$ changes so slowly with temperature; e.g., for several mixtures we observed a 200-fold change in P_x but for no mixture was there more than a twofold change in $P_x/P_3{}^0$. Using this as an ordinate all of the data can be displayed with high sensitivity on a single figure. For purposes of smoothing the data this is of considerable advantage over the use of several figures covering different ranges of pressure.

The lambda line, $R_\lambda = f(T_\lambda)$, is plotted as a dashed line in Fig. 2. In constructing this line we have used for T_λ results consistent with second sound velocity measurements,[12] and measurements of first sound velocity and attenuation.[6,7] For mixtures of 70 and 80% He^3, T_λ's were taken from our tentative thermal conductivity measurements.[30] R_λ's were obtained by interpolating our data on $R=f(T)$ to the temperature T_λ.

Where the lambda line intersects the solid lines drawn through the data we find a more or less abrupt change in slope. The discontinuity is made more apparent by plotting deviations from T_λ and from $(P_x/P_3{}^0)_\lambda$ as in Fig. 3. We note that there are abrupt changes in slope at T_λ for low values of X but that for $X>0.5$ the change in slope is not so striking.

As described by de Boer and Gorter[38] the change at the lambda point in the specific heat of the liquid at constant pressure, ΔC_P, can be calculated from the change in slope of the vapor pressure at T_λ provided we also know P_3 and P_4, the partial pressures of He^3 and He^4. Preliminary values of ΔC_P have already been

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TABLE I. ΔR is the observed value of R minus that calculated using Columns (a), (b), and (c) of Table II, where R is 1000 times the ratio of mixture vapor pressure, P_x, to pure He^3 vapor pressure, $P_3{}^0$. The temperature, T_E, is derived from $P_3{}^0$, using the scale of reference 31. Subheadings give the He^3 mole fraction, X. Asterisks denote readings taken in the region of stratification, for which Column (a) of Table II is used to calculate ΔR. Between runs the cell is completely emptied. The beginning of a new run is designated by symbol "A" for runs made with the set A, small bore, pressure sensing tubes and by "B" for runs with the set B, large bore, tubes. One quarter of the entries represent a single measurement of P_x and $P_3{}^0$ and three quarters are the average of two such readings taken several minutes apart in time and within a few millidegrees in temperature.

P_x	$P_3{}^0$	T_E	ΔR
	$X=0.100$		
120.99 *A*	367.4	2.573	...
107.02	332.3	2.499	...
91.58	292.1	2.406	...
75.68	249.8	2.303	1
62.81	214.4	2.206	−1
56.16	195.2	2.149	−1
50.83	179.6	2.100	−2
47.30	169.2	2.066	−2
42.12	152.1	2.006	−2
38.48	139.0	1.956	−2
35.04	126.5	1.908	−1
28.18	102.0	1.800	−1
22.85	82.76	1.704	−1
18.17	65.40	1.604	−1
14.27	50.74	1.504	0
11.07	38.51	1.404	1
8.31	28.01	1.301	1
5.84	18.70	1.185	0
4.23	12.81	1.090	0
3.40	9.88	1.031	−2
2.126	5.56	0.916	−4
1.221	2.924	0.810	−3
0.707	1.520	0.720	−2
	$X=0.200$		
89.54 *B*	232.4	2.257	−3
74.44	196.4	2.153	−2
6.89	13.42	1.101	0
4.66	8.42	0.996	0
2.680	4.37	0.874	0
1.657	2.484	0.785	2
0.987	1.371	0.708	0
141.42 *B*	336.2	2.507	...
118.57	288.6	2.400	...
98.98	248.4	2.300	7
82.67	213.0	2.202	4
78.90	205.6	2.180	1
75.81	198.5	2.159	0
68.04	179.8	2.100	0
56.66	150.6	2.000	3
49.88	134.6	1.940	−1
46.86	126.7	1.908	1
44.94	121.8	1.888	−1
43.20	117.6	1.870	−4
41.76	112.7	1.849	−1
40.00	107.1	1.824	1
38.38	102.0	1.801	1
33.66	87.60	1.729	1
26.92	67.21	1.614	2
20.12	47.97	1.482	2
14.54	32.73	1.350	−1
9.97	20.86	1.215	0
49.23 *B*	133.7	1.936	−2
41.76	112.9	1.850	−2
31.68	81.50	1.697	2
21.15	51.40	1.508	−4
12.58	27.48	1.295	1
2.702	4.43	0.876	−1
1.627	2.465	0.784	−5
0.857	1.176	0.689	−5
0.411	0.511	0.602	1
0.271	0.316	0.561	...
	$X=0.301$		
117.35 *A*	249.6	2.303	−1
98.79	212.4	2.200	1
82.66	179.4	2.099	0
67.58	148.6	1.993	−2
56.74	125.6	1.904	−2
44.44	98.56	1.784	−2
51.34	113.9	1.854	−1
40.87	90.42	1.744	−2
37.18	81.35	1.696	2
33.94	72.45	1.646	2
30.62	63.80	1.593	1
25.20	50.35	1.500	0
27.97 *A*	57.12	1.549	1
19.49	37.00	1.391	1
15.46	28.06	1.302	0
11.54	19.84	1.201	0
8.31	13.51	1.102	0
5.76	8.81	1.006	0
3.40	4.78	0.889	2
1.878	2.449	0.784	−5
1.298	1.602	0.726	3
0.935	1.108	0.682	5
0.672	0.769	0.642	1
42.65 *B*	93.47	1.759	4
40.91	90.07	1.742	1
40.00	88.02	1.732	1
39.15	86.13	1.722	2
38.28	84.02	1.710	2
37.40	81.91	1.699	3
35.90	77.80	1.678	3
35.33	76.20	1.668	3
33.99	72.66	1.647	2
37.30	81.83	1.699	2
41.94 *B*	93.22	1.758	−2
41.55	92.45	1.754	−3
40.76	90.45	1.744	−1
39.84	88.29	1.733	−2
40.64	90.24	1.743	−2
39.90	88.41	1.734	−2
38.92	86.18	1.722	−1
38.08	84.09	1.711	−1
37.42	82.27	1.701	1
36.76	80.36	1.691	1
35.91	78.03	1.678	1
34.62	74.50	1.658	1
37.00	81.29	1.696	0
28.15	57.68	1.553	0
20.05	38.09	1.401	2
10.80	18.25	1.178	3
19.87 *B*	37.92	1.399	0
9.32	15.44	1.135	0
4.67	6.88	0.956	1
3.54	5.01	0.897	0
1.819	2.351	0.778	2
0.992	1.186	0.690	4
0.730	0.848	0.653	−5
0.633	0.720	0.636	−2
0.548	0.613	0.620	0
0.464	0.514	0.603*	−1
0.384	0.420	0.584*	2
0.313	0.340	0.566*	0
	$X=0.398$		
137.32 *A*	251.2	2.308	−1
115.53	213.0	2.202	2
97.09	180.2	2.102	2
80.49	150.5	2.000	1
66.54	125.2	1.902	2
53.87	101.49	1.798	3
43.73	82.39	1.702	2
38.88	73.08	1.650	1
34.74	65.06	1.601	0
31.05	57.81	1.554	−2
34.73	65.29	1.602	−2
30.94	57.67	1.553	−4
27.58	50.44	1.501	1
24.68	43.97	1.451	0
21.80	37.74	1.398	1
19.51	33.09	1.354	0
14.75	23.80	1.252	−1
10.91	16.74	1.156	−1
7.62	11.05	1.055	−1
6.28	8.85	1.007	0
4.90	6.67	0.950	1
3.81	5.01	0.897	3
2.95	3.77	0.849	1
2.296	2.862	0.806	−1
1.638	1.956	0.752	3
1.145	1.326	0.703*	2
1.872	2.282	0.774	0
	$X=0.500$		
134.66 *A*	216.4	2.212	3
136.56	220.4	2.224	−1
110.20	179.0	2.098	−1
91.52	149.5	1.996	0
75.72	124.3	1.898	0
60.31	99.14	1.787	0
50.04	82.34	1.702	1
39.64	65.18	1.602	−1
31.12	50.94	1.505	1
27.25	44.40	1.454	0
23.78	38.50	1.404	0
20.76	33.32	1.356	−2
20.42	32.66	1.350	0
17.78	28.04	1.302	0
15.59	23.97	1.254	0
13.28	19.88	1.202	3
8.87	12.50	1.084	3
7.06	9.66	1.026	2
3.85	4.92	0.894	2
27.31 *A*	44.41	1.454	1
4.53	5.90	0.926	1
0.571	0.638	0.624*	1
0.523	0.585	0.615*	−3
0.832	0.952	0.665*	−3
1.251	1.467	0.716*	−2
1.815	2.175	0.768*	1
2.632	3.255	0.827	0
155.8 *A*	248.6	2.300	4
17.42 *A*	27.47	1.295	−1
11.33	16.64	1.154	−1
7.77	10.85	1.051	−3
5.74	7.71	0.979	−2
2.98	3.74	0.848	−3
	$X=0.597$		
135.06 *A*	195.99	2.152	...
103.11	151.06	2.002	0
86.07	126.31	1.907	0
69.69	102.42	1.802	0
56.36	83.00	1.705	−1
44.49	65.55	1.604	0
34.26	50.50	1.502	−1

TABLE I.—*Continued.*

P_x	P_3^0	T_E	ΔR
$X=0.597$			
24.87	36.47	1.386	0
20.62	30.07	1.323	0
17.52	25.46	1.272	−2
14.90	21.46	1.223	0
12.50	17.81	1.172	0
10.55	14.82	1.125	1
8.60	11.92	1.073	0
7.20	9.75	1.028	2
5.88	7.77	0.980	2
4.43	5.71	0.920	1
3.40	4.26	0.869	2
2.584	3.188	0.822*	0
1.932	2.325	0.776*	1
1.386	1.622	0.728*	4
1.014	1.168	0.688*	1
0.709	0.800	0.646*	2
19.55 *A*	28.51	1.307	−1
13.96	20.02	1.203	0
9.94	13.93	1.110	0
19.70 *A*	28.79	1.310	−3
9.88	13.89	1.109	−3
6.25	8.36	0.995	−1
3.82	4.85	0.892	1
33.94 *B*	49.91	1.497	1
23.38	34.05	1.363	2
17.34	25.07	1.268	1
11.74	16.72	1.155	−4
8.44	11.67	1.068	0
5.88	7.78	0.980	1
4.46	5.73	0.921	3
3.24	4.04	0.860	6
0.547	0.608	0.619*	3
$X=0.698$			
13.63 *B*	17.80	1.172	4
6.93	8.90	1.008	2
7.18	9.25	1.016	2
21.46 *B*	28.17	1.303	7
10.76	14.01	1.111	2
5.22	6.66	0.950	−1
3.92	4.94	0.894	1
3.16	3.92	0.856	−6
2.73	3.38	0.832*	3
2.571	3.160	0.821*	3
2.102	2.540	0.789*	4
1.183	1.365	0.707*	6
1.193	1.390	0.710*	0
0.733	0.828	0.650*	3
0.613	0.684	0.631*	4
1.031	1.188	0.690*	2
1.645	1.959	0.753*	1
$X=0.699$			
125.25 *A*	164.6	2.050	1
0.897	1.029	0.674*	−2
1.482	1.754	0.738*	−1
2.050	2.479	0.785*	1
2.760	3.419	0.834*	1
0.859	0.984	0.669*	−3
$X=0.699$			
21.20	27.98	1.301	3
15.24	20.02	1.204	1
10.67	13.91	1.109	1
8.55	11.08	1.057	−1
6.98	8.96	1.010	0
5.38	6.85	0.955	−1
4.12	5.21	0.904	−3
3.24	4.06	0.861	−2
2.724	3.385	0.832*	0
134.72 *A*	176.6	2.090	...
131.71	172.8	2.077	...
98.54	130.2	1.922	−1
$X=0.700$			
94.77 *A*	125.1	1.902	0
100.39	132.8	1.933	−2
108.82	144.1	1.976	−4
123.47	162.4	2.039	0
111.38	146.4	1.985	2
113.34	149.0	1.994	2
116.28	153.7	2.011	...
$X=0.798$			
130.75 *B*	156.5	2.022	...
67.76	81.49	1.697	1
20.13	24.30	1.259	1
6.27	7.50	0.973	−1
5.16	6.16	0.934	−2
3.49	4.15	0.865	4
2.728	3.232	0.825	5
0.836	0.952	0.665*	2
1.792 *B*	2.107	0.762	−3
1.197	1.383	0.708	8
0.710	0.802	0.647*	2
122.91 *B*	147.7	1.990	−1
73.30	88.23	1.733	0
0.355	0.387	0.577*	3
0.670	0.753	0.640*	4
1.071	1.242	0.695*	0
1.197	1.392	0.709	1
1.358	1.582	0.725	1
1.515	1.768	0.739	2
1.722	2.017	0.757	1
2.249	2.641	0.794	3
$X=0.799$			
134.82 *A*	160.2	2.034	6
113.23	135.3	1.942	4
88.01	105.4	1.817	2
69.23	83.17	1.706	1
54.31	65.39	1.603	0
41.59	50.27	1.500	−3
31.47	38.08	1.401	−2
23.30	28.18	1.303	0
19.74 *A*	23.79	1.252	3
13.84	16.67	1.155	1
9.07	10.89	1.052	0
5.51	6.58	0.947	1
4.20	4.97	0.896	3
$X=0.799$			
2.86	3.39	0.832	−3
1.951	2.290	0.774	7
1.369	1.599	0.726	−1
1.004	1.159	0.688*	0
0.695	0.790	0.645*	−4
0.619	0.704	0.634*	−10
12.07 *B*	14.47	1.119	4
7.28	8.75	1.005	−3
5.65	6.77	0.953	−3
4.31	5.17	0.903	−4
3.16	3.77	0.849	−6
2.714	3.216	0.824	−2
$X=0.897$			
137.72 *A*	150.9	2.003	−1
115.73	127.2	1.910	−1
92.76	101.93	1.800	0
73.10	80.42	1.691	−1
59.05	64.99	1.600	0
45.92	50.64	1.502	−1
34.85	38.47	1.404	0
25.44	28.09	1.302	−2
18.16	20.11	1.205	−1
12.54	13.84	1.108	0
8.00	8.80	1.006	2
4.61	5.07	0.899	0
21.69 *A*	23.94	1.254	0
18.23	20.17	1.206	−2
2.428	2.660	0.796	2
1.350	1.478	0.730	−2
0.751	0.819	0.649	−2
0.555	0.600	0.618	0
0.451	0.484	0.597	−3
0.916	1.002	0.671	−5
7.94 *A*	8.76	1.005	−1
4.70	5.17	0.902	2
2.309	2.532	0.788	1
1.200	1.317	0.702	−5
0.983	1.073	0.678	−2
0.751	0.821	0.649	−5
0.566	0.615	0.620	−8
0.461	0.494	0.599	5
2.158	2.366	0.779	1
3.372 *A*	3.716	0.846	−2
2.472	2.704	0.798	3
1.920	2.097	0.762	4
1.587	1.737	0.737	−1
1.364	1.494	0.718	−1
1.234	1.352	0.706	−2
0.915	0.997	0.670	−3
2.592 *A*	2.842	0.805	1
1.480	1.605	0.727	9
0.608	0.662	0.627	−7
0.296	0.309	0.558	...
6.27 *B*	6.89	0.956	3
1.622	1.773	0.740	1
0.502	0.539	0.608	3
0.309	0.326	0.562	...

calculated from our earlier results.[28] A recalculation is under way which will make use of the more complete vapor pressure data depicted in Fig. 3 and which will avoid the use of existing experimental vapor composition data,[1,2] whose accuracy is not sufficiently high for this purpose.

At its stratification temperature, T_s, a mixture will separate into two conjugate phases of low and high He^3 concentration, X_L and X_H. Since they are in thermodynamic equilibrium their Gibbs free energy and hence their vapor pressures, P_s, must necessarily be identical. Furthermore, all other liquids having an average concentration anywhere in the range X_L to X_H will have a vapor pressure equal to P_s at this same temperature since they will also be separated into two layers having the concentrations X_L and X_H. Figure 2 shows

TABLE II. Smoothed values of $R=1000P_X/P_3^0$, at stratification temperatures [Column (a)], at lambda temperatures [Column (b)], and at 0.1°K temperature intervals [Columns (c)], for values of X, the He^3 mole fraction. Parentheses enclose values of T_S below the range of our measurements and the somewhat uncertain interpolations near the consolute temperature. In Columns (c) asterisks separate He II and He I phases and the letter "S" designates the region of stratification. Question marks denote our unpublished and provisional values of T_λ obtained from heat flow experiments which have not yet been checked against the possibility that the superfluidity of the conjugate of a stratified mixture was inadvertently being detected. For purposes of extrapolation of Columns (c) it should be remembered that for each value of X the curve of R versus T terminates at T_S. When interpolating near T_λ one should also note that the slope changes abruptly at T_λ, except for $X=0$, for which there is an inflection at T_λ.

	(a)		(b)		(c). Values of R at the following temperatures:																	
X	T_S	R_S	T_λ	R_λ	0.6°	0.7°	0.8°	0.9°	1.0°	1.1°	1.2°	1.3°	1.4°	1.5°	1.6°	1.7°	1.8°	1.9°	2.0°	2.1°	2.2°	2.3°
0.00	(0.00)		2.1735	186	1	2	4	8	14	22	31	43	56	71	87	104	122	140	157	174*	190	205
0.02	(0.08)		2.145	205	166	128	106	95	89	89	91	98	107	117	129	142	156	170	184	199*	211	225
0.04	(0.16)		2.116	223	290	230	195	173	160	152	150	150	154	161	170	179	189	199	210	221*	232	245
0.06	(0.22)		2.087	240	395	319	277	249	228	214	205	201	200	204	209	214	221	228	234*	241	252	264
0.08	(0.27)		2.058	260	480	405	356	319	292	273	259	250	246	245	245	247	249	253	257*	263	272	284
0.10	(0.31)		2.028	279	558	478	425	384	352	328	309	296	287	281	279	277	277	278	279*	285	293	302
0.12	(0.35)		1.998	298	629	547	487	440	405	377	354	337	324	315	309	303	301	299*	298	305	313	322
0.14	(0.38)		1.967	316	687	605	541	490	450	418	392	371	356	345	334	327	323	318*	319	324	331	339
0.16	(0.42)		1.936	334	735	652	586	532	490	455	426	403	385	371	360	350	343	336*	337	342	348	357
0.18	(0.45)		1.904	352	775	692	623	567	522	485	456	432	411	395	381	369	360	352*	355	359	365	374
0.20	0.477		1.873	368	805	726	654	597	551	513	482	456	434	416	401	387	375*	369	373	378	384	391
0.22	0.507		1.840	386	834	751	681	625	579	538	505	480	455	436	420	403	389*	386	390	393	400	407
0.24	0.536		1.807	402	859	771	704	648	601	561	528	500	476	454	435	418	403*	403	406	410	416	423
0.26	0.563	922	1.773	419	879	792	724	669	621	582	548	519	493	471	452	431*	418	420	423	427	433	438
0.28	0.588	909	1.738	436	899	810	742	687	640	599	565	536	510	486	465	443*	435	435	439	443	448	454
0.30	0.614	898	1.704	453	S	824	757	703	656	616	581	551	524	500	477	454*	451	452	455	459	464	470
0.32	0.636	889	1.667	472	S	835	771	718	670	630	596	565	537	512	485*	470	467	468	472	476	479	485
0.34	0.658	880	1.630	490	S	847	782	730	683	642	608	578	549	522	496*	486	483	484	487	492	496	501
0.36	0.679	871	1.592	507	S	856	793	740	694	654	620	589	560	532*	506	501	499	500	503	507	511	516
0.38	0.700	863	1.553	526	S	863	802	749	704	664	630	599	570	540*	520	516	515	516	519	523	527	532
0.40	0.718	854	1.514	545	S	S	807	757	713	673	638	606	577	547*	536	530	530	532	536	539	542	547
0.42	0.737	846	1.472	564	S	S	812	763	720	681	646	614	584*	560	550	545	546	548	551	554	558	563
0.44	0.753	839	1.430	581	S	S	816	768	726	687	652	620	590*	572	565	561	562	564	567	570	574	578
0.46	0.769	833	1.387	600	S	S	818	772	731	693	658	626*	596	584	578	576	578	579	583	585	588	593
0.48	0.783	827	1.342	617	S	S	820	775	734	697	662	630*	607	597	593	592	593	595	598	601	604	608
0.50	0.796	821	1.297	635	S	S	821	777	738	701	666*	634	618	610	607	607	608	609	612	616	619	623
0.52	0.809	817	1.250	653	S	S	S	778	740	703	670*	644	630	624	621	621	623	625	627			
0.54	0.822	811	1.203	671	S	S	S	780	742	706	672*	654	643	638	636	636	638	640	642			
0.56	0.832	806	1.154	690	S	S	S	781	744	708*	681	665	656	652	650	651	653	654	656			
0.58	0.841	803	1.105	709	S	S	S	782	746	711*	689	677	669	667	666	666	667	668	671			
0.60	0.848	800	1.055	728	S	S	S	783	747*	717	699	689	683	681	681	682	682	683	684			
0.62	(0.86)		1.005	748	S	S	S	785	749*	725	710	701	696	696	696	697	697	698	699			
0.64	(0.87)		0.954	766	S	S	S	785*	754	735	723	716	712	711	711	711	713	713	715			
0.66	(0.87)		0.904	786	S	S	S	787*	762	745	735	729	726	726	726	727	728	728	729			
0.68	(0.86)		0.876?		S	S	S	789	770	756	747	743	740	740	741	742	743	743	745			
0.70	0.836	805	0.840?		S	S	S	793	779	767	761	756	755	755	756	756	757	758	759			
0.72	0.811	815	0.820?		S	S	S	799	788	780	774	771	770	770	770	771	772	773	774			
0.74	0.781	828	0.800?		S	S	825	807	798	792	788	785	784	785	786	787	787	788	789			
0.76	0.754	839	0.777?		S	S	832	817	809	805	802	801	798	800	800	802	802	803	804			
0.78	0.724	852	0.753?		S	S	840	829	822	818	816	815	814	815	816	817	818	819	820			
0.80	0.695	863	0.723?		S	861	849	841	835	831	829	829	829	831	831	832	833	834	834			
0.82	0.667	877	0.695?		S	871	860	852	848	846	844	844	845	846	848	848	848	849	850			
0.84	0.636	890	0.654?		S	880	871	865	862	860	859	860	860	862	863	864	864	865	866			
0.86	0.604	903	0.620?		905	892	884	880	876	875	876	876	876	878	879	879	879	880	881			
0.88	0.570	920	0.580?		917	904	898	894	892	892	891	892	892	893	895	896	896	896	897			
0.90	0.531		0.542?		930	918	912	910	908	908	908	909	909	910	911	912	912	913	914			
0.92	(0.48)				942	933	928	927	925	925	926	927	927	927	928	929	929	929	931			
0.94	(0.43)				956	947	943	942	941	942	944	945	945	946	946	946	946	946	947			
0.96	(0.36)				970	964	961	960	959	960	962	963	963	964	964	964	964	964	964			
0.98	(0.26)				983	981	980	979	979	980	980	981	981	981	981	981	982	982	982			

that the various mixtures do indeed appear to be approaching the same values of P_x/P_3^0 as they approach the region of stratification. For the mixtures of low He^3 concentration the rate of approach is sufficiently abrupt to serve as a fair determination of the value of T_s. However, for mixtures whose concentration is close to that of the consolute the approach is exceedingly gradual; e.g., the ratio $P_{x=0.6}/P_{x=0.5}$ is less than 1.020 and yet significantly greater than 1.000 for a quarter of a degree.

Figure 4 shows that portion of the data taken in the region of stratification, using values of T_s obtained from our sound velocity determinations.[6] We find as expected, that within the scatter of the measurements all the points fall on the same curve. This is very nearly a straight line whose equation is:

$$P_s/P_3^0=1.214-0.502T_s \quad \text{for} \quad 0.58<T_s<0.82°\text{K}.$$

A smoothed table of P_x/P_3^0 was constructed as follows: the solid curves of Fig. 2 were read off every 0.1°K and these values of P_x/P_3^0 were replotted versus X. Smooth curves were drawn (Fig. 5) through these points, except where abrupt changes in slope occurred at X_λ, and the curves were read off every 0.02 in X. As a final smoothing, a curve for each value of X was plotted versus T. Columns (c) in Table II were obtained from these curves. For convenience we tabulate $R \equiv 1000P_x/P_3^0$. Curves of R versus T terminate at the

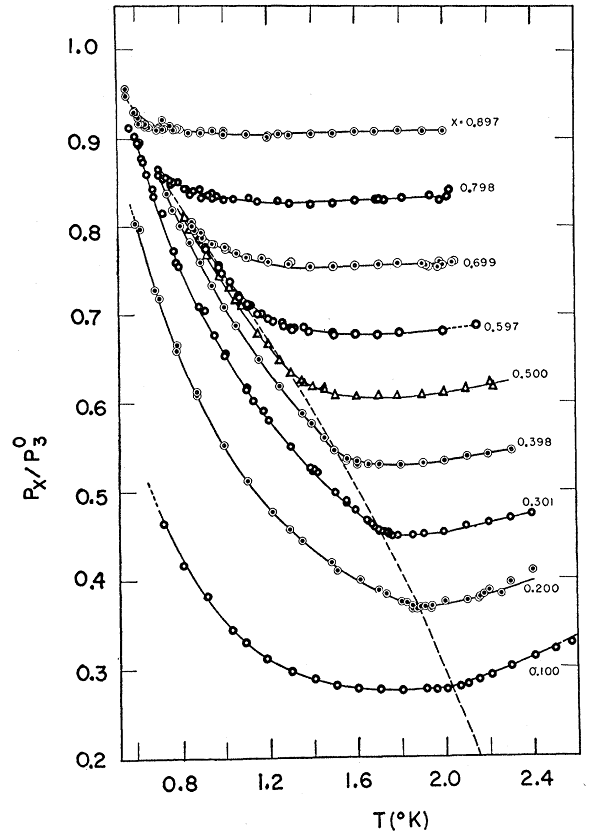

FIG. 2. Present results of vapor pressure measurements on nine He^3-He^4 mixtures of He^3 mole fraction, X, are shown as a plot of the ratio of mixture vapor pressure, P_X, to measured He^3 vapor pressure, P_3^0. The lambda line is shown in dashes. Measurements below the stratification temperature are omitted from this figure.

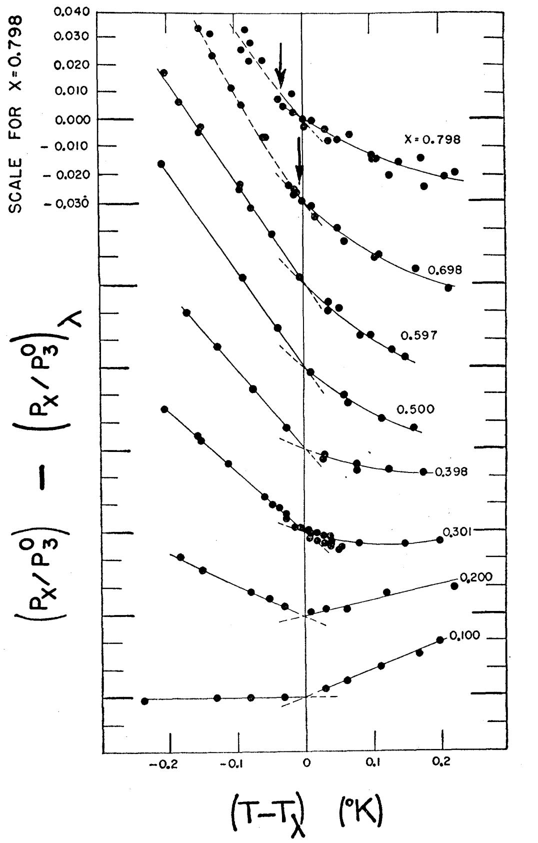

FIG. 3. Data in the vicinity of the lambda temperature, T_λ, of each mixture, are shown here on a greatly expanded scale. T_λ for the two uppermost curves is based on our preliminary and provisional determinations of T_λ for these mixtures. Arrows designate the temperature at which a mixture reaches its stratification temperature.

stratification temperature. As a mixture is cooled below T_s the pressure ratio, R_s, will be given by Column (a) in Table II. Abrupt changes in dR/dT may also occur at the lambda temperature. Values of T_λ and R_λ are given in Column (b) of Table II.

Table II was used to obtain the deviations column of Table I, $\Delta R = R_{\text{obs}} - R_{\text{calc}}$. The overall fit of the table to the data is satisfactory. For the 301 data points in the range of the table the average ΔR is $+0.11$. A measure of the precision of the measurements is given by the sum of ΔR without regard to sign. We find $\sum|\Delta R|/301 = 2.1$ in the units of the table. This can be

TABLE III. Our data on each mixture are compared to Table II with regard to the fit (average deviation from the table) and scatter (average deviation disregarding the sign of the deviation).

Mole fraction (X)	Observations (n)	Fit ($\Sigma\Delta R/n$)	Scatter ($\Sigma\|\Delta R\|/n$)	Percent scatter ($100\Sigma\|\Delta R\|/\Sigma R$)
0.1	20	−1.1	1.4	0.45
0.2	34	−0.1	1.8	0.39
0.3	59	+0.2	2.0	0.35
0.4	26	+0.5	1.5	0.24
0.5	28	+0.2	1.3	0.19
0.6	31	+0.2	1.3	0.18
0.7	23	+0.6	1.9	0.24
0.8	38	+0.8	2.5	0.29
0.9	42	−0.5	2.3	0.25

TABLE IV. The fit and scatter of our data in each of eighteen regions of temperature. The data in the region of stratification have been excluded from this tabulation.

T(°K)	Observations (n)	Fit ($\Sigma\Delta R/n$)	Scatter ($\Sigma\|\Delta R\|/n$)	Percent scatter ($100\Sigma\|\Delta R\|/\Sigma R$)
2.3±0.05	6	+1.2	2.8	0.62
2.2	9	+0.8	1.7	0.37
2.1	7	−0.6	1.1	0.28
2.0	16	+0.3	1.9	0.29
1.9	15	−0.6	1.5	0.28
1.8	14	+0.0	1.6	0.31
1.7	31	+0.5	1.5	0.28
1.6	15	−0.1	1.2	0.22
1.5	14	−0.1	1.1	0.20
1.4	14	+0.1	0.9	0.14
1.3	19	+0.4	1.4	0.21
1.2	16	+0.2	1.3	0.19
1.1	18	+0.2	1.1	0.16
1.0	23	+0.2	1.4	0.19
0.9	23	+0.7	2.1	0.27
0.8	26	−0.1	2.8	0.34
0.7	22	+0.3	3.4	0.40
0.6	13	−1.8	3.4	0.37

expressed as a percentage scatter with respect to the average value of R: $100\sum|\Delta R|/\sum R=0.31\%$. This is about equal to the sum of the precisions of the two vapor pressure measurements entering into a determination of R.

In Table III we show the over-all fit, scatter, and percent scatter for each group of concentrations. The data for $X=0.1$ is seen to be the poorest, both as to fit and as to percentage scatter.

Table IV shows the over-all fit, scatter, and percent scatter for 0.1°K intervals of temperature above T_s. The scatter is seen to increase at low temperatures, in the region where McLeod gauges are being used to measure both P_x and $P_3{}^0$. The poor fit and large scatter at the highest temperatures are probably due to allowing insufficient time for equilibration after charging the cell.

In Table V we have separately grouped the observations made in the region of stratification, for which R_{calc} is taken from Column (a) of Table II. The fit and scatter are seen to be comparable to those obtained above for the nonstratification region, in which Columns (c) of Table II were used.

TABLE V. The fit and scatter of all data points taken in the region of stratification.

T(°K)	Observations	Fit	Scatter	Percent scatter
0.8±0.05	11	+0.5	1.6	0.20
0.7	14	+0.5	1.9	0.22
0.6	14	+0.7	2.6	0.29

Table II should be useful for determining a liquid concentration *in situ* from a measurement of vapor pressure and temperature. Use of a He^3 vapor pressure thermometer would, of course, be most convenient for this purpose, since $P_x/P_3{}^0$ is given by the measurement directly. Since the T_E scale[31] was used in deriving Table II it would, in principle, be best to use this scale in deriving a temperature from a measured $P_3{}^0$. However, at 1.8° dR/dT is so small that the error due to using the T_L or some comparable future He^3 scale would be nil: The maximum effect on R would be only half the least count of the table. At lower temperatures dR/dT is higher. Thus at 1°K the error would be equal to the least count if the T_L scale were used.

If a He^4 vapor pressure thermometer is used it will be necessary to derive $P_3{}^0$ from the measured $P_4{}^0$. To do this rigorously the appropriate inter-related He^4 and He^3 temperature scales should be used. Since the T_E He^3 scale is based directly on the T_{55E} He^4 scale,[39] the latter should be used to convert $P_4{}^0$ to a temperature and the T_E He^3 scale should then be used to obtain $P_3{}^0$. These operations can be described by the formula:

$$P_4{}^0 \longrightarrow T_{55E} \equiv T_E \longrightarrow P_3{}^0.$$

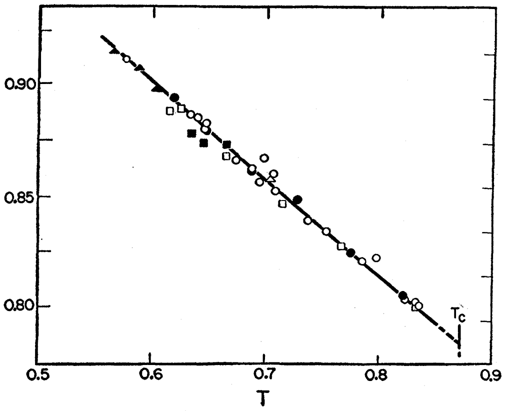

FIG. 4. Results of measurements in the region of stratification. The symbols ▲, △, □, ●, ○, and ■ designate concentrations $X_{\text{av}}=0.3$, 0.4, 0.5, 0.6, 0.7, and 0.8 of the input mixture, respectively. The fact that the points are all on the same curve is a demonstration of the occurrence of stratification. T_C is the consolute temperature.

For the convenience of users of Table II who may not have a copy of the T_{55E} scale, we present in Table VI a compilation of $P_4{}^0/P_3{}^0$ derived by the above formula. A T_E scale in millidegree steps is available from the authors on request.

COMPARISON WITH RESULTS OF OTHER WORKERS

The results of other workers can be compared to our own by reference to Table II. We are seen, Fig. 6, to be in good agreement, below 1.4°K, with the results of Weinstock, Osborne, and Abraham[4] on 20.3 and 25.5 mole percent He^3 mixtures. In this temperature region our calculated curve passes through their data points nicely. At temperatures above 1.4°K our curve begins to deviate, until it is up to 4.5% above their data. This is appreciably greater than the spread in their data, which is only about 2%. It is interesting to note, however, that their data show pronounced breaks in

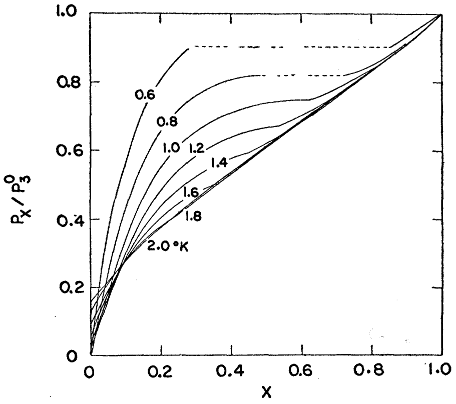

FIG. 5. The ratio of mixture to pure He^3 vapor pressures as a function of the He^3 mole fraction of the mixture. Dashed lines are in the region of stratification.

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[39] William E. Keller, Nature 178, 883–887 (1956).

TABLE VI. The ratio $1000P_4^0/P_3^0$, for converting a measured He^4 vapor pressure to a He^3 vapor pressure at the same temperature The pressures were taken from comparable inter-related temperature scales: the 55E scale for P_4^0 and the E scale for P_3^0.

T	+0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.80	4.10	4.42	4.76	5.11	5.48	5.86	6.26	6.68	7.12	7.58
0.90	8.05	8.54	9.06	9.59	10.14	10.70	11.29	11.90	12.52	13.17
1.00	13.83	14.51	15.23	15.95	16.70	17.47	18.24	19.05	19.88	20.72
1.10	21.59	22.47	23.37	24.29	25.24	26.20	27.18	28.18	29.20	30.24
1.20	31.30	32.37	33.47	34.59	35.72	36.87	38.04	39.22	40.42	41.65
1.30	42.89	44.14	45.42	46.71	48.01	49.34	50.68	52.03	53.40	54.79
1.40	56.19	57.61	59.04	60.49	61.95	63.42	64.91	66.42	67.93	69.46
1.50	71.0	72.6	74.1	75.7	77.3	78.9	80.5	82.1	83.8	85.4
1.60	87.1	88.7	90.4	92.1	93.8	95.5	97.2	98.9	100.6	102.4
1.70	104.1	105.9	107.6	109.4	111.1	112.9	114.7	116.5	118.2	120.0
1.80	121.8	123.6	125.4	127.2	129.0	130.8	132.6	134.4	136.2	138.0
1.90	139.8	141.6	143.4	145.2	147.0	148.8	150.5	152.3	154.1	155.8
2.00	157.6	159.4	161.1	162.8	164.5	166.2	167.9	169.6	171.3	172.9
2.10	174.6	176.2	177.9	179.5	181.1	182.6	184.2	185.7	187.2	188.7
2.20	190.3	191.8	193.2	194.7	196.2	197.7	199.2	200.6	202.1	203.6
2.30	205.0									

slope at points which are in excellent agreement with our lambda line. This would tend to suggest that the discrepancy is not in the vapor pressures but in the He^3 concentration. The trend of the discrepancy is consistent with occurrence of fractionation in the experiments under discussion, since this would have little effect on X at low temperatures, where m_g is small, but would have a progressively increasing effect at increasing temperatures. On the basis of this explanation the indication is that at T_λ fractionation had reduced the liquid concentration by about 1.5% in the experiments depicted in Fig. 6.

In Fig. 7 the circled data points show the data of Sommers[2] to be in somewhat better agreement with Table II but deviating in the opposite direction from the data of the previous figure. The squares show unpublished data of Kerr,[40] taken in conjunction with his density determinations. In general, his high-temperature points are on or above our table while his low-temperature points fall below. Agreement with our table is least satisfactory for high He^3 concentrations but no consistent dependence of the discrepancy on X is evident. Triangles show the data of Peshkov and Kachinskii[41] on a 93.6% mixture to be in excellent agreement with ours.

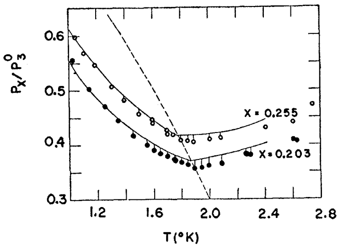

FIG. 6. Results of Weinstock, Osborne, and Abraham, reference 4, on two mixtures of high He^3 content. Vertical bars connect the data points to curves calculated from Table II. Since He^4 thermometry was used it was necessary in making the calculation to use appropriately inter-related He^4 and He^3 vapor pressure scales to convert from the measured P_4^0 to P_3^0.

Figure 8 shows most of the data of Esel'son and Berezniak,[1] hereafter designated E-B. In the interest of clarity we have omitted data for $X=0.008$, 0.030, 0.226, and 0.563. Since this research provides the most extensive existing series of measurements on He^3—He^4 mixtures, a detailed discussion of them will be given.

The stated accuracy of the measurement of pressure was of the order of 0.5%. It is apparent from an examination of Fig. 8 that although for some of their mixtures the scatter of the points with respect to the best smooth curve one can draw through them is comparable to ±0.5%, yet for other concentrations discrepancies of several percent are not infrequent. This is so much greater than errors one might reasonably expect in a pressure measurement that it appears more likely that the liquid concentration is not a constant throughout the measurements on a mixture of given average X. It is interesting to note, in this connection, that for nearly every concentration there is an abrupt apparent drop in X_{liquid} (or in R) when the bath temperature is lowered through the He^4 lambda temperature. In the figure $T_{\lambda,0}$ is indicated by a vertical dashed line. The observed effect is qualitatively what one would expect for an unjacketed pressure sensing tube immersed in liquid He^4, as outlined above: When surrounded by a mobile film the tube can have a greatly increased noxious volume, resulting in increased fractionation and therefore in a reduction in the He^3 concentration in the liquid. For mixtures in

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[40] E. C. Kerr, tables of data by private communication; for experimental details see reference 12, pp. 158–163; Phys. Rev. **96**, 551–554 (1954); J. Chem. Phys. **26**, 511–514 (1957).

[41] V. P. Peshkov and V. N. Kachinskii, J. Exptl. Theoret. Phys. (U.S.S.R.) **31**, 720–721 (1956) [translation: Soviet Phys.—JETP **4**, 607–609 (1957)].

the vicinity of $X=0.1$, R drops about 2%. This is equivalent to a decrease of about 6% in the value of X.

We have so far restricted the discussion to the scatter in the E-B data. As to a comparison of absolute magnitude, it can be said that most of the two groups of data are in good agreement, within the combined uncertainty in the determinations of X. They state their concentrations were known within 1.5–4% of the measured values. We estimate the uncertainty in our X's to vary linearly from $\pm 0.9\%$ of X at our lowest X to $\pm 0.1\%$ at our highest X. If we exclude the low-temperature end ($T<1.6°\mathrm{K}$) of the E-B high-concentration data ($X\geq 0.734$), then all their remaining data is found to be in agreement with ours to within 5% of X and the existing discrepancies can be attributed almost entirely to stated uncertainties in X.

As to the above, excluded portion of their data, it is probably in error. It disagrees by over 10% in pressure (or in concentration) with all the existing data of similar X of three independent researches: ours, the measurements of Kerr,[40] and those of Peshkov.[41] Furthermore, there is an apparent internal inconsistency between the E-B data on $X=0.734$ and 0.527, which appear to be about to meet or cross at 1.4°K. In this connection it may be worth noting that the authors used a different technique for $X\geq 0.734$, in that the cell was only half filled. For lower concentrations the cell was nearly full.

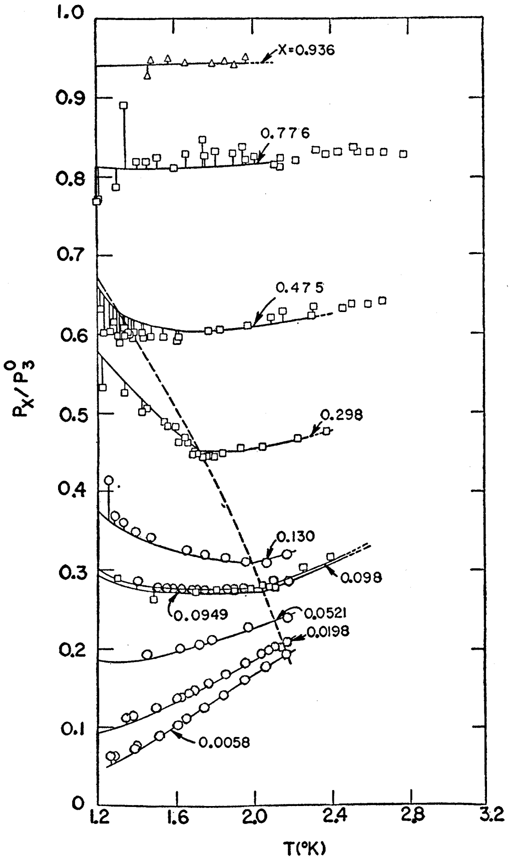

FIG. 7. The early results of Sommers, ○, reference 2; recent results of Peshkov, △, reference 41; and unpublished measurements of Kerr, □, reference 40. He^4 vapor pressure thermometers and He^4 baths were used in all of these experiments.

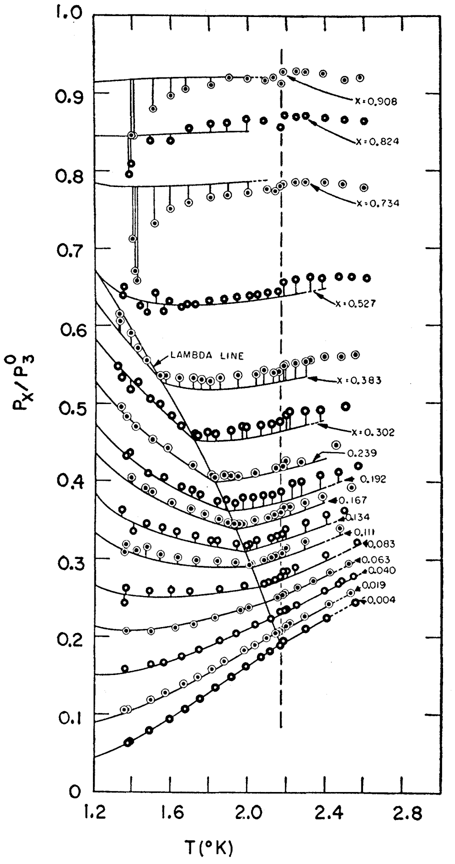

FIG. 8. Results of Esel'son and Berezniak, reference 1. The vertical dashed line is at the lambda temperature of the He^4 bath in which the experiment was conducted. Note the apparent discontinuity in P_X occurring near this temperature for most of the mixtures. Similar effects have been observed elsewhere, references 14–16, but were eliminated when the pressure-sensing tubes were completely vacuum jacketed, reference 17.

In conclusion, it is worthy of note that smooth curves through the E-B data would apparently "break" very close to our lambda line. As discussed previously in the discussion of Fig. 6, this indicates the discrepancies between their results and ours in the vicinities of the λ points do not lie in the measurement of pressure or temperature but rather to the assignments of liquid concentration.

We are unable to include, in figures similar to the preceding ones, the early results of Daunt et al.,[15,16] because they were not tabulated. A brief discussion will suffice. The differential pressure was measured between liquid He^4 and mixture bulbs, using unjacketed pressure-sensing tubes. Particular attention was directed in one of these papers[16] to discontinuities in slope

TABLE VII. Deviations of the smoothed table of Sreedhar and Daunt[a] from our Table II, in units of $R=1000P_x/P_3^0$. The conversion $T_{58}\rightarrow P_4^0\rightarrow T_{55E}\equiv T_E\rightarrow P_3^0$, was employed. The entries are in the sense $\Delta R=R_{\text{Sreedhar and Daunt}}-R_{\text{Table II}}$.

X T	0.0191	0.0334	0.0651	0.1204
1.4	−4	0	−4	−7
1.5	2	4	2	−2
1.6	3	5	0	1
1.7	−2	4	−5	−9
1.8	4	3	3	4
1.9	3	4	4	2
2.0	2	3	3	1
2.1	1	1	3	−1
2.2	1	1	2	−1
2.3	1	1	1	−2
$\Sigma\Delta R/n$	1.1	2.6	0.9	−1.4
$\Sigma\|\Delta R\|/n$	2.3	2.6	2.7	3.0

[a] See reference 17.

occurring at 2.17°K for all the solutions studied, and indeed, these were even more pronounced, by factors of 2 to 3, than the discontinuities we find in the E-B data on comparable concentrations. The authors stated that it was not clear whether this was a property of the solution itself or of the pure liquid He^4.

There is a third possibility which should be considered. As explained above, the effect could be a capricious one due to fractionation occurring when the pressure sensing tube is cooled by a He II film. This explanation is indirectly substantiated by the fact that recent results of Sreedhar and Daunt[17] show no such anomalies, despite the fact that again the differential pressure between liquid He^4 and mixture bulbs was being measured. Significantly, in these measurements the tubing was completely vacuum jacketed, so that no He II-induced fractionation could have occurred.

The recent results of Sreedhar and Daunt[17] do not include a table of the actual data. However, the authors found that their measurements are in good agreement with our Table II, and their smoothed tables do indeed show excellent agreement. The deviations of their table from ours is shown in Table VII. No large systematic deviations are evident. For each mixture the overall fit is quite good and the over-all fit of all the entries is remarkably good: The average ΔR is 0.8, which is only 0.27% of the average value of R. The agreement between their smoothed table and ours is thus quite similar to the agreement of our data with our Table II. There is therefore no need for a revision of Table II in the light of the recent results of Sreedhar and Daunt. This is particularly gratifying in view of the extensive graphic interpolations we made in the region of low concentrations.

The above comparisons with data of other workers is complete, to the best of our knowledge, except for some of the early isolated pieces of data on concentrations of the order of 1% He^3.

In summary, it appears that almost all of the existing literature data are in excellent agreement with our lambda vapor pressure table, Column (b) of Table II. All of Columns (c) in Table II below 1.2°K remains to be confirmed. Above this temperature the data of Peshkov and Kachinskii provide adequate confirmation for $X\sim 0.9$ and the recent data of Sreedhar and Daunt provides adequate confirmation for $X\leq 0.12$. For other portions of Columns (c) (Table II) existing data are generally too uncertain as to X to provide a confirmation of the table.

ACKNOWLEDGMENTS

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We thank Dr. E. C. Kerr, Dr. J. G. Daunt, and Dr. B. Weinstock for valuable discussions and for providing unpublished experimental results which made this paper more complete than it would otherwise be.