

Phase Diagram for the Liquid-Vapor System of Helium Isotopes (He^3 - He^4). I.

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The temperature dependence of the vapor pressure of twenty solutions of helium isotopes has been measured, with He^3 content varying from 0.4 to 90.8%. Measurements have also been made of the pressure corresponding to initiation of condensation for eight mixtures with He^3 content from 1.9 to 82.4%. The phase diagram of the liquid-vapor system of He^3 - He^4 is constructed, and the temperature dependence of the partition of He^3 between liquid and vapor and the concentration of the liquid phase have been determined.

1. INTRODUCTION

HE availability in comparatively large quantities of helium mixtures that are rich in the light isotope¹ has made possible the study of the thermodynamic properties of mixtures of the helium isotopes. In particular, it is possible to obtain data which are necessary to construct phase diagrams for the liquid-vapor system of helium isotopes. Such a diagram is naturally of great interest, not only because it characterizes the properties of binary mixtures of the isotopes, but also because the properties of each of the pure components are associated with quantum effects.^{2,3} The adherence of He^3 and He^4 to different statistics, the presence of superfluidity in He^4 and its absence in He^3 accentuates this interest. In addition, knowledge of the phase diagram has great significance for the technology of the separation of He^3 and He^4 ,¹ and makes possible the calculation of the change of concentration of the liquid phase, due to the transition of part of the He^3 into the vapor phase, in the quantitative investigation of the properties of this system.

Numerous attempts⁴⁻¹³ at the measurement of the dependence on concentration of the vapor pressure of the mixtures and the distribution coefficient of He^3 between liquid and vapor have not led to sufficiently accurate and complete data. Consequently, they do not permit the construction of the desired phase diagram. This is explained by the fact that, up to the present, only small quantities of the isotopic mixture have been used, the presence of equilibrium between vapor and liquid has not been maintained, and the effect of the HeII film has not been removed.

Having obtained an appreciable amount of mixtures of the helium isotopes with known content of He^3 , we set up a series of experiments to obtain sufficiently accurate data, which are necessary for the construction of the phase diagram.

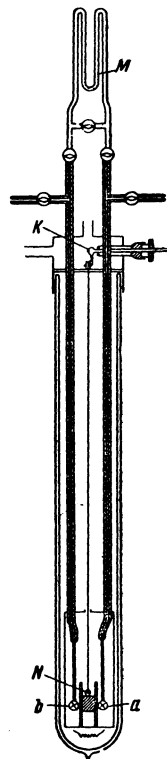


FIG. 1. Apparatus for measuring the vapor pressure of solutions of He^3 in He^4

2. APPARATUS AND METHOD OF MEASUREMENT

Inasmuch as we are discussing the liquid-vapor phase diagram, we must set up the dependence between the vapor pressure and the composition of the liquid and gaseous phases. Such data were obtained by the measurement of the vapor pressure of mixtures with different He^3 content in the liquid in a series of experiments, and by the measurement of the pressure at initial condensation of mixtures with various contents of He^3

in the gaseous phase in another series of experiments.

Measurements of the vapor pressure were carried out with the aid of the apparatus shown in Fig. 1.¹⁴ The mixture of isotopes with known He^3 content and ordinary helium (He^4) were condensed in the two glass globules *a* and *b*, equipped with light iron vanes. These vanes were put into vibratory motion by vertical displacement of the magnet *N*, which is accomplished by means of the crankshaft *K*, rotated by an electric motor at a speed of 12 rpm. The resulting agitation of the liquid led to a rapid establishment of equilibrium between the liquid and the vapor. With the aid of a differential manometer *M*, the difference in the vapor pressure Δp between the solution with known concentration of He^3 and the He^4 was measured. For work with mixtures with He^3 content up to 6.3%, the manometer was filled with oil, while mercury was used for the higher concentrations of He^3 . Measurement of the difference in vapor pressure in the manometer was obtained by the cathetometer KM-5, which enabled readings to be made to 0.001 mm. Before condensation, both the mixture of isotopes and the He^4 were led through coils submerged in liquid hydrogen, in which possible impurities were frozen out, so that both gases were completely pure upon entrance into the apparatus.

All parts of the apparatus, located above the globule with the mixture, had sufficiently small volume so that the space occupied by the vapor amounted to about 5 cm³. Usually, 350-400 cm³ of gas were condensed in the research with mixtures with content of He^3 up to 52.7% and about 200 cm³ in research with richer mixtures. Under such conditions, the impoverishment of the mixture due to the transition of part of the He^3 to the vapor state was inconsiderable and, consequently, one could assume in these experiments that the concentration of He^3 in the liquid was equal to the known concentration of He^3 in the gas up to its condensation. This circumstance was specially controlled by the saturation curves which were recorded at the time of condensation of the mixture of the isotopes, and which represented the dependence of Δp on the quantity *q* of the condensed gas. As the quantity of the mixture increases, a smooth increase in Δp was first observed; however, beginning approximately at 50 cm³ for low temperatures and with 150-200 cm³ at high temperatures, Δp is practically unchanged with further increase in *q*. Thus the quantity of the mixture ordinarily used guaranteed the small dependence of Δp on *q*, i.e., the in-

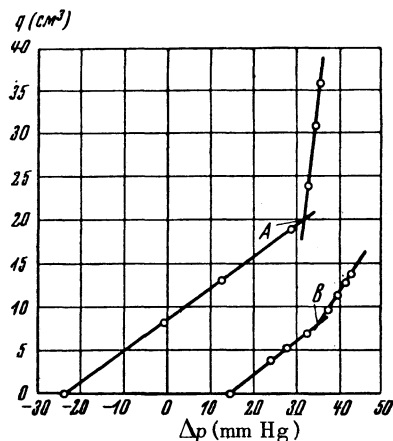


FIG. 2. Dependence of the pressure difference on the quantity of gaseous mixture supplied. The lower part of the graphs (up to the break) corresponds to gaseous state, the upper to the liquid. Point A: $T = 3,229^\circ\text{K}$, $X = 11.6\%$, $\Delta p = 31.4$; point B: $T = 1,865^\circ\text{K}$, $X = 73.4\%$, $\Delta p = 35.9$

significant impoverishment of the mixture with respect to the light isotope.

Establishment of equilibrium between the liquid and the vapor was achieved, as already pointed out, by the agitation of the liquid, and was also controlled by the method of reducing the dependence of Δp on time at constant temperature. Such an equilibrium was quickly established both in He II (3-4 min.) and in He I (10-15 min.). In addition to the presence of equilibrium between vapor and liquid, one noted the absence of hysteresis in going through the temperature interval above and below. In this case the data obtained in one experiment and on different days agreed very well.

The results obtained with mixtures of different content of He^3 , and in a wide temperature interval, made possible the establishment of the relation between the vapor pressure and the concentration of the liquid phase.

The connection between the vapor pressure and the composition of the gas phase was obtained by measurement of the pressure for initial condensation of the gas mixture with known content of the light isotope (dew point).¹⁵ These experiments were carried out with apparatus similar to that already described, adapted for the measurement of the vapor pressure. As before, two vessels were used, but now a definite portion of gas mixture of the isotopes was put in one of them, and liquid He^4 was put in the other. The pressure difference Δp was measured between these two vessels after introduction of each portion of the gas mixture

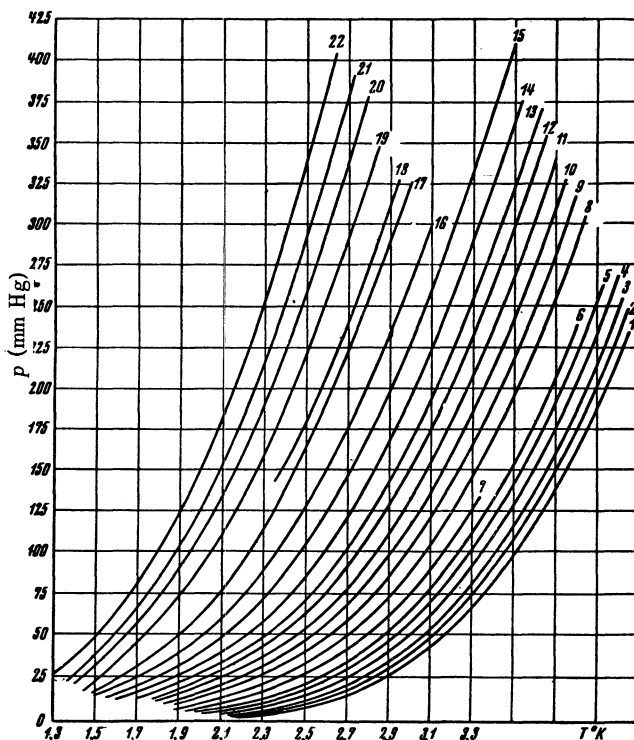


FIG. 3. Temperature dependence of vapor pressure for mixtures of isotopes of helium with different content of He^3 . Percent composition of He^3 in the mixture: 1—0; 2—0.4; 3—0.8; 4—1.9; 5—3.0; 6—4.0; 7—6.3; 8—8.3; 9—11.1; 10—13.4; 11—16.7; 12—19.2; 13—22.6; 14—23.9; 15—30.2; 16—38.3; 17—52.7; 18—56.3; 19—73.4; 20—82.4; 21—90.8; 22—100.0%

and the dependence of Δp on the amount of the given mixture q was constructed. The sharp break on the curve $\Delta p - q$ makes possible a precise determination of the dew point. It is natural that the measured pressure of onset of condensation is related to the mixture, supplied in the apparatus, for which the He^3 content is known, and it makes no sense to speak of what change there is in the concentration in this case. Two such typical curves are plotted in Fig. 2; one characterizes the mixture with He^3 content 11.6% ($T = 3.229^\circ \text{K}$), and the second, 73.4% ($T = 1.865^\circ \text{K}$). Usually, some amount of gas is supplied in the reservoir for the mixture until the pressure is close to the pressure for onset of condensation and only after this is the desired dependence recorded. Thus q in the graphs characterizes not the total amount of the mixture, but only part of it.

The vessel for the measurement of the dew point was changed depending on the concentration of the mixture investigated, since, as the concentration increased, i.e., with higher pressure for onset of condensation, the consumption of the mixture increased greatly. In experiments with mixtures with small amounts of He^3 , the volume of the vessel amounted to several cubic centimeters, but for

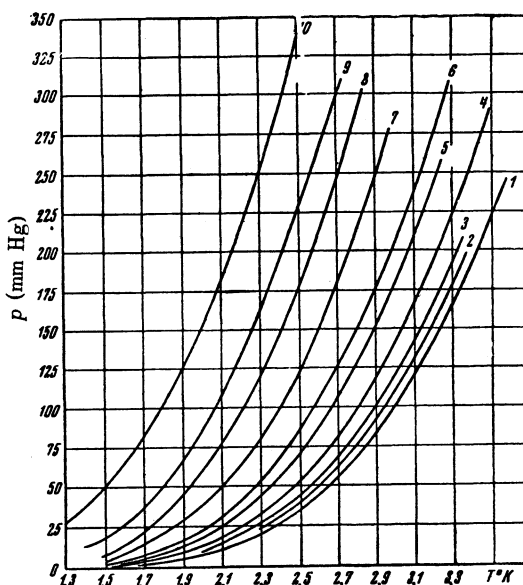


FIG. 4. Temperature dependence of the pressure at onset of condensation of mixtures of helium isotopes with different content of He^3 . Percent composition of He^3 in the mixture :

1—0; 2—1.9; 3—4.0; 4—11.6; 5—29.0; 6—35.4; 7—57.6; 8—73.4; 9—82.4; 10—100.0%

work with concentrated mixtures--about 1 cm.³ The data obtained for a given gas mixture at a particular temperature, with the use of reservoirs of different volumes, agreed well with one another.

The manometer for the measurement of Δp was filled with oil for work with low concentrations of the mixtures, and with mercury for rich He³ mixtures. The measurement was carried out with the same cathetometer KM-5. In order to exclude the effect of the position of the level of liquid helium in the dewar on the pressure in the vessel with the gas mixture, a tube, which joined this vessel with the manometer was embedded in the vacuum jacket.

The gaseous mixture of isotopes was brought into the apparatus by means of a calibrated Toepler pump. In these experiments, the mixture of isotopes and He⁴ were run through coils immersed in liquid hydrogen.

The temperature in the dewar was determined by the vapor pressure of the liquid helium with the use of the 1949 tables.¹⁴ Determination of the pressure by the manometer was also carried out in this case with the aid of a cathetometer, which is essential in the region of low temperatures, i.e., for small values of the vapor pressure. During the experiment, the pressure was kept constant with great accuracy, by means of an automatic regulator.¹⁷

3. RESULTS

By means of the above methods, the temperature dependence of the vapor pressure of twenty mixtures with He³ content from 0.4 to 90.8% was measured. The pressure at the onset of condensation of eight mixtures with He³ content ranging from 1.9% to 82.4% was also measured as a function of the temperature. The measurements were carried out in the interval 1.35-3.2°K for mixtures with He³ content up to 30.2%, and in the interval 1.35-2.7°K for the richer mixtures.

Part of the results obtained, which relate to the dependence of the vapor pressure of the mixture on temperature for different composition X_{liq} of the liquid are represented in the form of Table 1 and in Fig. 3. The analogous dependence for various compositions X_v of the vapor are shown in Table 2 and in Fig. 4 [the concentration was determined as $X = N_3 / (N_3 + N_4)$]. For convenience of observation, the curves in Figs. 3 and 4 are successively displaced to the right by 0.04°, except for curve 13 (Fig. 3) which is displaced by 0.08°

relative to curve 14. The dependencies for pure He⁴¹⁶ and He³¹⁸ have also been drawn in on the same curves for comparison purposes.

The accuracy of measurement of the difference in the vapor pressure was within 0.5% for small values of Δp and was appreciably larger for higher values of Δp . In experiments on the determination of the dew point, Δp was measured with less accuracy (2-3%). The concentrations of the isotope mixtures were known within 1.5-4% of the measured values.

The resultant data permit us to construct the phase diagram for the vapor-liquid system He³-He.⁴ Such a diagram is shown in Fig. 5 with the coordi-

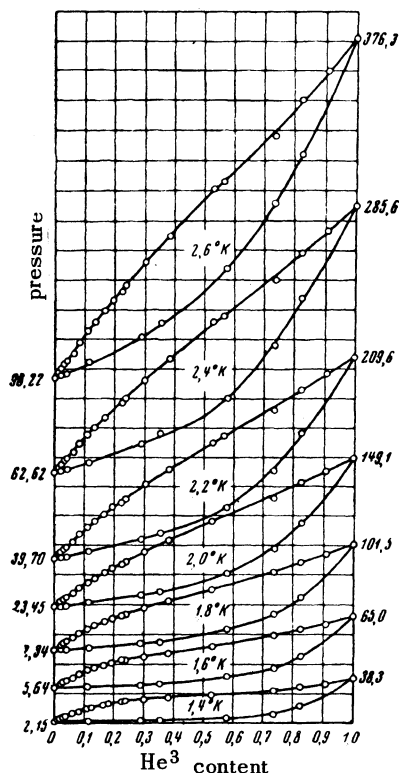


FIG. 5. Liquid-vapor phase diagram for the system of helium isotopes. Pressure in mm Hg.

nates pressure-concentration. In this drawing, a number of isotherms between 1.4 and 2.6°K are plotted. These isotherms have been displaced arbitrarily along the ordinate axis relative to one another, preserving the scale along this axis (one division corresponds to 25 mm Hg). For each isotherm the pressures for pure He³ and He⁴ are indicated. The reduced diagram, which is essentially the first detailed phase diagram of isotopic mixtures has a cigar shape like the diagrams of

the majority of ordinary liquid mixtures. In this case, as is seen in Fig. 5, the difference between the content of He^3 in the vapor and in the liquid increases with decrease in temperature.

Among the data in the literature on the vapor pressure and pressure at onset of condensation of He^3 - He^4 mixtures, the most complete are those of Sommers,¹⁸ in which measurements were carried out in the interval 1.25-2.15°K for a He^3 content in the liquid phase up to 13%, and in the vapor up to 78%. In Fig. 6 is shown a comparison of the results of the present work with the data of Sommers (crosses) which relate to the dependence of the vapor pressure on the composition of the liquid phase, and in Fig. 7, on the composition of the vapor. In this and in other cases, there is completely satisfactory

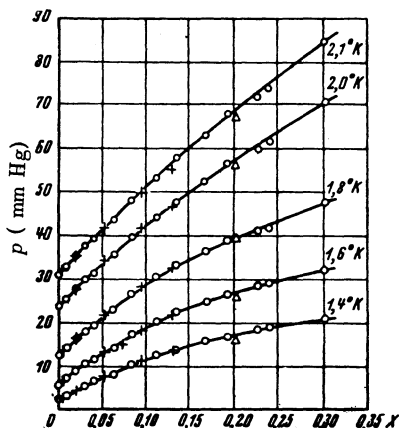


FIG. 6. Dependence of the vapor pressure on the composition of the liquid phase: \circ = results of the present research, \times = results of Sommers¹⁹, Δ = results of Weinstock, Osborne and Abraham.⁷

agreement. Along with this it is necessary to note that the formula assumed by Sommers for the calculation of the concentration of the gaseous phase from the known vapor pressure

$$X_v = (\Delta p / p) [1 + 0.080 \quad (1)$$

$$\times \{T - 1.100 + 0.600 (\Delta p / p)^3\}^2],$$

provides an inadequate description of the experimental data.

Figure 6 shows the results of measurement of the vapor pressure of mixtures of the isotopes of helium with a He^3 content of 20.3%, carried out by Weinstock, Osborne and Abraham.⁷ These results also agree well with ours.

Laying out the phase diagram, one can obtain data which characterize the distribution of He^3

between the vapor and the liquid. Such a distribution is described by the ratio X_v/X_l of the He^3 concentration respectively in the vapor and in the liquid. The dependence of this ratio on the tempera-

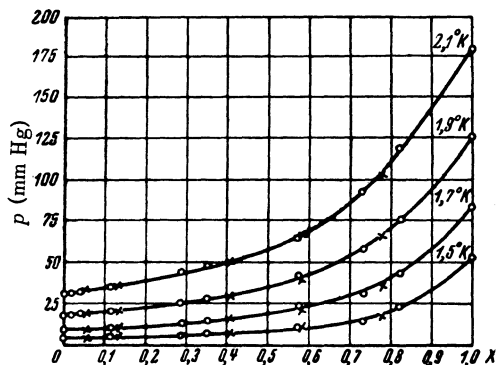


FIG. 7. Dependence of the vapor pressure on the composition of the gaseous phase: \circ = results of the present research, \times = results of Sommers.¹⁹

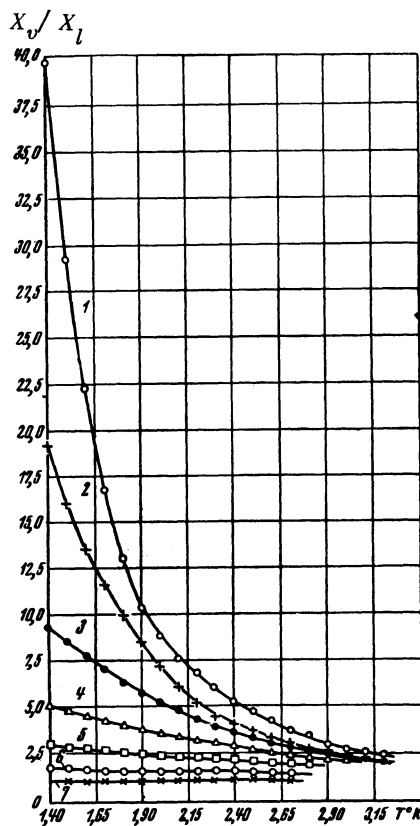


FIG. 8. Temperature dependence of the distribution of He^3 between the vapor and the liquid for different X_l . Curve 1 - $X_l = 0.4$; 2 - 3.0; 3 - 8.3; 4 - 16.7; 5 - 30.2; 6 - 52.7; 7 - 90.8.

ture for different X_l and on X_l for different temperatures is shown in Figs. 8 and 9. The computed values are given in Table 3. Inasmuch as these data were obtained, not by direct measurement, but from the diagram, the accuracy of the determination of X_v/X_l is not very great. It follows from the drawings that X_v/X_l decreases with rising temperature and with increase in X_l .

It follows directly from the form of the diagram that it differs appreciably from that for an ideal solution. In the entire region of concentration investigated, the vapor pressure is larger than would follow from the generalized rule of Raoult:*

$$p = X_l (p_3^0 - p_4^0) + p_4^0, \quad (2)$$

where p_3^0 and p_4^0 are the vapor tensions of pure He³ and He⁴ respectively.

In the region of low concentrations of He³, Henry's law is satisfied

$$p_3 = aX_l, \quad (3)$$

where p_3 is the partial pressure of He³.

For the linear portion of the curve showing the dependence of the vapor pressure on X_l (for small X_l), we can write

$$p = X_l (a - p_4^0) + p_4^0 \quad (4)$$

*In the earlier works, incorrect concentrations were given (not the fault of the authors). This led to erroneous conclusion of the positive and negative deviations from Raoult's law. We take this occasion to list the correct values:

Published, in %	Corrected concentrations, in %	Literature references
0,49	0,4	[14]
1,00	0,8	[14, 20]
2,40	1,9	[14, 15, 20, 21]
4,23	3,0	[14, 20]
5,18	4,0	[14, 15]
8,08	6,3	[14]

Published, in %	Corrected concentrations, in %	Literature references
14,5	11,6	[15]
31,7	25,8	[21]
34,7	29,0	[15]
37,0	31,2	[21]
41,8	35,4	[15]
63,8	57,6	[15, 21]

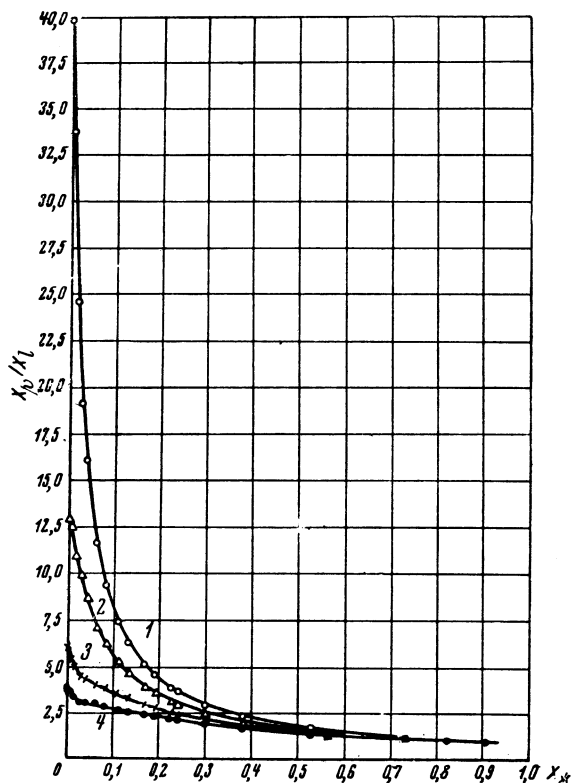


FIG. 9. Dependence of the distribution of He³ between the vapor and the liquid in the composition of the liquid phase X_l for different temperatures. Curve 1— $T=1.4$; 2—1.8; 3—2.3; 4—2.7 °K

and we can determine the constant a and its temperature dependence from the tangent of the curve $p-X_l$. The ratio a/p_3^0 characterizes the departure of the solution from the ideal, inasmuch as this ratio is equal to unity for an ideal solution. The dependence of a/p_3^0 on temperature is shown in Fig. 10, from which it follows that the maximum deviation from ideal is observed at low

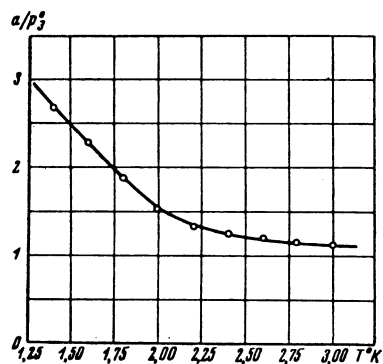


FIG. 10. Temperature dependence of the ratio of the Henry's law constant to the vapor pressure of He³.

TABLE I (continued)

X_l	T	p	X_l	T	p	X_l	T	p
11,1	1,635	21,32	19,2	2,384	106,13	23,9	3,136	333,87
	1,730	26,16		2,530	134,41		3,211	363,31
	1,842	32,96		2,656	162,07		1,336	15,54
	1,936	39,42		2,805	200,80		1,362	16,39
	2,015	44,96		2,900	228,16		1,406	18,21
	2,020	45,62		3,028	269,00		1,498	22,65
	2,086	51,88		3,155	314,27		1,579	27,15
	2,125	56,13		3,219	339,33		1,710	35,07
	2,148	58,71		1,360	14,61		1,806	41,82
	2,180	62,49		1,379	15,59		1,826	43,10
	2,200	65,97		1,474	19,19		1,873	47,81
	2,298	79,37		1,558	23,60		1,908	51,12
	2,476	108,64		1,650	28,57		1,948	54,97
	2,699	154,57		1,706	32,10		2,038	65,46
	2,796	178,77		1,752	35,06		2,149	80,07
	2,904	207,62		1,839	41,04		2,184	85,28
	3,023	243,69		1,883	44,91		2,198	88,61
3,215	309,33	1,930	48,58	2,279	100,87			
13,4	1,342	11,63	1,974	53,62	2,458	138,48		
	1,399	12,74	2,027	59,13	2,601	171,54		
	1,469	15,99	2,081	65,43	2,754	213,45		
	1,553	19,64	2,128	71,07	2,885	253,67		
	1,628	23,15	2,175	77,42	3,035	305,70		
	1,725	28,48	2,233	87,67	3,206	372,35		
	1,807	33,34	2,278	94,66	30,2	1,316	16,23	
	1,844	35,89	2,376	111,85		1,341	17,11	
	1,944	42,87	2,469	129,86		1,380	18,70	
	1,995	46,88	2,571	152,18		1,423	21,59	
	2,045	51,43	2,688	180,74		1,485	24,60	
	2,087	56,30	2,799	211,32		1,537	27,80	
	2,122	60,15	2,900	241,21		1,597	31,24	
	2,156	64,07	2,999	273,69		1,649	34,40	
	2,181	67,19	3,107	312,17		1,722	39,73	
	2,199	70,59	3,202	348,09		1,735	40,71	
	2,301	85,25	22,6	1,336		15,14	1,784	45,58
2,409	103,12	1,353		15,68		1,830	49,96	
2,501	119,52	1,460		20,74		1,911	58,94	
2,600	140,17	1,502		22,80		1,972	66,74	
2,701	163,41	1,554		25,64		1,992	69,14	
2,802	189,58	1,646		30,52		2,069	79,85	
2,884	212,07	1,704		33,99		2,126	88,03	
3,063	267,83	1,802		40,58	2,170	95,37		
3,215	321,79	1,831		42,53	2,202	102,22		
16,7	1,388	14,86		1,864	45,14	2,218	105,97	
	1,463	17,84		1,905	48,88	2,302	121,12	
	1,496	19,23		1,968	55,53	2,375	135,95	
	1,596	23,86		2,007	59,75	2,508	166,50	
	1,701	29,80		2,068	66,98	2,655	205,91	
	1,771	34,01		2,101	71,32	2,773	241,97	
	1,849	39,14		2,126	74,71	2,878	276,70	
	1,896	42,53		2,173	81,47	3,004	322,59	
	1,930	45,06	2,202	86,68	3,102	361,65		
	1,955	47,15	2,294	101,82	3,205	404,75		
	1,980	49,79	2,414	124,29	38,3	1,331	18,99	
	2,037	55,60	2,474	136,54		1,334	18,95	
	2,107	63,35	2,552	154,02		1,389	21,76	
	2,138	67,25	2,611	168,17		1,422	23,21	
	2,174	71,79	2,719	196,36		1,471	25,80	
	2,189	75,00	2,809	222,64		1,543	30,11	
	2,213	78,15	2,906	252,03		1,570	32,27	
2,298	90,91	3,052	301,99					

TABLE I (continued)

X_e	T	p	X_e	T	p	X_e	T	p		
38,3	1,641	37.91	56,3	2,163	127.30	82,4	2,710	340.66		
	1,715	44.94		2,193	136.18		1,380	28.56		
	1,757	49.06		2,254	150.86		1,392	30.15		
	1,804	53.89		2,330	171.00		1,490	41.09		
	1,857	60.38		2,390	186.91		1,595	53.71		
	1,949	72.69		2,474	211.68		1,694	68.86		
	2,046	86.79		2,540	232.01		1,808	88.66		
	2,090	94.65		2,617	257.47		1,894	105.38		
	2,141	102.24		2,669	275.95		1,996	128.22		
	2,170	107.71		2,737	301.49		2,085	149.67		
	2,194	113.66		2,786	320.42		2,176	172.34		
	2,199	114.78		73,4	1,400		27.27	90,8	1,392	31.26
	2,253	125.72			1,411		26.52		1,405	32.49
	2,306	137.19			1,422		26.89		1,507	45.32
	2,331	142.88			1,515		38.52		1,601	58.41
	2,408	161.34			1,596		48.30		1,678	70.71
	2,488	181.52			1,691		61.06		1,809	94.55
	2,554	199.62			1,806		79.06		1,906	115.67
	2,604	213.13			1,897		95.09		2,004	138.61
	2,680	237.15			2,007		117.08		2,097	163.04
2,757	262.36	2,108	140.19		2,139	175.30				
2,856	296.94	2,152	150.56	2,182	186.34					
52,7	1,350	21.06	2,177	157.95	2,193	192.94				
	1,356	21.83	2,194	162.98	2,259	214.74				
	1,437	26.70	2,257	181.08	2,303	229.99				
	1,471	28.94	2,306	195.48	2,395	263.90				
	1,519	34.15	2,404	226.82	2,507	309.00				
	1,562	36.58	2,499	259.30	2,586	343.55				
	1,592	40.29	2,606	298.89	2,648	371.96				
	1,652	45.84								
	1,686	49.87								
	1,728	54.79								
	1,803	64.71								
	1,877	75.24								

temperatures.

There is great interest in the comparison of the experimental results with the dependence of the equilibrium vapor pressure p on the composition of the liquid and gaseous phases obtained from purely thermodynamic considerations under the assumption of an ideal vapor:^{2,2}

$$X_l = X_v - X_n(1 - X_n) \partial \ln p / \partial X_n. \quad (5)$$

The results of such a comparison are shown in Fig. 11. These results are plotted for the isotherms 1.8 and 2.6°K by means of a calculation (according to the above formula) of the dependence of the vapor pressure on the composition of

the gaseous phase X_v (the corresponding points are marked with crosses). For low temperatures and small concentrations, satisfactory agreement is observed with experiment, while for high concentrations and higher temperatures, a divergence is observed, occasioned by the non-ideal character of the vapor.^{2,3}

In conclusion, let us take this occasion to express our appreciation to N. E. Alekseevskii and his co-workers for carrying out a great deal of work connected with the determination of the content of He³ in the helium isotope mixtures that were used. We also thank L. D. Landau and I. M. Lifshitz for their criticism of the results and B. G. Lazarev and E. S. Borovik for their advice.

TABLE 2

Temperature dependence of the pressure for onset of condensation ($\rho, \text{mm Hg}$)
for mixtures with different content of He^3 ($X_v, \%$)

X_v	T	p	X_v	T	p	X_v	T	p
1.9	2,037	26,4	35,4	1,986	31,5	73,4	1,998	51,4
	2,166	37,2		2,349	78,4		2,101	66,5
	2,369	59,7		2,533	112,7		2,444	137,4
	2,520	81,5		2,676	146,3		2,652	204,4
	2,776	129,3		2,826	187,0		2,825	267,4
	3,033	193,5		3,012	248,3			
4,0	1,748	10,4	57,6	1,404	3,3	82,4	1,451	9,5
	2,077	30,2		1,836	21,9		1,691	29,6
	2,411	66,4		2,044	40,2		1,865	51,3
	2,732	122,3		2,159	54,4		2,254	127,1
	3,040	198,7		2,298	76,4		2,489	199,3
				2,516	121,1		2,731	294,8
11,6	1,350	1,9	57,6	2,706	167,6	82,4	1,412	16,1
	1,795	14,0		2,808	197,0		1,611	30,3
	2,131	38,0		2,899	225,7		1,818	59,0
	2,309	58,7		3,100	299,7		2,106	119,7
	2,628	111,8		3,355	418,6		2,283	173,7
	2,853	164,2					2,404	210,5
	3,229	281,6					2,640	296,3
29,0	1,410	3,3		1,581	13,8			
				1,811	31,5			
	1,768	15,5		1,963	47,8			

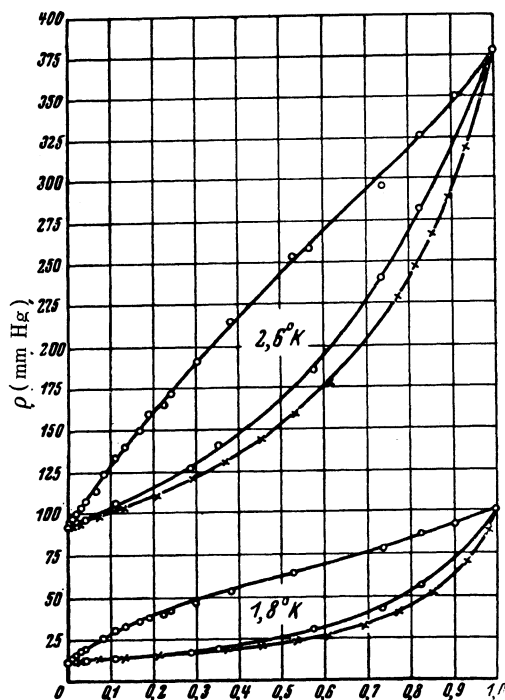


FIG. 11. Phase diagram for liquid-vapor of $\text{He}^3 - \text{He}^4$. Comparison of the experimental results with Eq. 5. The points obtained by calculation are denoted by crosses.

TABLE 3

Distribution of He^3 between vapor and liquid (X_v/X_l) for different compositions of the liquid phase X_l and for different temperatures.

X_l	X_v/X_l																		
	4.4° K	4.5° K	4.6° K	4.7° K	4.8° K	4.9° K	2.0° K	2.4° K	2.5° K	2.6° K	2.7° K	2.8° K	2.9° K	3.0° K	3.1° K	3.2° K			
0.004	39.75	29.25	22.25	16.75	13.00	10.25	8.75	7.50	6.75	6.00	5.25	4.75	4.25	3.75	3.50	3.00	2.75	2.62	2.50
0.008	33.75	25.62	20.00	15.87	12.62	10.12	8.37	6.87	6.00	5.37	4.75	4.37	4.00	3.62	3.25	3.00	2.75	2.62	2.50
0.019	24.53	19.63	16.05	13.26	11.00	9.21	7.79	6.68	5.74	5.05	4.42	4.05	3.68	3.37	3.05	2.84	2.63	2.47	2.26
0.030	19.17	16.03	13.53	11.57	9.93	8.43	7.10	6.00	5.10	4.43	4.03	3.70	3.30	3.10	2.87	2.67	2.47	2.27	2.07
0.040	16.40	13.82	11.92	10.22	8.67	7.47	6.42	5.50	4.80	4.25	3.97	3.62	3.20	3.07	2.82	2.57	2.40	2.22	—
0.063	11.67	10.43	9.24	8.11	7.11	6.35	5.75	5.21	4.59	3.98	3.75	3.44	3.17	3.00	—	—	—	—	—
0.083	9.34	8.52	7.76	7.04	6.24	5.70	5.22	4.77	4.30	3.87	3.54	3.25	3.04	2.89	2.73	2.54	2.37	2.20	2.06
0.111	7.32	6.76	6.29	5.79	5.33	4.90	4.57	4.19	3.85	3.61	3.31	3.05	2.86	2.71	2.60	2.45	2.31	2.17	2.04
0.134	6.22	5.79	5.42	5.04	4.68	4.36	4.07	3.79	3.51	3.33	3.11	2.90	2.72	2.59	2.48	2.36	2.25	2.14	2.04
0.167	5.12	4.82	4.53	4.24	3.96	3.74	3.53	3.32	3.12	2.99	2.84	2.66	2.52	2.43	2.33	2.19	2.10	—	—
0.192	4.53	4.28	4.03	3.80	3.58	3.39	3.22	3.04	2.87	2.79	2.66	2.50	2.39	2.33	2.23	—	—	—	—
0.226	3.91	3.71	3.52	3.34	3.15	3.01	2.88	2.73	2.61	2.54	2.44	2.33	2.24	2.19	2.10	—	—	—	—
0.239	3.72	3.53	3.36	3.19	3.02	2.89	2.76	2.64	2.53	2.46	2.37	2.27	2.19	2.14	2.05	—	—	—	—
0.302	3.00	2.87	2.75	2.64	2.53	2.44	2.35	2.27	2.20	2.15	2.08	2.03	1.96	1.93	1.87	—	—	—	—
0.383	2.39	2.31	2.24	2.17	2.11	2.05	1.99	1.94	1.90	1.86	1.81	1.78	1.73	1.71	1.68	—	—	—	—
0.527	1.78	1.73	1.69	1.66	1.63	1.61	1.58	1.55	1.53	1.51	1.48	1.47	1.44	1.43	1.41	—	—	—	—
0.563	—	—	—	—	—	—	—	—	1.46	1.44	1.42	1.41	1.39	1.37	1.36	—	—	—	—
0.734	1.31	1.29	1.28	1.26	1.26	1.24	1.23	1.22	1.21	1.20	1.20	1.19	1.18	1.17	—	—	—	—	—
0.824	1.18	1.17	1.16	1.15	1.15	1.14	1.14	1.13	1.12	1.12	1.12	1.11	1.11	1.10	—	—	—	—	—
0.908	1.09	1.08	1.08	1.07	1.07	1.07	1.06	1.06	1.06	1.06	1.05	1.05	1.05	1.05	—	—	—	—	—

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133