THE MAGNETIC SUSCEPTIBILITY OF HELIUM, NEON, ARGON, AND NITROGEN

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Abstract

The apparatus described in a recent paper by Wills and Hector[1] for the measurement of the magnetic susceptibilities of gases, has been rebuilt so as to enable the temperature to be controlled to .02° and the sensitivity of the method increased. The gases used were all carefully purified, and spectroscopic examination showed no oxygen lines. The results obtained for the volume susceptibilities at 20°C and 760 mm pressure for helium, neon, argon and nitrogen are -0.780, -2.77, -7.52, and -4.91, respectively, all times 10^{-10}. They are probably accurate to within 2 per cent. These results are of the order of magnitude required by Pauli's modification of the Langevin theory of diamagnetism and also agree with values predicted by Joos from the electron arrangements.

Introduction

In a previous paper by A. P. Wills[1] and the writer a method was developed for determining the susceptibility of fairly strong magnetic gases by balancing them magnetically against a water solution of nickel chloride. It was further shown that the method could be extended to the case of the nearly neutral diamagnetic gases by balancing the gases magnetically at various densities (pressures) against the same solution at slightly different temperatures, since the magnetic temperature coefficient of the solutions was large and that of these gases relatively negligible. The method was carried out for the cases of hydrogen and helium, but only tentative results were obtained for the latter gas because of its extremely small value. The present research involves perfecting the details of the method in order to be able to determine such small susceptibilities as that of helium, and applying the method to the measurement of the other gases, argon, neon, and nitrogen.

It was shown in the previous paper that the working formula for this method of determining the susceptibilities of diamagnetic gases is:

$$\kappa_0 = -\frac{P_0\theta}{\theta_0}\;\frac{\rho_w\chi_w}{1+R-K}\;\frac{dR_0}{d\theta}\;\frac{\Delta\theta}{\Delta P} \qquad (1)$$

where κ_0 is the volume susceptibility at the absolute temperature θ_0 and standard pressure P_0 in mm mercury, and R_0 is the ratio of mass of

[1] A. P. Wills and L. G. Hector, Phys. Rev. **23**, 209 (Feb. 1924)

water to mass of nickel chloride for a magnetically neutral solution at the absolute temperature θ at which the experiment is performed. ρ_w is the density and χ_w the volume susceptibility of water at the temperature θ.

R is the actual ratio of the mass of water to mass of nickel chloride in the solution used, and may be replaced by R_0 without appreciable error for these nearly neutral solutions. K is a constant depending solely on the chemical concentration and density of the mother solution from which all the solutions used were made by dilution by weighing.

The mother solution used was the same as that employed in the previous research, and hence we have the same value of K, 0.88102. We have also the same Curie constant ($C=R_0\theta$) for this solution of nickel chloride. As before specified, there was about 0.08 per cent cobalt chloride in this solution, and the Curie constant obtained was C=13890. The value of χ_w is taken to be -0.720×10^{-6}. If we insert these values in Eq. (1) we have for standard pressure (760 mm Hg) and a temperature of 20°C

$$\kappa_0 = -0.02594 \frac{\rho_w}{0.1190\,\theta + 13890} \frac{\Delta\theta}{\Delta P} \tag{2}$$

where $\Delta\theta/\Delta P$ is to be determined by experiment and expressed in degrees per mm Hg pressure. The temperature θ must be observed at the same time and the corresponding value of ρ_w taken from a table of water density.

The method employed was to determine a fairly large number of values of θ and the corresponding values of P for a given solution. These values were then plotted, and the quantity $\Delta\theta/\Delta P$ determined from the graph by an approximate least squares solution.

PROCEDURE

Oxygen coming from the air dissolved in the solution formed a principal source of trouble at the beginning of our attempts to measure the diamagnetic gases. However, by means of a vacuum pump a pressure of about 1 cm of mercury was held on the balance for about one half hour at the beginning of a run. This process hastened the removal of dissolved air from the solution. The apparatus was then flushed with hydrogen for from two to three hours, and then with the gas to be measured for about one half hour.

The apparatus was similar to that used in the previous research with the addition of a double-walled house about the entire magnet. The temperature of the air within the house was controlled to within plus or minus 0.02°C by means of a bi-metallic strip which applied potential to the grid of a three electrode tube, in the plate circuit of which was a high resistance relay. Temperature adjustment was effected by means of a bank of lamps controlled by the relay, and by means of pails filled with ice and placed in openings in the top of the house. An electric fan kept all the air in the house in circulation.

The gases (except neon) were supplied to us under high pressure in steel cylinders. Pressures, except for neon, were read by means of an ordinary gauge calibrated against the mercury manometer described in the previous paper. Absolute values of temperature were read from a mercury thermometer calibrated to 0.02°C, placed between the poles of the magnet, very near to the balance. The small variations in the temperature were read from the constant deflections produced on a galvaometer by means of a copper-constantin thermopile. One set of junctions was kept in a Dewar bottle filled with ice and water, and the other set was wrapped about the horizontal tube of the balance and protected from the air by cotton wool and tape, so that variations in temperature would come from the liquid within. The temperature variations in the liquid were produced by slightly varying the temperature of all the air inside the double-walled house. These variations were small, seldom exceeding 0.2 or 0.3° at a time.

All the gases measured were examined spectroscopically for oxygen, but in no case were any oxygen lines observed.

Helium

The helium supplied to us contained about 8 per cent nitrogen. It was purified by passing it through a long tube filled with magnesium granules and kept at a dull red heat by means of an electric furnace. This procedure served to remove any traces of oxygen as well as the nitrogen.

The following tables give the data from which the graphs and calculations were made. Galvanometer readings and gauge pressure readings are omitted and only the corresponding columns of corrected pressures and temperatures are given. The numbers in the temperature column are in centigrade degrees, but are referred to an arbitrary zero which is different in the different tables. Pressures are in mm Hg at 0°C.

Fig. 1 shows the $(\theta - P)$ graph for only one set of data for each gas. All the values of $\Delta\theta/\Delta P$ given have, however, been taken from similar graphs of the various sets of data given in this paper.

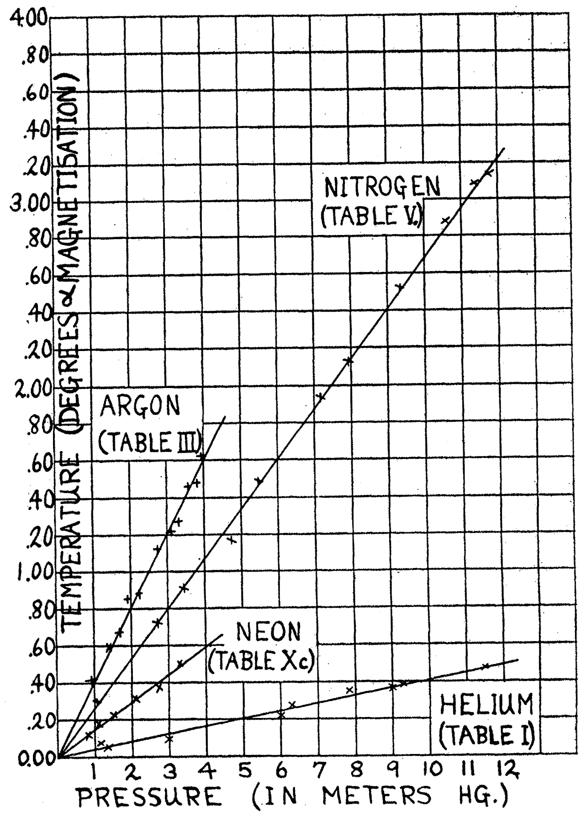

Fig. 1.

TABLE I

Results for helium

Pressure	Temperature
1230mm	.94°
6000	1.11
9000	1.26
11440	1.36
9280	1.27
7870	1.25
6200	1.15
2930	.99
1180	.96

TABLE II

Results for helium

Pressure	Temperature
1180mm	3.17°
4950	3.31
8450	3.46
10880	3.70
10875	3.64
10570	3.58
7770	3.51
5950	3.46
5200	3.43
3820	3.34
3220	3.32
2400	3.31
1230	3.26
930	3.25

From the data of Tables I and II with the aid of Eq. (2) we find the following values

	θ	ρ_w	$\Delta\theta/\Delta P$	κ_0
(I)	292.2°K	.9985	4.12×10^{-5}	-0.766×10^{-10}
(II)	294.1°	.9980	4.28	-0.795
			Mean	-0.780×10^{-10}

Argon

The argon as supplied to us contained about 4.5 percent nitrogen and 0.5 per cent oxygen. The purifying train consisted of heated tubes, one filled with magnesium granules, the other with copper filings which had previously been oxidized and reduced.

Table III

Results for argon

Pressure	Temperature
1680mm	1.86°
2250	2.11
3320	2.47
3875	2.69
3950	2.82
3580	2.67
3080	2.41
2750	2.34
1980	2.07
1380	1.80
990	1.62

Table IV

Results for argon

Pressure	Temperature
1375mm	.83°
4740	2.13
4920	2.38
4590	2.12
4180	2.03
3500	1.99
3120	1.79
2850	1.63
2600	1.46
2140	1.26
1680	1.07
1375	.91
1200	.86
1080	.74
900	.72

From the data of Tables III and IV, with the aid of Eq. (2), we obtain the following values

	θ	ρ_w	$\Delta\theta/\Delta P$	κ_0
(III)	291.7°K	.9985	4.10×10^{-4}	-7.63×10^{-10}
(IV)	290.1°	.9989	3.98	-7.41
			Mean	-7.52×10^{-10}

Nitrogen

The nitrogen as supplied to us was supposed to be better than 99.9 percent pure, but as a final precaution against oxygen we passed it through a heated tube filled with oxidized and reduced copper filings.

Table V

Results for nitrogen

Pressure	Temperature
4720mm	2.68°
7140	3.43
10570	4.38
11340	4.59
11700	4.63
9330	4.02
7970	3.64
5400	2.98
2700	2.23
1030	1.80
3380	2.40

Table VI

Results for nitrogen

Pressure	Temperature
3710mm	1.58°
6810	2.15
8220	2.63
9890	3.16
11340	3.48
11640	3.56
10410	3.28
8890	2.93
7250	2.48
5750	2.02
3250	1.45
1860	1.11
1230	.88

Table VII

Results for nitrogen

Pressure	Temperature
7250	3.44°
9950	4.33
11340	4.75
8030	3.93
5350	3.20
2700	2.49
1320	2.08

From the data of Tables V, VI, and VII, with the aid of Eq. (2) we find the following values

	θ	ρ_w	$\Delta\theta/\Delta P$	κ_0
(V)	291.2°K	.9986	2.68×10^{-4}	-4.98×10^{-10}
(VI)	290.6°	.9987	2.57	-4.78
(VII)	291.4°	.9986	2.67	-4.97
			Mean	-4.91×10^{-10}.

Neon

The neon was purified by passing it through a trap packed with charcoal and immersed in liquid air. Quantitative chemical analysis showed no oxygen present, but there was a small amount of residual nitrogen and some helium. These impurities were estimated at 2 per cent or less nitrogen and 3 per cent helium. Such a mixture would have a susceptibility so near that obtained for neon that any errors arising from considering the mixture to be 100 per cent neon would be within the experimental limits of precision. As a final precaution against oxygen a tube of hot reduced copper filings was kept in the gas train throughout the measurements.

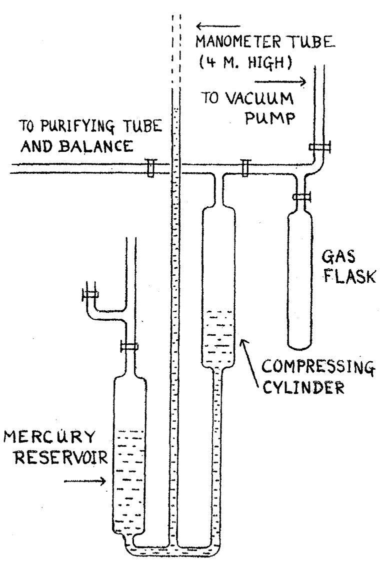

Fig. 2. Apparatus used in compressing neon.

The neon was supplied to us in 350 cc glass flasks at atmospheric pressure. Fig. 2 shows the method of compressing this gas in the balance without any opportunity of introducing impurities.

TABLE VIII

Results for neon

(a) Pressure	Temp.	(b) Pressure	Temp.	(c) Pressure	Temp.
2017mm	2.53°	1867mm	2.65°	3532mm	2.95°
1349	2.44	1290	2.62	2697	2.84
910	2.33	896	2.57	1808	2.75
1379	2.47	2236	2.72	871	2.60
1967	2.52	2824	2.82		
3572	2.82	3074	2.90		
3213	2.76	3562	2.95		
2655	2.72				
2117	2.63				

TABLE IX

Results for neon

(a) Pressure	Temp.	(b) Pressure	Temp.
808mm	1.77°	848mm	1.91°
908	1.80	1526	2.02
1906	1.91	2305	2.14
2964	2.11	3053	2.26
3313	2.19	3323	2.29
2405	2.06	2305	2.16
1576	1.95	987	1.95
848	1.84		

TABLE X

Results for neon

(a) Pressure	Temp.	(b) Pressure	Temp.	(c) Pressure	Temp.
836mm	1.86°	796mm	1.99°	816mm	2.03°
1892	1.99	1922	2.12	1484	2.13
2919	2.13	3248	2.34	2760	2.29
3288	2.27	3059	2.30	3284	2.41
2092	2.06	2172	2.19	2042	2.22
796	1.89	816	2.02	1055	2.09

From these data with the aid of Eq. (2) we find

		θ	ρ_w	$\Delta\theta/\Delta P$	κ_0
VIII	(a)	291.0°K	.9987	1.72×10^{-4}	-3.20×10^{-10}
	(b)	291.3°	.9986	1.56	−2.90
	(c)	291.4°	.9986	1.26	−2.34
IX	(a)	292.3°	.9985	1.51	−2.81
	(b)	292.4°	.9984	1.53	−2.85
X	(a)	292.8°	.9983	1.48	−2.75
	(b)	293.0°	.9983	1.35	−2.51
	(c)	293.0°	.9983	1.47	−2.73
				Weighted mean	$-277.\times10^{-11}$

In obtaining the mean, the mean values from each of the three tables were given equal weight.

TABLE XI

Volume susceptibilities at 20° C and 760mm pressure

	$\kappa_0\times10^{10}$
Helium	−0.780
Neon	−2.77
Argon	−7.52
Nitrogen	−4.91

The neon, argon, and nitrogen were made by fractional reduction of liquid air by the Air Reduction Company of New York City. I am indebted to Dr. F. J. Metzger of this company for providing me with exceptionally pure samples for our measurements. In the case of argon and nitrogen, which were furnished us under high pressure, water lubricated compressors were used to avoid contamination with oil vapors. The helium was provided by the Bureau of Aeronautics, Navy Department.

Sensitivity of Apparatus and Precision of Measurements

A variation of plus or minus about 0.03° from the ideal zero setting corresponded to the smallest magnetic difference for which a lack of magnetic balance could be observed. The corresponding change in the susceptibility of the solution is about 0.7×10^{-10}. With the field used (25,000 gauss) and a tube of diameter 4 mm, this gives a force of about 1/300 dyne as the limit of the sensitivity of the device. These figures give some idea of the dependability of the individual points determined. But the slope of a line on the (θ,P) graph is, of course, determined from a number of points. Judging from the agreement of the independent determinations, the mean values are probably accurate within ±2 per cent. The accuracy of the results depends also on the value of the susceptibility of water, which I have assumed to be -0.72×10^{-6} plus or minus one half of one per cent.

Discussion of Results

Pauli[2] has shown, by a modification of the Langevin theory of diamagnetism, that the order of magnitude of the susceptibility of helium and argon as based on the knowledge of atomic magnitudes from other sources should be less than -2×10^{-10} for helium at 0°C and between -2.7 and -8.1×10^{-10} for argon at 0°C. By a comparison of data on the susceptibilities of ions having similar electron arrangements, Joos[3] has also predicted values for these gases, and obtained -1.3×10^{-10} for helium at 0°C and -7.8×10^{-10} for argon at 0°C. An extension of his method and data would give -3.9×10^{-10} for neon at 0°C. The agreement between the experimental values and these predicted orders of magnitude is striking.

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Department of Physics,
Columbia University,
June 10, 1924.

[2] W. Pauli, Jr. Zeit. f. Physik **2**, 201 (1920)
[3] George Joos, Zeit. f. Physik **19**, 347 (1923)