28. *The Determination of Magnetic Susceptibility by the Gouy Method.*

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An apparatus is described for determining the magnetic susceptibility at room temperatures of pure liquids and solutions. It has been found capable of giving reproducible results with an accuracy of at least 1 part in 600 with diamagnetics. The following values have been found for $-10^6\chi$: water 0·7200 ± 0·0002, benzene 0·7023 ± 0·0007, acetone 0·5806 ± 0·0008.

The object of this paper is to describe the construction and operation of an apparatus for the measurement of magnetic susceptibility at room temperature. This equipment has been used in these laboratories for a few years and has been found capable of giving reproducible results with an accuracy of at least 1 part in 600 with diamagnetics. It consists essentially of an electromagnet mounted under an air-damped semimicro-balance with automatically adjusted riders. A thin brass rod is attached to the left-hand balance pan; it passes freely through a hole in the base and ends in a hook. From this hook hangs the specimen tube which contains the substance under examination. The general arrangement is shown in Fig. 1.

The magnet is a copy of that described by Bates and Lloyd Evans (*Proc. Physical Soc.*, 1933, **45**, iii, No. 248; p. 425) and was constructed in the electrical engineering department of this College. We are much indebted to Dr. Lloyd Evans for supervising its construction and for help and advice in its operation. The coils consist of cotton-covered wire wound on paxolin spacers, and are cooled by transformer oil which a pump circulates round the coils and through a water cooler. This arrangement gave very effective cooling; a current of 18 amps. could be used in the coils for 15 minutes without causing a rise of more than 1° in the temperature recorded by a thermometer close to the specimen. The interpole distance was usually 3·1 cm.; this comfortably accommodated the glass draught-screen inside which the specimen tube hung freely. With a current of 18·0 amps. in the coils the field in the gap was approximately 8000 oersteds. This current was read with an accuracy of ±0·1 amp. on a Western ammeter; since a current of this magnitude produced approximate saturation of the coil a small error in adjusting the current caused a much smaller variation in the field intensity. This large current was drawn from the D.C. mains and controlled by a number of Zenith resistances in parallel; one of these with wheel and worm gear was used to make final adjustment of the current to 18·0 amps. The choice of suitable material for the core caused the residual field, when no current passed, to be negligible. To minimise hysteresis effects the current was switched on and off ten times before a measurement was made. For this purpose a large double-pole knife-switch was used as the large inductance of the coils caused considerable arcing at " break ".

The magnet rested on a slate slab supported by brick pillars cemented to the foundations of the laboratory; the balance was supported on a strong table above it. A hole in this table carried the male half of a standard glass joint; the female part of the joint was attached to a glass tube about 3 cm. in diameter which formed a draught screen. A brass rod from the bottom of the left-hand balance pan extended to this ground joint so that the specimen could be suspended and the draught screen placed around it. The small dotted circle in Fig. 1 indicates a side tube carrying a thermometer.

A number of experiments with specimens of powders packed in cylindrical glass tubes led to the conclusion that reproducible packing within 2% could not be obtained. Hence measurements with powders were abandoned and pure liquids or solutions used in subsequent work.

FIG. 1.

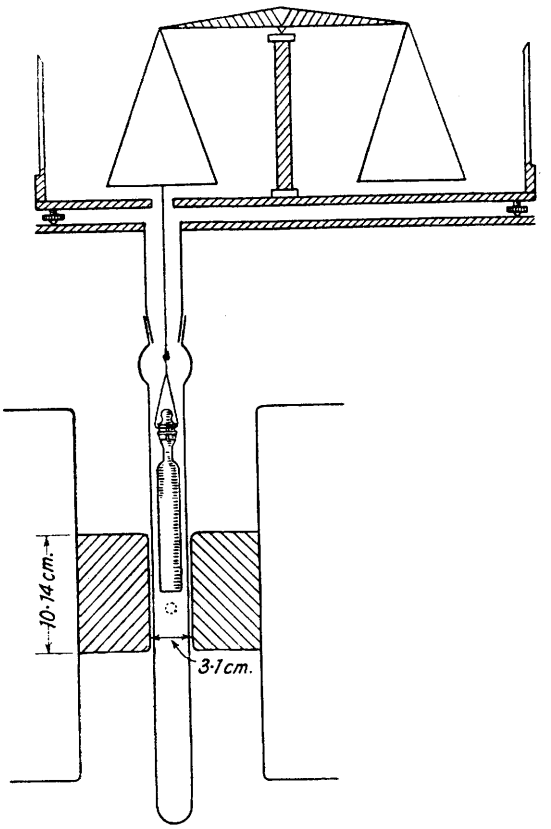
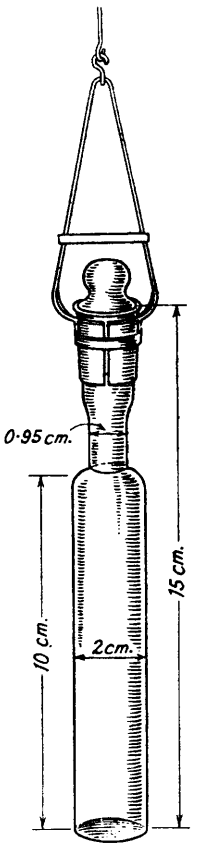


FIG. 2.



The experimental tube used had the shape shown in Fig. 2 and was made of clear fused silica. Glass has frequently been used for such tubes and gives a much smaller value for the pull on the empty vessel; this, however, is due to the opposing effects of its diamagnetic and its paramagnetic constituent. Since the susceptibility of the latter varies approximately inversely with the absolute temperature, the net effect in the glass has a large temperature coefficient and appreciable variations were found when the room temperature varied between summer and winter conditions. With silica tubes such differences were not observed.

The tube was filled to a reference mark in the neck which was about 9·5 mm. in diameter. Corrections for variation in shape of the meniscus with different liquids were negligibly small. The tube was suspended from the brass rod by means of a fitting of feebly magnetic phosphor-bronze which had the shape shown in Fig. 2 (some specimens of phosphor-bronze were found to be ferromagnetic and were discarded). A mark in the silica tube enabled it to be placed always with the same orientation so that the angle its axis made with the vertical was always the same (and was very small). By pushing down the loop the two halves of the collar were tightened

just below the flange at the top of the tube and held it securely. The silica tube was long enough to ensure that the square of the field at the meniscus was negligible compared with the square of the field at the base. The lower end of the tube was adjusted to be very nearly in the centre of the gap between the pole-pieces, and therefore in the middle of the uniform field region. The small displacement of the tube due to movement of the balance had then negligible effect.

The general procedure in taking observations was as follows. The tube was filled with a drawn-out teat pipette, the liquid was adjusted to the mark, and the tube placed in position. It was allowed to hang for a suitable time, to get into temperature equilibrium with the atmosphere, and then balanced to the nearest gram. The final balance was made with the automatic riders of the balance. A series of measurements (usually about 6) were then made with the exciting current alternately off and on; the difference gave the pull on the specimen. This difference was always measured in terms of the automatic riders; hence a calibration of these served for all subsequent measurements.

In the earlier experiments some trouble was experienced with slow fluctuations on apparent weight of the order of a few tenths of a mg. This was attributed to the accumulation of static electrical charges in the highly insulated suspended system; it was eliminated by placing a little uranium oxide in the draught tube and the balance case to ionise the air feebly. With this arrangement the forces were reproducible to within $\pm 0{\cdot}03$ mg. Since the force on the tube filled with the more concentrated nickel solution was 860 mg. and filled with acetone -43 mg., this was amply accurate.

The tube was calibrated with two nickel chloride solutions as described by Nettleton and Sugden (*Proc. Roy. Soc.*, 1939, *A*, **173**, 313). The following figures indicate the degree of reproducibility attained :

$NiCl_2$, g./g. soln.	β.	$NiCl_2$, g./g. soln.	β.	
0·1398	0·28243	0·24304	0·28275	
,,	0·28236	,,	0·28217	
,,	0·28236	,,	0·28217	Mean 0·28236
,,	0·28249	,,	0·28236	Mean deviation $\pm$0·00015
,,	0·28204	,,	0·28204	
,,	0·28275	,,	0·28243	

The value 0·2824 was used in subsequent measurements.

The volume of the silica tube to the mark was 25·18 c.c. and the force in the empty tube with the exciting current 18·0 amps. was $-27{\cdot}34$ mg.

A series of measurements was made with conductivity water and gave the following results :

Magnetic susceptibility of water (t = 13—18°).

$-10^6\chi$.	$-10^6\chi$.	$-10^6\chi$.	$-10^6\chi$.	
0·7204	0·7198	0·7195	0·7200	Mean 0·7200
0·7202	0·7202	0·7200	0·7200	Mean deviation $\pm$0·0002

These result agrees with the value usually employed for water and is almost identical with that found by Piccard and Devand (quoted by Stoner, " Magnetism and Matter "), namely, $\chi_{20°} = -0{\cdot}71993 \times 10^{-6}$. No appreciable variation with temperature was observed over the small interval at which the measurements were made.

A few observations were also made with benzene. This was purified by washing with concentrated sulphuric acid until colourless, then with water. The product was dried over calcium chloride, shaken twice with mercury, twice recrystallised, and then distilled over sodium.

Magnetic susceptibility of benzene (t = 13—18°).

$-10^6\chi$.	$-10^6\chi$.	$-10^6\chi$.	$-10^6\chi$.	
0·7013	0·7031	0·7009	0·7018	Mean 0·7023
0·7026	0·7028	0·7017		Mean deviation $\pm$0·0007

Recent values found for this quantity are :

Authors.	Ref.	$-10\ \chi$.
Cabrera & Fahlenbach	*Z. Physik*, 1934, **89**, 682	0·6803
Trew & Spencer	*Trans. Faraday Soc.*, 1936, **32**, 701	0·7098
Seely	*Physical Rev.*, 1936, **49**, 812	0·6977
Angus & Hill	*Trans. Faraday Soc.*, 1943, **39**, 185	0·7023
French & Trew	*Ibid.*, 1945, **41**, 437	0·702
Cutforth & Selwood	*J. Amer. Chem. Soc.*, 1948, **70**, 278	0·7065

Two specimens of acetone were also examined. Both were prepared from " AnalaR " acetone and were distilled over potassium permanganate. Specimen (*a*) was finally dried and fractionally distilled over magnesium perchlorate,† whilst (*b*) was similarly dried with anhydrous copper sulphate. As the following table shows, they gave indistinguishable results.

Magnetic susceptibility ($-10^6\chi$) *of acetone* (t = 13—18°).

Specimen (*a*).				Specimen (*b*).			
0·5811	0·5804	0·5807	0·5799	0·5801	0·5814	0·5812	0·5805
0·5816	0·5798	0·5824		0·5793	0·5792	0·5822	0·5814
0·5806	0·5787	0·5799					

Mean of all observations, $-10^6\chi = 0{\cdot}5806$; mean deviation $\pm 0{\cdot}0008$. This gives $-10^6\chi_M = 33{\cdot}71$.

The value found in the present work is in good agreement with that reported by Bhatnagar, Neoge, and Mathur (*Z. Physik*, 1936, **100**, 141), *viz.*, $-10^6\chi = 0{\cdot}583$, but is lower than the figures obtained by a number of other workers.

The apparatus described in this paper has been used to follow the fractionations of some rare earths and for measurements in organic liquids. These are reported in the following papers.

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