# Paramagnetic and diamagnetic materials

www.iop.org/journals/physed

# Paramagnetic and diamagnetic materials

**Frank Thompson**

Department of Electrical Engineering and Electronics, University of Manchester, UK

**Abstract**

Paramagnetic and diamagnetic materials are now generally known as the 'Cinderella' materials of the magnetic world. However, susceptibility measurements made on these materials in the past have revealed many details about the molecular bonding and the atomic structure of the so-called 'transition' elements. Indeed, the magnetic moment of neodymium has been well known for decades, although it is only recently that such properties have begun to be exploited. The experiment concerning susceptibility reported here may act as a link between past and present.

## Introduction

We have recently had a short note [1] entreating us to examine materials that exhibit para- and diamagnetic properties. Here the author has made a first important step—engendering the interest of students with a simple but effective demonstration which can then lead into useful discussions about the topic of magnetism in a more general way. But, as all physicists know, the next step is even more important as we pose the question 'can we measure these properties?'

Over 40 years ago, *Physics Education* contained an article about a Gouy balance [2] and this is one of several methods by which para- and diamagnetism are measured.

It may seem repetitive to consider such an experiment again but there are three reasons for this.

(a) The previous article [2] was rather too concise and one of the formulae given in the article was in need of correction.

(b) It is quite staggering to contemplate the changes that have occurred over 40 years: the image of this journal, *Physics Education*, has changed dramatically (please see [2]) in this period and the all-pervasive web has changed our lives; e.g. to learn a little more about magnetism one can visit Dr R Clarke's workshop page http://info.ee.surrey.ac.uk/Workshop/advice/coils/mu/ and see a demonstration of diamagnetism.
In addition, data capture by computers is now a matter of routine.

(c) At Leeds University, 1959/ 62, I had the privilege to be taught by Professor E C Stoner who specialized in this area of magnetic measurement. Perhaps a published article would ensure that present physicists would gain a better appreciation of magnetism and, from a personal viewpoint, it would be a chance to pay tribute to a long-departed charming person and great scientist.

## Theoretical aspects

The set up for a Gouy measurement is relatively simple and is shown in figure 1.

A specimen, in the form of a long cylinder, is suspended from a sensitive balance. Application of a magnetic field will cause the sample to be pulled into the magnet poles if the sample is paramagnetic whereas the sample will be pushed out of the pole area if the sample is diamagnetic.

 0031-9120/11/030328+04$33.00 

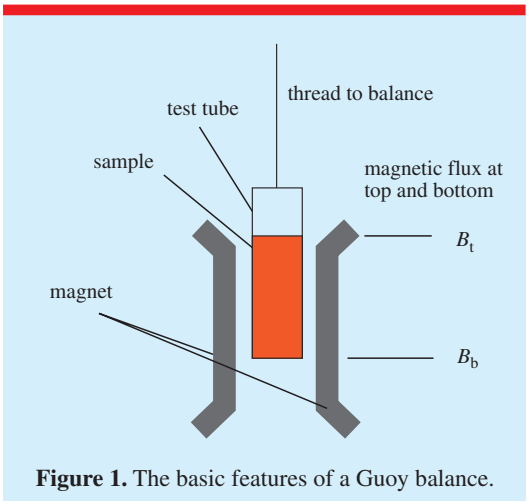


**Figure 1.** The basic features of a Guoy balance.

**Figure 2.** System for carrying out a Gouy measurement.

It is relatively straight forward to see that the force, $F$, is given by:

$$F = A\chi(B_b^2 - B_t^2)/(2\mu_o) \qquad (1)$$

where $A$ is the area of the sample, $\chi$ is the volume susceptibility of the specimen, $\mu_o$ is the permeability of free space and $B_t$ and $B_b$ are, respectively, the magnetic flux values at the top and bottom of the sample.

If the susceptibility is negative or positive then the force will have the same sign and thus para- and diamagnetic samples can easily be identified.

In many cases the magnetic flux at the top of the sample will be small and equation (1) simplifies to that given in [2] except that the formula in [2] requires a multiplying factor of $\mu_o$ (the author [2] has used the symbol $\kappa$ for volume susceptibility).

## Experimental details

The glass sample tube, of length 17 cm, had internal diameter 1.5 cm and external diameter 1.7 cm. It was filled with a powdered (or liquid) sample to a height of about 10 cm. (At this point one needs to be aware of problems of packing a powdered sample into a tube. It requires patience in that the powder needs to be added by small amounts at a time and the end of the glass test tube has to be tapped on the bench during filling. Repeatable results will only be obtained if the sample has been packed consistently.)

A permanent magnet became available when a microwave isolator was being dismantled; this had a pole gap of 2 cm and the pole length was 6 cm so that each pole face had dimensions 6 cm × 1.5 cm. A field profile was taken with an Tesla metre (Model C, HEL Ltd) and, at the centre of the magnet poles, the reading was $B_b = 240$ mT. The value of $B_t$ was found to be negligibly small. Whereas the magnet was slid forward to engage the sample in [2], the present apparatus used a different method. With the magnet mounted on a hydraulic jack the magnet was lifted to engage the sample. Subsequently a valve on the jack was opened minutely and the magnet fell sedately to its rest position as mass values were recorded into a PC by a serial interface. The apparatus is shown in figure 2.

The measurement procedure is as follows.

The glass sample tube is filled with material to a height of approximately 10 cm and is suspended from a balance (Mettler PM 460).

The magnet is raised so that the bottom of the sample tube is mid-way down the magnet pole gap.

The balance is tarred to give a zero reading and then a small additional mass is added to the balance pan so that all readings from the balance were positive. (No scientific justification is given for this last step other than the serial link sometimes gave spurious data if negative mass values were recorded.)

The hydraulic jack release screw was opened by a small amount and readings were taken from the balance as the magnet descended.

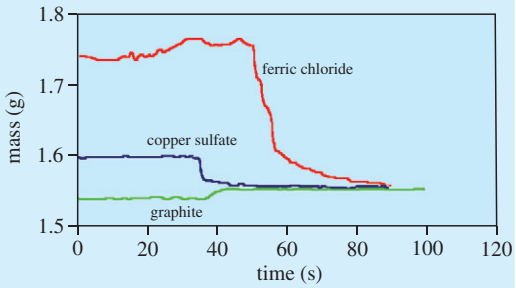


**Figure 3.** Mass change as samples are removed from a magnetic field.

## Results

Results from three samples are shown in figure 3.

The ferric chloride granules (shown in figure 2) were those normally used for etching copper on printed circuit boards, the hydrated copper sulfate sample was in the usual form of blue crystals and the graphite was a powdered sample.

In [2] there is a list of precautions:

(a) avoid air currents;
(b) a rigid support frame for both the balance and the magnet is required;
(c) the sample needs to be in the same position each time.

Another important correction, not mentioned in [2], may be necessary. The sample tube will be affected by the magnet and this may have to be accounted for. Also, the air within the tube, may give an added correction since some of the air is displaced when the sample is present.

Simplifying equation (1) to that given in [2] (corrected version) gives the following equation:

$$(m_2 - m_1)g = A\chi B_b^2/(2\mu_o) \qquad (2)$$

where the mass change is given by $m_2 - m_1$ and $g$ is the acceleration due to gravity.

Volume susceptibilities, $\chi$, are tabulated (table 1).

Now, the volume susceptibility of air is $0.37 \times 10^{-6}$ so that, within the sensitivity of the present apparatus, a correction for displaced air would not be necessary. It was also found that the empty glass sample holder did not create a measurable mass difference from being 'in' and 'out' of the magnetic field. Hence, a correction for the empty sample holder was not possible.

**Table 1.** Susceptibility values for three samples.

| Specimen | Mass difference (g) | Susceptibility (SI units) |
|---|---|---|
| Ferric chloride | 0.20 (±0.003) | 48.3 (±0.4) × $10^{-5}$ |
| Copper sulfate | 0.045 (±0.003) | 10.8 (±0.5) × $10^{-5}$ |
| Graphite | −0.015 (±0.003) | −3.6 (±0.6) × $10^{-5}$ |
| $B_b = 0.24$ T | | $A = 1.77$ cm$^2$ |

For the copper sulfate sample, the packing density was 1320 kg m$^{-3}$ and the mass susceptibility (volume susceptibility/density) was therefore calculated to be 8.1 (±0.4) × $10^{-8}$ m$^3$ kg$^{-1}$.

With graphite the packing density was 884 kg m$^{-3}$ which gives a mass susceptibility of −4.1 (±0.7) × $10^{-8}$ m$^3$ kg$^{-1}$.

These results agree favourably with the respective values of 7.7 × $10^{-8}$ and −4.4 × $10^{-8}$ m$^3$ kg$^{-1}$ given in Tennent [3].

The true composition of the ferric chloride sample was in some doubt so the mass susceptibility was not determined for this sample.

## Conclusions

Measurements of the volume susceptibility of three samples have been made. Calculated values of the mass susceptibility of copper sulfate and graphite are listed and these are in reasonable agreement with accepted values.

A corrected formula has been presented for that in a previous article in this journal [2].

The present Gouy apparatus proved to be somewhat limited in accuracy but data averaging helped to increase sensitivity. Even so, a mass change for the empty glass tube could not be detected.

Further refinements may be considered to rectify this deficiency. Alternatively, a commercial instrument such as that from Sherwood Scientific Ltd, www.sherwood-scientific.com, may be available.

Experiments with a Gouy balance may lead students into other techniques for magnetic susceptibility measurements [4].

Students may wish to 'Google' the scientist E C Stoner and see how important magnetic measurements have been in the past. Stoner's work helped in correctly ordering the 'rare earth' elements in the periodic table.

## Acknowledgments

The author wishes to thank David Coidan from Coidan Graphite Products Ltd for providing the graphite sample. This company has a website at: www.coidangraphiteproducts.com.

*Received 4 January 2011, in final form 13 February 2011*
*doi:10.1088/0031-9120/46/3/013*

## References

[1] Featonby D 2009 How to demonstrate the little-known forces of para- and diamagnetism *Phys. Educ.* **44** 122

[2] Saunderson A 1968 A permanent magnet Gouy balance *Phys. Educ.* **3** 272–3

[3] Tennent R M 1971 *Science Data Book* (Edinburgh: Oliver and Boyd) p 67

[4] Bowmer C J, Lowes P M and Thompson F 1983 A low cost electronic method for investigating paramagnetism *Educ. Chem.* **20** 20–3

**Frank Thompson** joined the Physics School at Manchester Polytechnic after spending some years working in oil prospecting in Libya. In the late 1990s he took early retirement, and he has done consultancy work since then. At present, he is working at the Joule Centre, University of Manchester, UK.