Gas Torque Anomaly in Weak Magnetic Fields*

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When a circular cylinder is immersed in some gases at pressures near 0.05 Torr, application of a weak magnetic field (0.2–200 Oe) parallel to the cylinder axis results in a torque about that axis when a temperature difference exists between the gas and the cylinder surface. This torque is a linear function of the temperature difference. It reverses when either the temperature gradient or the field direction is reversed. At a given pressure the torque exhibits a maximum at a definite value of the magnetic field, and the position of this maximum is a characteristic of the gas involved.

I. INTRODUCTION

IN determining gyromagnetic ratios by the Einstein–de Haas effect it is necessary to measure very small torques acting on a suspended cylindrical sample. In the course of improving measurement techniques, a small anomalous torque was observed when a weak magnetic field (0.2–200 Oe) was applied along the axis of a cylinder suspended in a gas at a temperature different from that of the cylinder (Fig. 1). The effect is observed in the pressure range between 0.001 and 1.0 Torr, and the torque reverses when either the magnetic field or the temperature gradient is reversed. The torque-field-pressure relationships depend on the nature of the gas.

The purpose of this communication is to describe the experimental investigation of this anomalous torque. A theoretical explanation of the effect has not been developed.

II. EXPERIMENTAL EQUIPMENT

The pendulum used to measure these torques (Fig. 2) was designed for experiments on the Einstein–de Haas effect.[1] The usual ferromagnetic sample was replaced with a brass rod. The temperature elevation was obtained by passing a 60-cps current through the winding immediately beneath the pendulum surface. This surface is the outside of a thin bronze cylindrical shell 1.9-cm diam and 20 cm long. The temperature of the pendulum was determined by measurement of the winding resistance.

The temperature of the wall of the vacuum chamber was measured with an ordinary mercury thermometer. The temperature differential reported in this paper is the difference between the vacuum-chamber wall and the pendulum winding. Because of the long thermal time constant of this pendulum it was possible to turn off the 60-cps heating current for several minutes

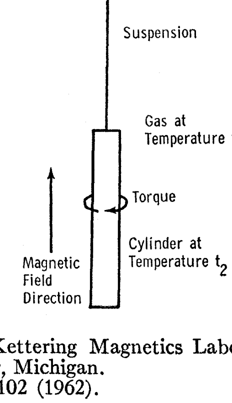

FIG. 1. Schematic arrangement of torsional pendulum for observation of gas-torque phenomenon.

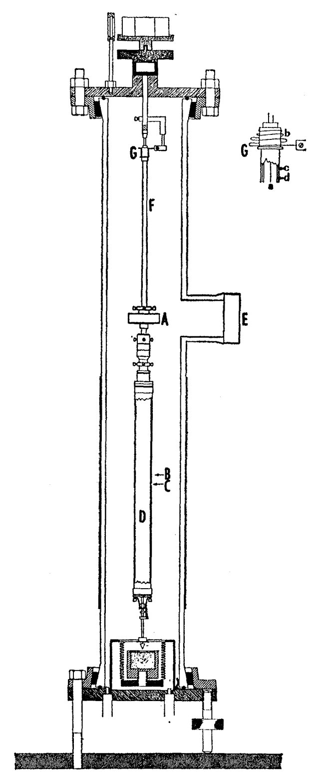

FIG. 2. Sectional drawing of torsional pendulum used to measure gas-torque anomaly. Relevant components are lettered. (This pendulum was designed for measurement of the Einstein–de Haas effect.) A: mirror (four 90° spaced faces); B: cylindrical bronze shell; C: winding (11 000 Ω); D: solid-brass cylinder; E: 16-m lens; F: conducting tube; G. current-return arrangement; a: supporting and conducting ribbon; b: return-current spiral; c: outer conducting tube (at spiral potential); d: inner tube (at ribbon potential).

* Experiments conducted at The Kettering Magnetics Laboratory, Oakland University, Rochester, Michigan.
[1] G. G. Scott, Rev. Mod. Phys. 34, 102 (1962).

without making measurable changes in the observed torque. The pendulum surface was grounded to the inner wall of the vacuum chamber through the suspension system. The vacuum chamber consisted of a 7.6-cm-diam glass cylinder made conducting on the inside with a transparent layer of tin oxide.

The torsional constant of the ribbon used to support the pendulum was about 6 dyn cm/rad. Deflections were observed on a scale 16 m from the pendulum mirror and the resolution was such that a scale could be read to $\frac{1}{10}$ mm. The smallest observable torque was therefore about 2×10^{-5} dyn cm. Random motions of the pendulum were below this level. The largest measured value for the anomalous torque (22×10^{-3} dyn cm) corresponds to a scale deflection of about 12 cm.

III. OBSERVATIONS

Measurements were made at constant pressure and temperature differential by applying a vertical field in a time which was very short compared to the period of the pendulum and observing the shift in the oscillation center. This pendulum has a period of about 35 sec. Auxiliary experiments using resonance techniques in-

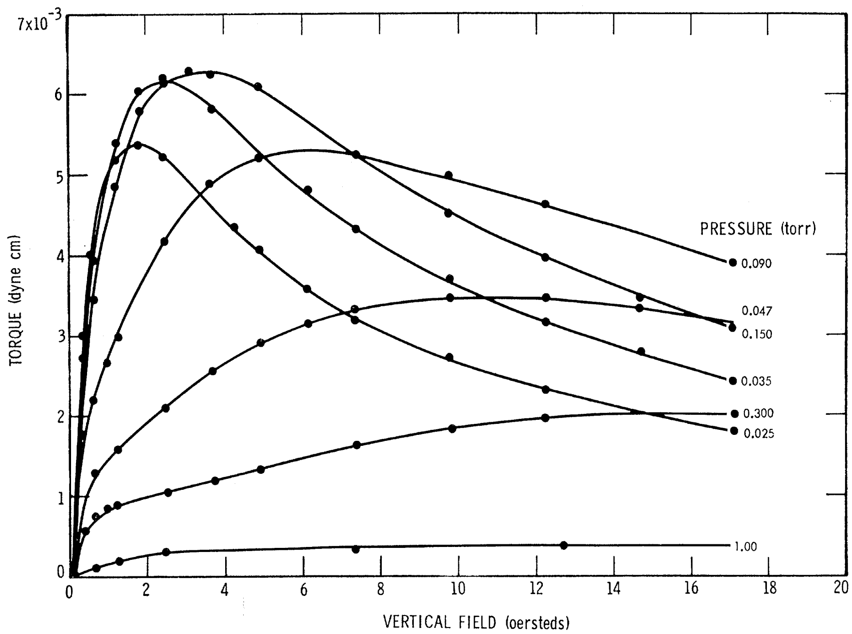

FIG. 3. Torque-field-pressure relationships for oxygen for a temperature differential of 30°C.

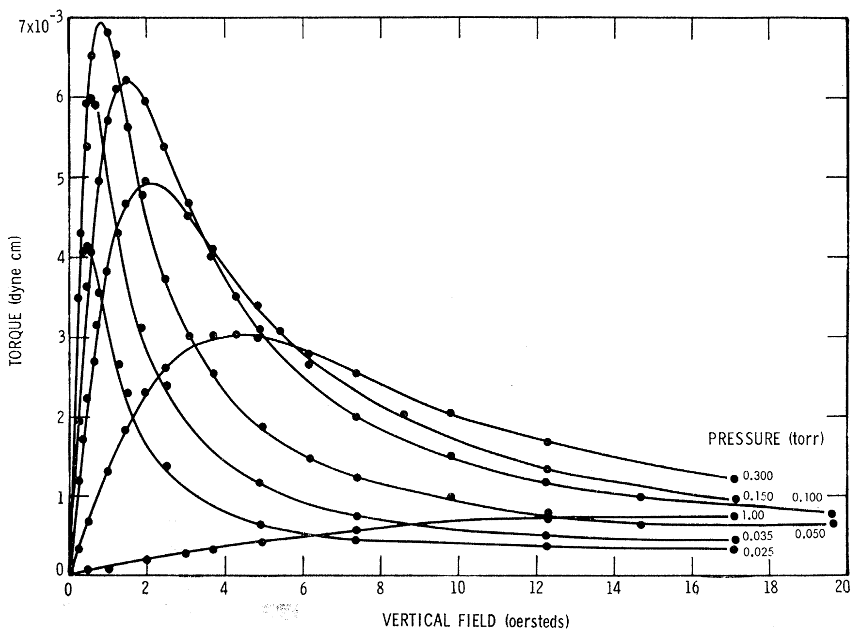

FIG. 4. Torque-field-pressure relationships for nitric oxide for a temperature differential of 30°C.

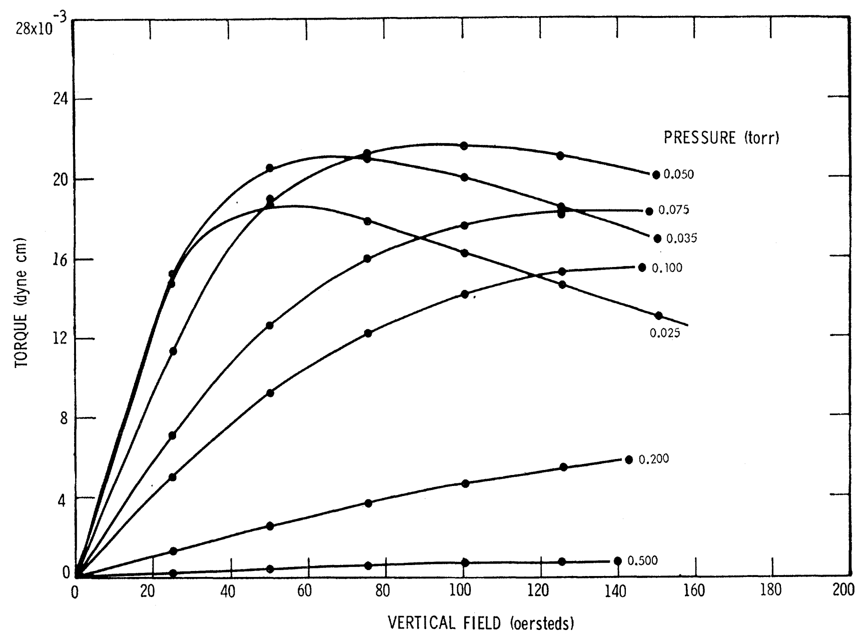

FIG. 5. Torque-field-pressure relationships for nitrogen for a temperature differential of 30°C.

volving symmetrical phase shifting indicated that the torque reached its full value <0.01 sec after application of the magnetic field.

This torque is a linear function of the temperature differential over the range studied ($0<\Delta T<55$°C) and the magnetic field intensity required for maximum torque depends on the nature of the gas. A family of curves displaying the field-torque relationships for various pressures of oxygen are given in Fig. 3. It will be noted that the torque maximizes at a certain field value and that the peaks shift to higher fields and broaden as the pressure is increased. The pressure and field values required for maximum torque appear to be linearly related. The highest peak occurs at a pressure in the neighborhood of 0.05 Torr[2]—a characteristic of all gases which display this effect. The field-torque curves for nitric oxide are shown in Fig. 4 and for nitrogen in Fig. 5. Curves for carbon monoxide are very similar to those for nitrogen. Curves for carbon dioxide indicate that the 0.05-Torr peak occurs at a field value of about 700 Oe. All of the above gases display torque in the same sense with respect to the field direction and temperature gradient. This sense is the same as that of the flow of electrons in the current sheet which is producing the magnetic field when the cylinder surface is hotter than the gas.

The torque for hydrocarbons in the methane series is in the opposite direction, and the field intensity required to produce a maximum becomes greater as the molecular weight increases. Gases in this series investigated are methane, ethane, propane, butane, and isobutane.

The effect is not observed with helium, argon, xenon, hydrogen, water vapor, carbon tetrachloride, ammonia, and acetylene in the pressure-field region investigated. A summary of the torque characteristics for the various gases at a pressure of 0.05 Torr is given in Table I.

Experiments on gas mixtures were also conducted. The results for various combinations of oxygen and nitrogen are shown in Fig. 6. It is clear that the torque curve for a given mixture can be derived by simple addition of the fractional parts, using the total pressure values for each gas. This independent action of each molecular species is further emphasized by the common crossover point at 10 Oe.

Additional experiments with mixtures of oxygen and argon indicate that the magnetic field required to produce a maximum torque depends upon the total

[2] This is the pressure at which the Crookes radiometer becomes most effective.

TABLE I. Summary of torque characteristics at a pressure of 0.05 Torr (cylinder 1.9-cm diam; 20 cm long).

Gas	Field required for maximum torque (Oe)	Value of maximum torque[a] (10^{-3} dyn cm)
O_2	3.5	+ 6.5
NO	0.8	+ 7.0
N_2	90.	+22.
CO	120.	+24.
N_2O	>200.	+22.
CO_2	>200.	+ ?
Methane	150.	− 5.
Ethane	>200.	− ?
Propane	>200.	− ?
Butane; isobutane	>200.	− ?
He, Ar, Xe, H_2, H_2O, CCl_4, NH_3, C_2H_2	These gases do not exhibit a measurable torque (2×10^{-5} dyn cm) in the pressure-field region investigated.	

[a] Temperature of cylinder 50°C. Temperature of vacuum-chamber wall 20°C.

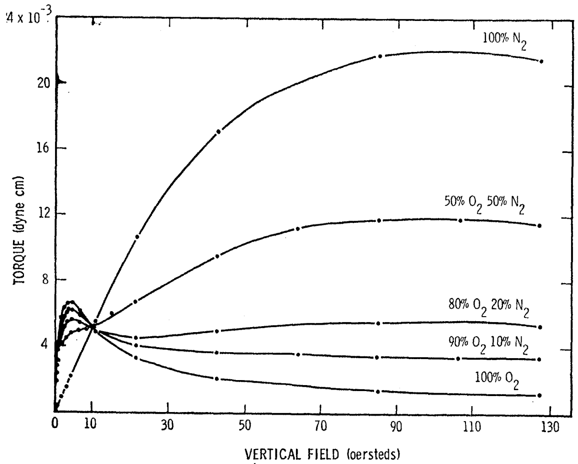

FIG. 6. Torque-field relationships for mixtures of oxygen and nitrogen at a total gas pressure of 0.05 Torr and a temperature differential of 30°C.

gas pressure, and that the height of the peak depends upon the partial pressure of the active component.

All of these observations were made with the surface of the pendulum at a higher temperature than the surrounding gas. It was determined, however, that the observed torque would reverse in direction if the temperature gradient were reversed. This was accomplished by heating the outside of the vacuum chamber and making observations before thermal equilibrium could be established.

IV. DISCUSSION

This phenomenon was first investigated because of its possible influence on measurements of the Einstein–de Haas effect. In these measurements resonant reversals of magnetization are applied to a ferromagnetic cylinder which forms an integral part of a delicate torsional pendulum. If these reversals are accompanied by any changes in torque, a phase shift results which affects the period. If the procedures used in the Einstein–de Haas measurements are correct, the average oscillation time for a series of experiments should be equal to the free period. However, for several years we have noted an average change in the oscillation time of about 1 part in 2000, during the resonant reversals. This indicated the presence of an unknown torque on the system which was dependent on the direction of magnetization of the sample. The torque was very small and the phasing of the magnetization reversals was such that errors in the g' measurements were insignificant. However, when the vertical-field and gas-pressure values are optimized, this anomalous torque can be two to three orders of magnitude larger than the torques involved in the gyromagnetic ratio measurements.

Measurements of this anomalous torque were made with residual horizontal fields below 10^{-5} Oe. The pendulum itself was nonmagnetic. When vertical fields were replaced with horizontal fields of the order of 1 Oe, no torque was detected. Thus, direct magnetic coupling could not be responsible for the observations. The fact that no torque is observed with gases such as helium, argon, and xenon provides further assurance that magnetic-coupling torques are not involved.

In these experiments vertical magnetic fields can be applied either with a 1-ft-diam Helmholtz pair capable of producing fields up to 200 Oe, or with the 9-ft-diam Helmholtz system normally used[1] for neutralizing the vertical component of the earth's magnetic field. The latter system produces fields which are very homogeneous, and intensities of about 10 Oe can be attained. Most of the data however, were taken with the 1-ft-diam Helmholtz pair, but when comparisons could be made, as in the case of nitric oxide, no difference was observed between torques generated by these two coil systems. Thus, it is improbable that magnetic-field gradients are involved.

Since the torque for nitrogen is larger than the torque for oxygen and in the same direction, a high paramagnetic susceptibility does not appear to be a requirement.

Although ionization of gas molecules by stray radiation would be far too small to account for these torques, this possibility was investigated by placing a 1-mCi radium source immediately outside the vacuum chamber. No effect of the radiation was observed.

In one set of experiments with nitrogen, the pendulum surface was completely covered with two layers of 0.003-in. thick Teflon tape. The torque-field-pressure relationships were identical, both with and without the Teflon covering.

This anomalous torque can be consistently reproduced for a particular gas such as nitrogen even after a previous filling with gases such as water vapor and carbon tetrachloride. No attempt was made to use high-purity gases in the experiments, and hence it appears that small percentages of molecular impurity have no effect. This is consistent with the results obtained with the oxygen-nitrogen mixtures.

An explanation for this anomalous torque could involve either magnetically induced changes in the gas-surface collision process itself, or changes in the distribution of momentum among the entire population of gas molecules. A deviation from isotropy of 10^{-6} in the surface scattering process could cause torques of the observed magnitude.

The effect of an applied magnetic field on the viscosity and thermal conductivity of paramagnetic gases was discovered by Senftleben.[3] Beenakker[4] has pointed out that the forces of interaction between molecules must

[3] H. Senftleben, Z. Physik **31**, 961 (1930).
[4] J. J. M. Beenakker, G. Scoles, H. F. P. Knaap, and R. M. Jonkman, Phys. Letters **2**, 5 (1962).

have radial asymmetry for effects such as these to be observed. Beenakker[4,5] and Gorelik[6] have shown that a variety of polyatomic gases exhibit the Senftleben effect. More recently, Korving *et al.*[7] have reported a transverse component in both the viscous flow and the heat flow of gases in a magnetic field. It has been shown by a number of theorists[8–10] that rotational-flow terms would result with external fields if the participating particles have internal degrees of freedom. However, detailed calculations have not yet been made to indicate whether or not the correct magnitude for this torque could be predicted.

ACKNOWLEDGMENTS

Since the explanation for these observations was not immediately apparent the data and equipment have been exposed to numerous physicists both in our own organizations and elsewhere over a period of a year and a half. The authors wish to acknowledge these many helpful discussions.

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Decay of Excited Species in a Pulsed Discharge in Krypton

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The emission in the afterglow of a pulsed discharge in krypton has been investigated. Measurements of the decay times of the resonance radiation at λ1236 Å and a diffuse molecular radiation at λ1250 Å and longer wavelengths have been made as functions of pressure at 295 and 196°K. The measurements have been interpreted on the assumption of a simple two-time-constant model, leading to values of the collision frequencies for collision-induced transitions between the metastable level ($1s_5$) and the resonance level ($1s_4$) of 13×10^{-14} cm³/sec and 22×10^{-14} cm³/sec at 295 and 196°K, respectively, for de-exciting collisions ($1s_4-1s_5$), and 7.6×10^{-16} cm³/sec and 1.3×10^{-16} cm³/sec, respectively, for exciting collisions ($1s_5-1s_4$). The coefficients for the conversion of metastable atoms to molecules in two- and three-body collisions with normal atoms has also been determined. The two-body collision frequency for molecule formation was found to be 15×10^{-16} cm³/sec and 26×10^{-16} cm³/sec at 295 and 196°K, respectively, and the three-body collision frequency was found to be 4×10^{-32} cm⁶/sec and 6.9×10^{-32} cm⁶/sec at 295 and 196°K. The results are compared with existing measurements in other rare gases. The two-body part of the molecule formation is discussed in terms of an interatomic potential which has a hump similar to that proposed in the case of helium.

EXPERIMENTS on metastable lifetimes,[1] referred to as I, and the decay of resonance radiation[2] in krypton, referred to as II, have been reported earlier. The present paper describes an extension of the work to higher krypton pressures and also to lower temperatures.

The interpretation of the results of II was based on a three-level model having a ground state, metastable state (M) and resonance state (R). The decay of the excited atom populations was attributed to the effects of (a) diffusion of excited atoms, (b) escape of resonance radiation, and (c) collision-induced transitions between R and M.

In the present work, measurements of the decay of radiation emitted during the krypton afterglow have been made using a vacuum monochromater to isolate certain regions of the spectrum. It has been established that at higher pressures a considerable fraction of the afterglow energy is dissipated as molecular radiation. From the lifetime of radiation in isolated regions of the spectrum it is now possible to give a more complete picture of the decay of energy of the afterglow in terms of resonance and metastable atomic levels R and M and a molecular level. Coefficients for the collision-induced transitions have been determined. The conclusions reached in II regarding the diffusion of resonance radiation are still relevent and the differential equations for the decay of excited states are unchanged if the coefficient α_d in II is interpreted to include an extra term to allow for the conversion of metastable atoms into excited molecules.

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