MEASUREMENT OF DYNAMIC BEHAVIOR OF THE THERMOMAGNETIC GAS TORQUE EFFECT

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Experiments in which a modulating magnetic field has been superimposed on the steady magnetic field necessary to observe the thermomagnetic gas torque effect have yielded a twofold behavior. For magnetic fields below that for maximum torque, a frequency-dependent torque reduction ΔN is observed. For magnetic fields equal to or somewhat greater than that for maximum torque, a second effect is superimposed on the first: an absorptionlike peak which occurs at frequencies proportional to the magnetic field strength.

Scott, Sturner, and Williamson[1,2] have found a thermomagnetic torque N in polyatomic gases. The phenomenon is related to the Senftleben effects, and theories have been developed.[3,4] The torque is pressure dependent, with maximum effect at around 0.050 Torr, independent of the gas.[1] Furthermore, N passes through a maximum at a magnetic field H_0 which is characteristic of the gas and depends linearly on pressure,[1] with a nonzero intercept at zero pressure;[5] hence, $H_0 = b(P+a)$. This equation is qualitatively derivable from the Gorter–Zernike–Van Lier molecular precession model[6,7] with the inclusion of wall-collision effects.[8] The constants b and a depend on the molecular g_J value and collision cross section.

In an effort to understand better the molecular dynamics of the gas torque, we have performed experiments in which a large modulating field $h_m \cos 2\pi\nu t$ is superimposed collinearly with the steady field H necessary to observe the torque ($h_m \approx H$). By thus modulating the molecular precession frequency, we hoped to perturb the observed torque. We expected a reduction ΔN in torque for $\nu < \nu_{\text{coll}}$, the molecular collision frequency, since the average torque over a modulation cycle would usually be less than or equal to that with $h_m = 0$. However, for $\nu > \nu_{\text{coll}}$ the torque would return to its value for $h_m = 0$, since it would be unable to follow the field changes. Although in these experiments a metal torsion pendulum was used, a number of independent tests showed that eddy current effects were small.

We have performed experiments on NO and O_2, both of which at low P have low H_0 values (and hence require only small h_m). Both gases were studied with $H = H_0$ and $h_m = H_0$. We also studied NO at $H \approx \frac{1}{2}H_0$ and at various field values greater than H_0.

The results for NO at $H \approx \frac{1}{2}H_0$ were as expected; shown in Fig. 1 are curves of the fractional reduction in torque $-\Delta N/N$ vs ν for $P = 0.066$ Torr and three values of h_m. It is apparent that the effect increases rapidly with h_m. The cutoff occurs in the range 20-400 kHz. The average molecular collison frequency at this pressure (and $T = 300°\text{K}$) is about 434 kHz. We might expect the effect to go as[9] some correlation-function transform, $(1+4\pi^2\tau_c{}^2\nu^2)^{-1}$, which in our experiment would be proportional to the number of molecules having undergone a collision within a time $1/\nu$. In Fig. 1, such a correlation function is plotted and shows good agreement with experiments.

Results with $H = H_0$ for NO and O_2 are shown in Fig. 2. Here the torque defect $-\Delta N$ is normalized to unity at low ν for a number of pressures. With $h_m = H_0$, the low-frequency defect is about 20% for NO and about 14% for O_2. A plot of the cutoff frequencies ν_{cut} [where $\Delta N(\nu_{\text{cut}}) \equiv \frac{1}{2}\Delta N(0)$] vs P is given in the inset. The straight-line pressure dependence is clearly that of a collision-dominated process. If we write $\nu_{\text{cut}} = \text{const}$

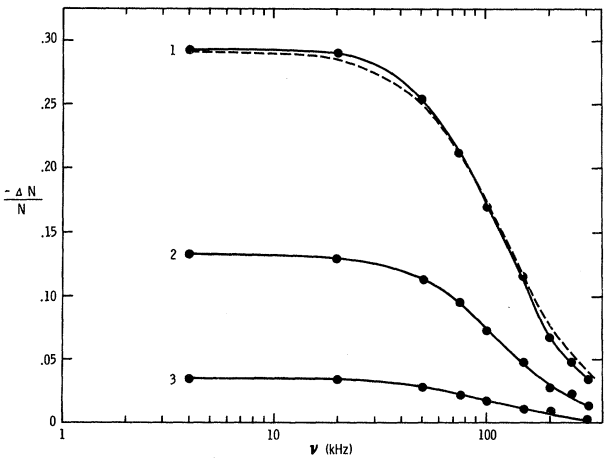

FIG. 1. Fractional torque defect $-\Delta N/N$ vs ν for NO gas at 0.066 Torr and $H = 0.55\ H_0$. Curves 1, 2, and 3 are for $h_m = 3H/2$, H, and $H/2$, respectively. The dashed curve is a normalized plot of $(1+4\pi^2\tau_c{}^2\nu^2)^{-1}$.

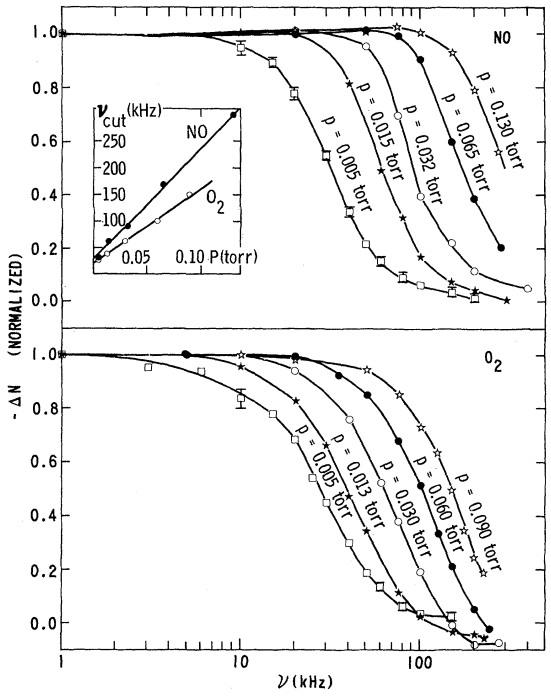

FIG. 2. Normalized plots of $-\Delta N$ vs ν for NO and O_2 for $H=H_0$ at different P. In these experiments $h_m=H_0$. Inset: ν_{cut} vs P for NO and O_2.

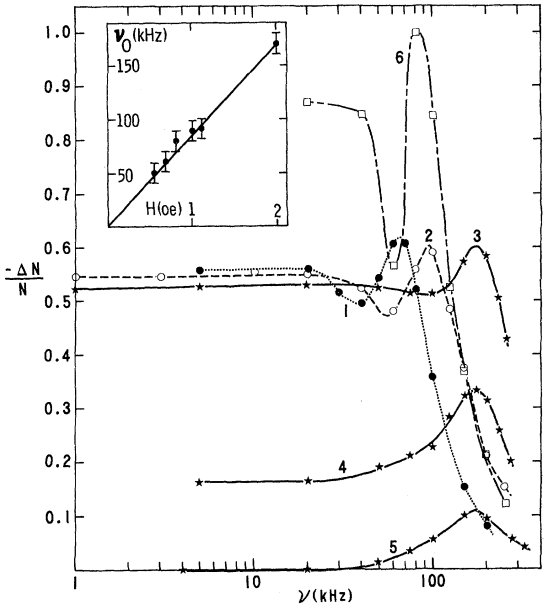

FIG. 3. $\Delta N/N$ vs ν for NO at field values above H_0. Values of H, P, h_m, and H_0 for the curves: (1) 0.69 Oe, 0.015 Torr, 1.03 Oe, 0.34 Oe; (2) 1.0, 0.025, 1.6, 0.46; (3) 2.0, 0.065, 3.0, 1.0; (4) 2.0, 0.065, 2.0, 1.0; (5) 2.0, 0.065, 1.0, 1.0; (6) 0.86, 0.010, 1.63, 0.28. Inset shows plot of ν_0 vs H.

$\times(P+a)$, the constant a for NO and O_2 turns out to be about the same as that found from the pressure dependence of H_0. The frequency intercept is about equal to the average wall-collision frequency. Although the shape of the curves of Fig. 2 is qualitatively like that of Fig. 1, they cannot be fitted by $(1+4\pi^2\tau_C{}^2\nu^2)^{-1}$, possibly because of the fact that two effects are contributing here. This view is supported by higher field experiments described next. It is interesting to note that the high-frequency effect for some O_2 curves is negative, indicating a larger torque with high-frequency modulation than without.

Figure 3 shows the frequency dependence of the fractional defect $-\Delta N/N$ for NO gas at four magnetic fields $H>H_0$. Two effects are evident: a cutoff curve at low ν and an absorption curve at higher ν. Although the shape and height of the absorption curve depend on P and h_m, its frequency position ν_0 does not. The h_m independence is evident from the three highest-frequency peaks with $H=2.0$ Oe but different h_m values. It is interesting to note that as $h_m\to 0$, the low-frequency cutoff curves vanish. In the inset of Fig. 3 is plotted the field dependence of ν_0 as determined from several curves like those of the figure.

The straight-line fit seems independent of P and yields a g_J value of about 110, in terms of the nuclear magneton—roughly twice that measured for NO ($^2\Pi_{1/2}$) by Ramsey.[10] As yet we have no clear understanding of the absorption effect, although we do associate it with molecular precession. Perhaps the factor of two can be associated with a double quantum effect involving two colliding molecules, or perhaps it is a consequence of nonlinearity of the magnetothermal effect.[11] In the latter event we would expect to see peaks at higher multiples of the Larmor precession frequency, which we evidently do not see.

As H is decreased through H_0 toward zero, the intensity of the absorption curve decreases. However, even at $H=H_0$ we expect the absorption effect to contribute; this probably accounts for the deviation of the curve shapes of Fig. 2 from those of Fig. 1. Although we do not yet fully understand these dynamic experiments, it seems evident that they are quite sensitive to both molecular collision and precession. We plan further experiments in the belief that they will shed light on the magnetothermal gas torque.

Finally, we should mention that we have also made measurements with transverse modulating

fields. Although we did observe results similar to those of Fig. 1, experimental difficulties forced us to devote most of our efforts to the longitudinal mode.

Note added in proof.—Borman, Gorelik, Nikolaev, and Sinitsyn[12] have measured the effect of an alternating magnetic field on the thermal conductivity of oxygen and have observed an effect related to molecular precession.

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VELOCITY OF SECOND SOUND NEAR THE λ POINT OF HELIUM

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We report measurements of the velocity of second sound near T_λ. It is found to vanish with the 0.386 power of $T_\lambda - T$. The results confirm the theoretical expression and permit a direct asymptotic comparison for the first time of independent but theoretically equal quantities.

We have measured the velocity of second sound, U_2, as a function of temperature near the λ transition of helium. The results, which extend from 2×10^{-4} to 4×10^{-1} deg below T_λ, are shown in Fig. 1, which displays on a log-log plot the square of the measured velocity as a function of the temperature difference $t = T_\lambda - T$. The straight line given by

$$U_p^{\,2} = 1203 t^{0.772} (\mathrm{m/sec})^2 \qquad (1)$$

represents the data well for $t < 0.08$°K, the exponent being determined with a nominal uncertainty of ±0.005. In spite of this agreement, however, (1) is almost certainly not the correct asymptotic form.

The second-sound velocity was determined by observing the resonant frequency of a rectangular ($3\times4\times4$ cm) cavity made of lavite and Perspex. The cavity is the same one, slightly modified, as described elsewhere.[1] Absolute velocities could be determined with an estimated error of 2%, it being assumed that no systematic error, such as temperature-dependent end effect, was involved in the conversion from frequency to velocity.

The temperature of the helium was measured with a carbon resistance thermometer embedded in a copper block sunk into the floor of the cavity. Temperature differences and, by extrapolation, the origin of t could be determined with a precision of $\pm2\times10^{-5}$ °K, suitable for the medium resolution for which the experiment was intended.

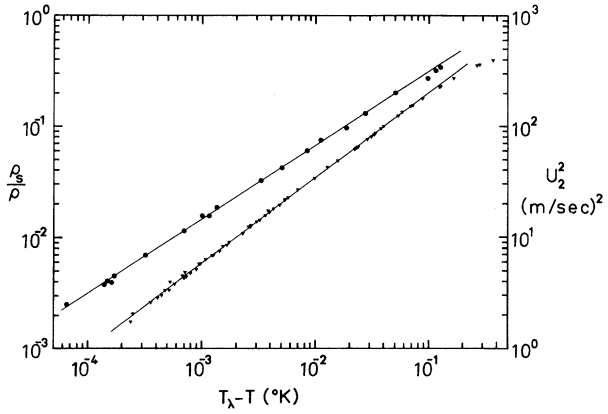

FIG. 1. Measured values of U_2^2 (triangles, right scale) shown as a function of $T_\lambda - T$ on logarithmic scales. Also shown (full circles, left scale) are values of ρ_S/ρ measured by Tyson and Douglass, Ref. 5. The straight lines represent the simple power expressions (1) and (3) in the text.