Influence of nuclear spin couplings on the thermomagnetic torque in HD

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(Received 18 December 1973)

Burgmans, Wang, and Adair[1] recently measured the thermomagnetic torque (TMT) for HD at 330 K and 91 K. The purpose of this communication is to explain the anomalous curves that they present.

The TMT is a Burnett effect that arises from the collisional alignment of nonspherical molecules.[2] This produces polarizations in angular momentum, J space, and angular momentum–velocity, W–J space, where W is the reduced velocity. An applied magnetic field causes J to precess about the field direction with a Larmor frequency ω_J (corresponding to $\Delta m_J \neq 0$). This continues for a free flight time τ_f, after which collisions interrupt the precessional motion. There is thus a competition between the precessional motion and the collision rate.[3] The maximum contribution to the TMT occurs when $\omega_J \tau_f = 1$. Since, in the binary collision regime $\tau_f \propto 1/p$, where p is the pressure and $\omega_J \propto H$, this Burnett effect is found to be a universal function of the form $1/p\, f(H/p)$ for most gases.[4]

For HD, however, the effects of nuclear spin couplings between the proton spin of $\frac{1}{2}$, the deuteron spin of 1, and the rotational angular momentum J modify the Larmor precession. The energy level diagram including these hyperfine interactions is quite complicated, especially for the field strengths at which the TMT experiments are carried out. Figure (1) gives the energy levels[5] for HD for the case that $J = 1$. This is sufficient to describe the situation at 91 K (see the population diagram, Fig. (6) of Ref. 1). The $|Fm_F\rangle$ representation ($F = J + I_p + I_D$) is appropriate at low fields, while the $|Jm_J I_p m_p I_D m_D\rangle$ representation is used for high fields.

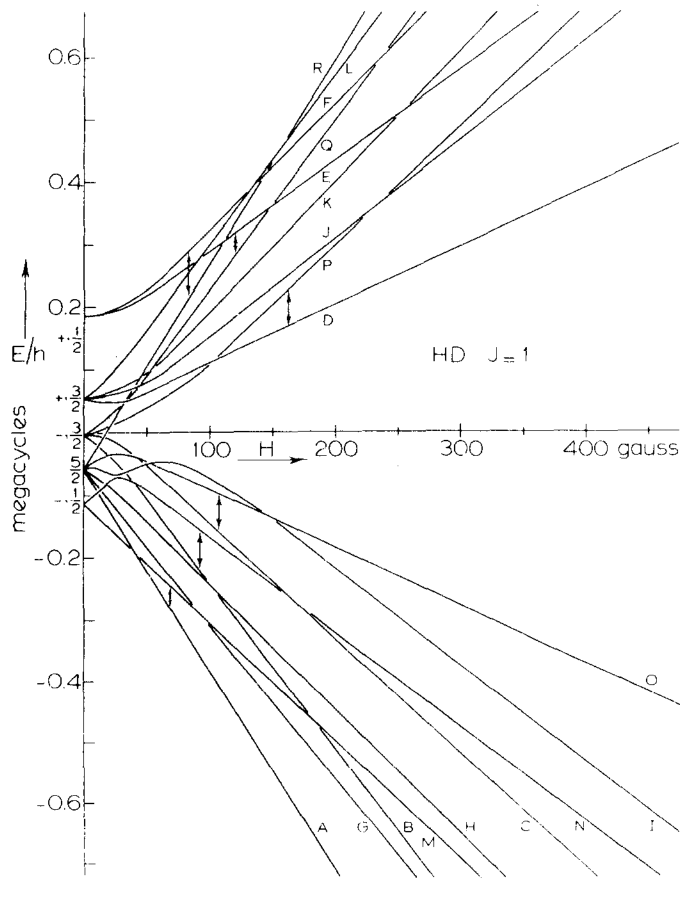

FIG. 1. Energy levels of HD in the first rotational state as functions of magnetic field. The letters refer to a notation of Ramsey and Lewis.[5]

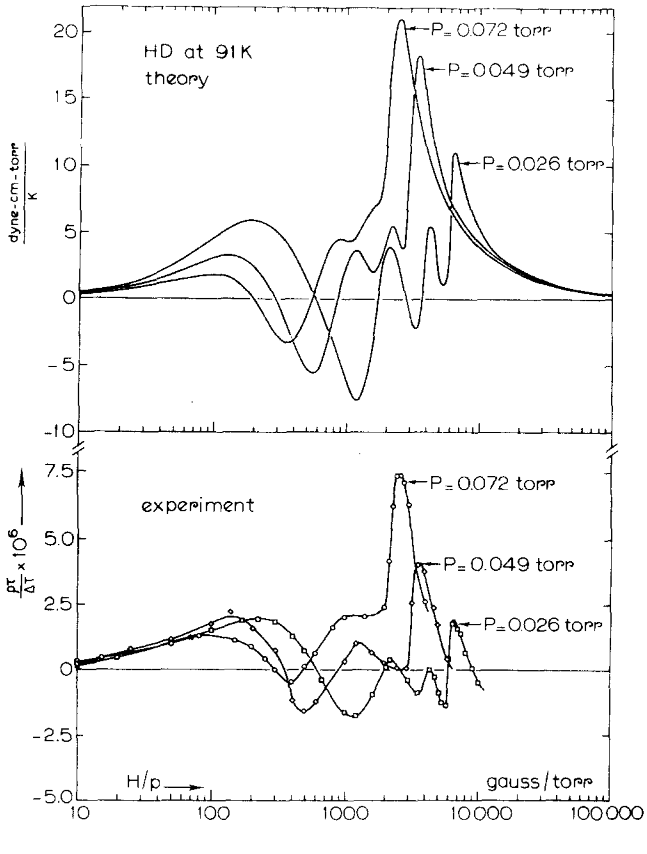

FIG. 2. The theoretical and experimental thermomagnetic torque τ for HD at 0.072, 0.049, and 0.026 torr and at 91 K.

Owing to the coupling between the nuclear spins and J, the $\Delta m_J \neq 0$ selection rule is changed to $\Delta m_F \neq 0$, and many more transitions are possible. There are two classes of transitions: (1) those that do not involve spin transitions, $\Delta m_F = \Delta m_J \neq 0$ and $\Delta m_p = \Delta m_D = 0$, and (2) those that involve spin transitions, $\Delta m_F \neq 0$ with $\Delta m_p \neq 0$ or $\Delta m_D \neq 0$. The importance of each component to the TMT depends on two factors: $\omega\tau_f$ must be of the order of one and, simultaneously, the transition probability must be nonnegligible. At low fields where there is much mixing of the states, all the components have about the same—small—intensity, while at high fields the transition probabilities for class (1) frequencies are much larger than those of class (2).

The results of theoretical calculations for the TMT which include all the effects described above, are given in Fig. (2). All coefficients and constants are known from other sources, and there are no adjustable parameters. The lower part of Fig. (2) displays the experimental curves of Ref. (1), Fig. (8). In comparing the theoretical and experimental curves in Fig. (2), it is seen that the positions of the peaks are accurately predicted. The differences in intensities may be due to the fact that the experimental results have not been corrected for Knudsen effects and that there is a small contribution for $J=2$ that is not included in the theory.

The structure in the curves results mostly from crossings of certain levels which belong to class (1) transitions. These ($\Delta m_F = \Delta m_J = 2$) transitions are indicated on Fig. (1) by arrows. In fact, the H/p values at which the peaks occur are determined by the field strength at the crossings divided by the pressure. Details will appear soon in Physica.[6]

This work is supported by the National Research Council of Canada and by the research program of the "Stichting voor Fundamenteel Onderzoek der Materie (F.O.M.)" and has been made possible by financial support from the "Nederlandse Organisatie voor Zuiver Wetenschappelijk Onderzoek (Z.W.O.)."

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