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This Week's Citation Classic®

Beenakker J J M & McCourt F R. Magnetic and electric effects on transport properties. *Annu. Rev. Phys. Chem.* 21:47-72, 1970.
[Kamerlingh Onnes Laboratorium, Leiden, The Netherlands]

In 1963 it was shown that the influence of a magnetic field on gaseous transport properties was not limited to paramagnetic molecules but was a general property of all rotating molecules. This paper reviewed the field at that time. [The *SCI*® indicates that this paper has been cited in over 210 publications.]

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A remark by C.J. Gorter, well known for his low-temperature research on magnetism in Leiden, drew my attention to the fact that the Senftleben effect[1,2] still had some poorly understood aspects. I was just starting work in the field of molecular physics and, to be honest, I did not even know that such an effect existed, although kinetic theory had always fascinated me. Gorter explained to me how the precession of the magnetic moment of paramagnetic molecules, such as oxygen, gives rise to a change in the transport properties of these gases, an explanation that he came up with first.[3]

In the late 1950s a central problem in kinetic theory of simple gases was the influence of the nonspherical interaction between molecules on the gaseous properties. It was also the time of the revival of molecular beam-scattering experiments. One day I was considering the possibility of using polarized beams to get information on nonsphericity effects in collisions. The most elegant way seemed to be by comparing the polarized situation with the nonpolarized one. From studies of molecular beams I had learned that all rotating molecules had a small magnetic moment arising from their rotation. So I considered the possibility of using the precession of the moment in a magnetic field to depolarize the beam.

When I remembered Gorter's story on the Senftleben effect, I suddenly realized that all rotating molecules ought to show an effect similar to that of oxygen in a magnetic field under similar precession conditions; the smaller magnetic moment required only larger fields and longer free-flight time to make the precession mechanism effective. This was the basis of an experimental breakthrough in Leiden.

At nearly the same time, in Moscow, Yu.M. Kagan showed how the distribution of molecular angular momentum was no longer isotropic in the presence of a gradient of a macroscopic property such as temperature. Together with L.A. Maksimov[4] he was able to explain Senftleben's results on oxygen in terms of precessional destruction of this nonequilibrium polarization.

Also at that time, in Vancouver, Bob Snider had a PhD student, F.R. McCourt, working on the role of molecular angular momentum in transport properties starting from his (and L. Waldmann's from Erlangen) quantum mechanical extension of the Boltzmann equation. During the course of his work McCourt became familiar with both the Leiden and the Moscow results. The combination of the two was the subject of his thesis. Subsequently, he went as a postdoctoral fellow to the Leiden group. This was the start of a fruitful and still-existing cooperation. One result was the 1970 paper.

Why has this paper been cited so often? I guess because the generalized Senftleben effect became an important tool in the study of polyatomic gases. The paper is still the most easily accessible introduction to the subject. In fact, so far, no modern book on kinetic theory adequately treats rotating molecules as well, a gap we hope to fill shortly.[5]

The idea of the role of anisotropy in angular momentum—"nonequilibrium polarization"—has been a fruitful one. Not only has it been applied to the dilute gas regime, but it has also proven to be a useful tool in studying the rarefied gases[6] and the effects of molecular orientation in boundary-layer phenomena and in molecule-surface collisions.[7,8]

1. **Senftleben H.** Einfluss eines Magnetfeldes auf das Wärmeleitvermögen von paramagnetischen Gasen (Effects of magnetic fields on paramagnetic gas heat conductivity). *Phys. Z.* 31:822, 1930. (Cited 50 times since 1955.)
2. ————. Magnetische Beeinflussung des Wärmeleitvermögens paramagnetischer Gase (Further studies concerning the effects of magnetic fields on paramagnetic gas heat conductivity). *Phys. Z.* 31:961-3, 1930. (Cited 80 times since 1955.)
3. **Gorter C J.** Zur Interpretierung des Senftleben-Effektes (Interpretation of the Senftleben effect). *Naturwissenschaften* 26:140, 1938. (Cited 35 times since 1955.)
4. **Kagan Yu M & Maksimov L A.** Transport phenomena in a paramagnetic gas. *Sov. Phys. JETP* 14:604-10, 1962. [Translated from: *Zh. Eksp. Teor. Fiz. SSSR* 41:842-52, 1961.] (Cited 120 times.)
5. **McCourt F R, Beenakker J J M, Kohler W & Kuscer I.** Nonequilibrium phenomena in polyatomic cases. (In preparation.)
6. **Ten Bosch B I M, Beenakker J J M & Kuscer I.** Field-dependent viscous flow in rarefied molecular gas. *Physica A* 134:522-42, 1986.
7. **Borman V D, Krylov S U, Maksimov L A, Nikolaev B I & Troyan V I.** On kinetic thermomagnetic phenomena in polyatomic Knudsen gases. *Phys. Lett. A* 67:25-7, 1978.
8. **Hermans L J F, van der Tol J J G M & Beenakker J J M.** Angular momentum polarization produced by molecule-surface collisions in a Knudsen flow. *J. Chem. Phys.* 84:1029-33, 1986.

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