Giant opalescence and anomalous magnetokinetic effects in spin-polarized gases

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The scattering of particles by fluctuations of the transverse magnetization in gaseous Rb↑, ^{3}He↑, and H↑ and also in other systems of this type makes low-density gases opaque to molecular beams, produces anomalies in the scattering of light and neutrons, and reduces the mean free path in the gas.

1. Spin-polarized gases have several surprising properties, which are presently the subject of extensive theoretical and experimental research.[1] The interaction of paramagnetic molecules with fluctuations of the transverse magnetization in such gases may be stronger than the interaction of these molecules with each other. If so, there are major implications for kinetic problems. Transverse fluctuations of this sort may be of the nature of either a homogeneous precession of the magnetization or slightly inhomogeneous spin waves.[1] For definiteness, we consider the case of spin-1/2 particles. The Hamiltonian of the interaction of a particle with the field of fluctuations of the magnetic induction vector $\mathbf{B}(\mathbf{r},t)$ is written in the standard form $\hat{H} = -\beta_0\vec{\sigma}\mathbf{B}$, where $\vec{\sigma}$ are the Pauli matrices, and β_0 is the magnetic moment of the particle. Using this Hamiltonian to calculate the probability for the transition $|\mathbf{p}\rangle \to \langle\mathbf{p}'|$, where $\mathbf{p}$ is the momentum of the particle; averaging this probability over the fluctuations of the magnetic induction, using the magnetostatic equations; and normalizing the initial wave function to a unit flux density, we find the scattering cross section per gas atom to be (cf. Ref. 2)

$$d\sigma = \frac{1}{2vN}\left(\frac{4\pi\beta_0}{\hbar}\right)^2 (1+\cos^2\theta) S_{ii}(\omega,\mathbf{q}) \frac{d^3p'}{(2\pi\hbar)^3}, \qquad (1)$$

where $v = p/m_0$ is the initial velocity of the particle, N is the number of gas atoms per unit volume, θ is the angle between the vector $\hbar\mathbf{q} = \mathbf{p} - \mathbf{p}'$ and the spin-polarization vector (the z axis), $\hbar\omega = (p^2 - p'^2)/2m_0$, $S_{ik}(\omega,\mathbf{q})$ is the dynamic magnetic form factor of the gas, and a repeated index means a summation. Expression (1) presupposes a small momentum transfer $qr_0 \ll 1$, where r_0 is an atomic dimension. In this case, we can ignore the effect of nonuniform microfields over distances on the order of r_0, and we can assume that the atomic form factor is equal to unity. Cross section (1) describes the scattering of unpolarized particles. The cross section for the scattering of polarized particles with conservation of spin orientation, $d\sigma_{\uparrow\uparrow}$, is found from (1) by replacing the numerical factor $(1+\cos^2\theta)$ by $\sin^2 2\theta/4$. The scattering of polarized particles with spin flip is characterized by the cross section $d\sigma_{\uparrow\downarrow} = d\sigma - d\sigma_{\uparrow\uparrow}$. In (1) we have ignored the component S_{zz}, as we are always justified in doing in the case $\omega \sim \omega_S \gg \tau^{-1}$ if the condition $\alpha\tau(\omega_S\tau_S) \gg \hbar$ holds. Here ω_S and τ are the frequency and relaxation

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time of the transverse spin fluctuation, and $\tau_S \gg \tau$ is the long relativistic relaxation time of the longitudinal magnetization. For the function $S_{ii}(\omega,\mathbf{q})$ in (1) we have[1]

$$S_{ii}(\omega,\mathbf{q}) = 4\pi\beta^2 N\alpha(1-e^{-\hbar\omega/T})^{-1}\,[\delta(\omega-\omega_S)-\delta(\omega+\omega_S)],\quad \alpha=(N_\uparrow - N_\downarrow)/N, \tag{2}$$

where β is the magnetic moment of a gas particle. A finite damping of the fluctuations can be incorporated in (2) through the replacement

$$\delta(\omega \mp \omega_S) \to \{\pi\tau\,[(\omega\mp\omega_S)^2+\tau^{-2}]\}^{-1}\,. \tag{3}$$

2. We first consider the inelastic scattering of particles by quanta of the homogeneous precession in an external magnetic field $\mathbf{H}\uparrow\uparrow\mathbf{z}$. In this case we have $\omega_S = \Omega_H = 2\beta H/\hbar$ and $\tau \sim \tau_S$, and from (1) and (2) we immediately find, under the condition $\Omega_H \tau > 1$

$$d\sigma = 2\pi(4\beta\beta_0 m_0/\hbar^2)^2\,(1+\cos^2\theta)\,\alpha\,\frac{T}{\hbar\Omega_H}\,\frac{do'}{4\pi}\,, \tag{4}$$

where m_0 is the mass of the scattered particle. If $\alpha=\text{const}$, the H dependence of the scattering cross section is thus resonant: $d\sigma$ increases with decreasing H in accordance with (4), goes through a maximum at $\Omega_H \sim \tau^{-1}$, and then begins to fall off as the magnetic field is reduced further. This situation can be realized if the external magnetic field is scanned rapidly in comparison with τ_S. The most convenient subjects for such studies are gases in which the spins of the particles are polarized by an external source, usually through optical pumping. The lifetime of a spin-polarized state of a gas after the pump is turned off can be extremely long (in gaseous ^{3}He↑, e.g., τ_S is more than 2 days[3]). By immersing such a gas in a weak magnetic field we could arrange a situation such that for certain values $H \leqslant H_C$ the cross section for inelastic scattering by magnetization fluctuations begins to exceed the cross section for the scattering of particles by each other, with major implications for the kinetic properties of the gas.

As an illustration, we consider the passage of a rather cold ($pr_0 \ll \hbar$) particle beam through gaseous Rb↑, ^{3}He↑, and H↑, in the direction parallel to the spin-polarization vector (and parallel to the magnetic field $\mathbf{H}$). Cold beams of this sort could be produced, for example, from hydrogen atoms at low temperatures or from other specially cooled paramagnetic molecules, e.g., atoms of alkali metals. For example, the temperature of a beam of hydrogen atoms should be no greater than 50 K, and for a beam of cesium atoms we would have $T<0.4$ K. Extremely low beam temperatures, $T\sim0.24$ mK, have now been achieved by laser cooling; such temperatures would be sufficient by a wide margin for satisfying the "slowness" condition $pr_0 \ll \hbar$. Under ordinary conditions, a layer of gaseous Rb with a thickness $d=1$ cm, with $N=10^{10}$ cm^{-3} and $T=40°$ C, would be absolutely transparent to any atomic beam. For the scattering of a Cs beam by Rb↑ with $\alpha=0.9$ and the same values of N and T, on the other hand, the field H_c would be 9.5×10^7 G, while at $H<950$ G the mean free path of the beam particles [which is determined by cross section (4) at $H<H_c$] becomes less than 1 cm. In other words, the gas becomes totally opaque to a beam of Cs atoms. The values of H_c for the scattering of Cs atoms by ^{3}He↑ ($\alpha=0.5$, $T=6$ K) and $H\uparrow$ ($\alpha\approx1$,

$T = 0.25$ K) are 1.2 kG and 85 kG, respectively. The values of H_c for the scattering of a H beam by Rb↑, ^{3}He↑, H↑ are far lower, 5 kG, 0.07 G, and 4 G, respectively. At $H < H_c$ it is always possible to find values of N and d for which the gas will completely scatter an atomic beam but will be absolutely transparent to the beam at $H > H_c$ or if there is no spin polarization.

While the numerical estimates found above with the help of (4) are absolutely rigorous for gaseous H↑, and they also are correct, if not absolutely, for ^{3}He↑, they may turn out to be far too high in the case of Rb↑ and to serve instead as upper limits on the effect. The reason is that, although the probing beam is cold, the atoms of a gaseous Rb↑ target at $T = 40$ °C themselves do not come close to satisfying the condition $pr_0 \ll \hbar$, so that an additional factor of the nature of a magnetic form factor may arise and cause a decrease in cross section (4). However, despite the fact that the parameter $pr_0/\hbar$ is large, $pr_0/\hbar \approx 24$, there is also a huge margin in terms of the possibility of reducing the magnetic field, $2\beta H_c \tau/\hbar \approx 5 \times 10^{12}$, so that there is reason to hope that the effect can be observed even at room temperature.

For certain media the effect described here could be observed on the basis of the scattering of neutrons or light. In the latter case, the extinction coefficient for an arbitrary value of the parameter $\Omega_H \tau$ would be

$$dh = 2\pi \left(\frac{4\beta^2 k}{\hbar c}\right)^2 \epsilon N \alpha \frac{T}{\hbar \Omega_H} \frac{\Omega_H^2}{\Omega_H^2 + \tau^{-2}} \frac{do'}{4\pi}, \quad (5)$$

where ϵ is the dielectric constant, and k is the wave number of the light. In a cold gas, $T \ll \hbar^2/mr_0^2$ (H↑ or a liquid solution of ^{3}He↑–^{4}He), these effects would influence the kinetic coefficients proper. In the ^{3}He↑–^{4}He solution, these effects would limit the growth of the mean free path and of the kinetic coefficients in the limit[1,5] $\alpha \to 1$; in gaseous H↑ at $H < H_c = 4$ G, under which conditions the collisions between atoms and thus the primary recombination mechanism are effectively suppressed, we would expect some increase in the lifetime of atomic hydrogen in a weak field $H < H_c$.

3. The existence of nuclear spin waves[1] in gaseous H↑ leads to the appearance of yet another resonant peak on the curve of $d\sigma(H)$. For the scattering of particles by spin waves we need to replace ω_S and Ω_H in (2)–(4) by the frequency of a collective mode:

$$\omega_S = \Omega_H - \frac{(q v_T)^2}{|\Omega_{int}|}, \quad \Omega_{int} = - \frac{4\pi a \hbar N \alpha}{m}, \quad v_T^2 = \frac{T}{m}, \quad (6)$$

where $a = 0.72$ Å. In strong fields, the spin mode "softens" ($\omega_S = 0$) and the cross section $d\sigma$ increase sharply. At $T = 0.25$ K, $H = 7$ T, and $N = 10^{18}$ cm^{-3}, the resonance condition $\omega_S \approx 0$ corresponds to very small scattering angles, $\gamma = 0.2°$. The maximum of $d\sigma$ is reached at $\omega_S \sim (qv_T^2)^2/\Omega_{\rm int}^2 D_0$, where D_0 is the spin diffusion coefficients of the gas. The detailed results will be published separately.

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