# New mechanism for spin-flip scattering in spin-polarized gases

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A new exchange mechanism is proposed for transport phenomena which occur in spin-polarized systems and which are accompanied by a spin flip of the scattered particle and the emission or absorption of a collective spin wave. The corresponding scattering cross section turns out to be anomalously large. This circumstance may strongly influence the stability of H↑ and D↑ and may lead to giant effects in neutron optics.

The existence of collective spin waves in polarized gases[1] plays an extremely important role and signifies the presence of an additional Bose branch of excitations in the system. The interaction of the actual gas particles (fermions or bosons) with such collective excitations—magnons—may turn out to be very important. It has usually been assumed that the scattering of paramagnetic particles by spin waves is a purely relativistic process and is a consequence of a Zeeman interaction of the spin of the particle with the magnetic field induced by the oscillating macroscopic magnetic moment $\mathbf{M}(r,t)$. Nevertheless, under certain conditions even such a weak magnetostatic coupling has resulted in an anomalously large scattering cross section.[2] The basic assertion of the present letter is that in polarized gases (and Fermi liquids) a direct exchange mechanism involving an inelastic scattering of particles by thermal fluctuations of the transverse magnetization operates. The cross section for the process turns out to be on the order of the ordinary gas-kinetics cross section for the elastic scattering of particles by each other; it is significantly larger under certain special conditions.

The existence of spin waves in low-density gases is a consequence of quantum refraction effects, which lead to the appearance of a sort of self-consistent field of a Fermi-liquid type, which is exerted on each atom of the gas by all of the other particles. An important point is that the formation of such a field occurs at distances shorter than a mean free path. The existence of an effective average field is expressed in the appearance of a specific term in the self-energy of the particle. This term is a linear functional of the distribution function of the gas atoms.[1] If the temperature is not too high, $T \ll \hbar^2/ma^2$, where $m$ is the mass of the particle, and $a$ the scattering length (if the gas is degenerate, this condition holds automatically), the interaction is dominated by $s$-wave scattering, whose amplitude $(-a)$ does not depend on the momenta. In this case the integration in the linear functional becomes a trivial matter and leads to the expression

$$\hat{V} = gN(\mathbf{r},t) - \frac{1}{\beta} g\vec{\sigma}\mathbf{M}(\mathbf{r},t), \qquad g \equiv \frac{2\pi\hbar^2}{m}a, \tag{1}$$

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where $\beta$ is the magnetic moment of the particle, $\vec{\sigma}$ are the Pauli matrices, and $N$ is the atomic density. The second term in (1) describes the interaction of a gas particle with the macroscopic magnetization distribution, in this case with the oscillating magnetic moment in the field of the spin wave. We are interested in the probability for the emission or absorption of a magnon by a gas particle. For definiteness, we consider a system of spin-1/2 particles. Since we are concerned with only the exchange interaction, it is obvious at the outset (and verified by the subsequent calculations) that only two processes (Fig. 1), in which the total magnetic moment is conserved, are possible. In each process, the spin of a gas atom flips; this flipping is offset by the magnetic moment of the spin wave which is emitted or absorbed. In a sense, the spin wave may be thought of as a delocalized and collectivized flipped spin. Standard calculations[3] with Hamiltonian (1) lead to the differential cross section

$$d\sigma_{\alpha\beta} = \frac{2m}{pN}\left(\frac{g}{\beta\hbar}\right)^2 [\sigma^x_{\alpha\beta} S_{xx}(\omega, \mathbf{q}) - \sigma^y_{\alpha\beta} S_{xy}(\omega, \mathbf{q})] \frac{d^3p'}{(2\pi\hbar)^3}, \qquad (2)$$

$$\hbar\omega = \frac{1}{2m}(p^2 - p'^2) - \beta H(\sigma^z_{\beta\beta} - \sigma^z_{\alpha\alpha}),$$

where $\alpha$ and $\beta$ are spin indices, $S_{xx} = S_{yy}$ and $S_{xy} = -S_{yx}$ are components of the dynamic magnetic structure factor (the Fourier transform of the magnetization correlation function), and $H$ is the external magnetic field. Using the relation

$$S_{ik}(\omega, \mathbf{q}) = -i\hbar(1 - e^{-\hbar\omega/T})^{-1}[\chi_{ik}(\omega, \mathbf{q}) - \chi^*_{kl}(\omega, \mathbf{q})], \qquad (3)$$

we can easily express cross section (2) in terms of the circular components of the magnetic susceptibility, $\chi_{\pm} = \chi_{xx} \pm i\chi_{yx}$:

$$d\sigma_{\uparrow\downarrow} \equiv d\sigma_1 = \mathrm{Im}\chi_+(\omega, \mathbf{q}) A d\Gamma'; \quad d\sigma_{\downarrow\uparrow} \equiv d\sigma_2 = -\mathrm{Im}\chi_+(-\omega, -\mathbf{q}) A d\Gamma', \qquad (4)$$

$$A d\Gamma' = 4\hbar(m/pN)(g/\beta\hbar)^2 (1 - e^{-\hbar\omega/T})^{-1} d^3p'/(2\pi\hbar)^3.$$

For spin waves which are damped only slightly we have

$$\mathrm{Im}\chi_+(\omega, \mathbf{q}) = \frac{2\pi}{\hbar}\beta^2 N\alpha\delta(\omega - \omega_q), \quad \alpha = \frac{N_\uparrow - N_\downarrow}{N}, \qquad (5)$$

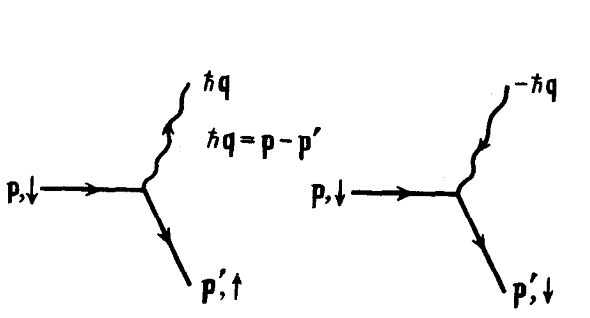


FIG. 1.

where $\hbar\omega_q$ is the magnon energy, given by[1]

$$\omega_q = \Omega_H - \frac{1}{3}\frac{\hbar q^2}{m}\frac{E_\uparrow - E_\downarrow}{g(N\alpha)^2}. \tag{6}$$

Here $\Omega_H = 2\beta H/\hbar$ is the Larmor precession frequency, and $E_{\uparrow,\downarrow}$ is the total energy of each of the spin components in the approximation of an ideal gas. In the temperature region under consideration here, all of the momenta are small: $p|a| \ll \hbar$. Furthermore, Landau damping limits the region of wave vectors $\mathbf{q}$ to fairly small values, so the second term in (6) will usually be considerably smaller than the first. In the leading approximation we can thus restrict the dispersion law for the spin waves to the Larmor gap, $\omega_q \approx \Omega_H$. We then finally find the following expressions for the total cross sections ($\Omega_H \tau_s \gg 1$, where $\tau_s$ is the relativistic relaxation time of the longitudinal magnetization):

$$\sigma_1 = 16\pi a^2\alpha(1 - e^{-\hbar\Omega_H/T})^{-1} = 16\pi a^2\alpha(N_m + 1) \tag{7}$$
$$\sigma_2 = 16\pi a^2\alpha(e^{\hbar\Omega_H/T} - 1)^{-1} = 16\pi a^2\alpha N_m ,$$

where $N_m$ is the number of magnons (uniform-precession quanta) at the given temperature, so Einstein's relations for the emission and absorption probabilities hold automatically. The mechanism described here may have a very important effect on the transport properties of spin-polarized gases and on the stability of atomic H↑ and D↑, since the spin flip in this case leads to a recombination of atoms into $H_2$ and $D_2$ molecules.[4–6] The contribution of scattering (7) may turn out to be huge in systems of particles with a nuclear spin ($^3$He↑, the nuclear dynamics of H↑, etc.), in which it is a simple matter to arrange a long-lived state with a high degree of polarization $\alpha$, but in weak magnetic fields, $\beta H \ll T$. As an illustration, we find the cross section for the depolarization of a beam of slow neutrons with spins oriented along the field as this beam passes through a target of gaseous $^3$He↑ with the typical experimental parameter values[7] $\alpha \approx 0.5$, $T \approx 2$ K, and $H \approx 1$ G. The cross section is found from (7), in which we shoud replace $a$ by $a_{ex} = (a_+ - a_-)/4$, where $a_\pm$ is the triplet and singlet scattering length for the elastic scattering of a neutron by a nucleus:

$$\sigma_2 \approx 16\pi a_{ex}^2 \alpha \frac{T}{\hbar\Omega_H} \sim 10^6 \text{ b}. \tag{8}$$

The cross section for the process turns out to be huge, greater than the cross section for the capture of a neutron by a $^3$He nucleus in singlet scattering.

Similar calculations with the first term in Hamiltonian (1) lead to the result

$$d\sigma = \frac{m}{pN}\left(\frac{g}{\hbar}\right)^2 G(\omega, \mathbf{q}) \frac{d^3p'}{(2\pi\hbar)^3}, \tag{9}$$

where $G(\omega,\mathbf{q})$ is a dynamic form factor for the density correlations. Expression (9) describes an inelastic scattering of gas atoms which is accompanied by the emission or absorption of phonons (or of zero-sound quanta in the case of a highly degenerate Fermi gas).

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