Spin waves in polarized paramagnetic gases

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Weakly damped magnetization oscillations can propagate in paramagnetic gases with unequal spin-state populations (external magnetic field and dynamic polarization). The spectrum of these oscillations is obtained.

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The classical Boltzmann equation, whose kinematic part corresponds to the free motion of gas molecules, is usually used to study the properties of gases, and all changes in the particle states are described by the collision integral. On the other hand, specific linear terms with respect to the dispersion amplitude, which describe the unique, self-consistent interaction (Fermi-liquid type) of the gas particles, appear in the kinematic part of the quantum-mechanical derivation of the kinetic equation.

It is easy to see that at sufficiently low temperatures, when $r_0 < < \lambda$ (λ is the de

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Broglie wavelength and r_0 is the interaction radius of the gas molecules), these essentially quantum corrections in the kinetic equation are much larger than the nonlocal terms in the expansion of the collision integral in gradients of the distribution function. Therefore, for $r_0 << \lambda$ allowance for the quantum corrections in the Boltzmann equation with a local collision integral does not exceed the accuracy and may produce collective effects in the gas. Unfortunately, the propagation of collective, high-frequency modes (zero-sound or spin-wave type in a Fermi liquid[1]) in the absence of external fields is impossible in a Boltzmann gas, because of strong Čerenkov absorption. This changes completely, however, as a result of polarization of the magnetic moments of gas molecules; this can be achieved by turning on the external magnetic field and by using dynamic polarization methods (optical pumping or injection of a polarized beam). A change of the magnetic symmetry of the system gives rise to the propagation of magnetization oscillations with a quadratic dispersion law.[2-5] The collisionless damping of long-wave modes is exponentially small.

1. Because of the condition $r_0 << \lambda$, the gaseous paramagnetic materials, in which such quantum effects are observed, are primarily ^{3}He and different hydrogen modifications (atomic hydrogen, orthohydrogen, deuterium, and HD). In this case, the kinetic equation is obtained by the standard method. The true interaction potential of gas molecules is replaced by the pseudopotential, which makes it possible to use the perturbation theory. The commutator of the density matrix and the Hamiltonian with the pseudopotential are calculated in the form of the perturbation-theory series, and the final result is expressed in terms of the true length a of the s scattering. This procedure is equivalent to the addition of a certain self-consistent term that is linear in a to the Hamiltonian function of the particle in the kinetic equation. Specifically, we shall examine Fermi particles with spin $\frac{1}{2}$. The spin part of the self-consistent correction $\delta\hat{\epsilon}$ to the energy of the molecule is

$$\delta\hat{\epsilon} = -\frac{4\pi a\hbar^2}{m}\sum_{\mathbf{p}}\hat{n}_{\mathbf{p}}, \tag{1}$$

where $\hat{n}$ is the spin part of the density matrix, m is the particle mass, and $\mathbf{p}$ is the momentum. The equilibrium value of $\hat{n}$ is defined by the expression

$$\hat{n}^{(0)}_{\mathbf{p}} = \frac{1}{2}(n^+_{\mathbf{p}} - n^-_{\mathbf{p}})\vec{\sigma}\vec{\mathscr{M}}. \tag{2}$$

Here $n^{\pm}_{\mathbf{p}}$ are the equilibrium distribution functions of particles with spins oriented in the direction of magnetic polarization $\vec{\mathscr{M}}$ and $\vec{\sigma}$ are the Pauli matrices. The solution of the linearized kinetic equation using Eqs. (1)-(2) determines the spectrum of magnetization oscillation in the plane perpendicular to $\mathscr{M}$. If the spin system is polarized by injection of a polarized beam or by pumping optical (the external magnetic field is subsequently turned off), then the dispersion law of oscillations must have the form

$$\omega = -\frac{(kv_T)^2}{\Omega_{int}}, \qquad \Omega_{int} = \frac{4\pi a\hbar}{m}Na, \tag{3}$$

where ω and $\mathbf{k}$ are the frequency and wave vector of the spin wave, $v_T = (T/m)^{1/2}$ is the thermal velocity of gas molecules, N is the number of molecules in a unit volume, and $\alpha = (N_+ - N_-)/N$ is the degree of polarization. The smallness condition of the relaxation absorption (in the exchange approximation) and the collisionless absorption determines the range of k values and the condition for α

$$1 >> (kr_{int})^2 >> Na^2 r_{int}, \quad r_{int} = v_T/\Omega_{int} \tag{4}$$

$$\alpha >> |a|/\lambda.$$

Because of the condition $N\lambda^3 < < 1$, the inequality $k\lambda < < 1$ is satisfied automatically. We emphasize that in this case we are dealing with a magnetically nonequilibrium system, which can exist a relatively long time, since the time of the spin flip due to weak relativistic interactions is much longer than the time needed to establish the momentum equilibrium of gas particles.

At the present time, optical pumping is capable of polarizing gaseous ^3He to values $\alpha = 0.3$–0.6.[6,7] Under these conditions, weakly damped spin modes can propagate with wavelengths of the order of $10^{-3} - 10^{-2}$ cm at temperatures $T < < 100$ K. If the spin system is polarized by a magnetic field **H**, then an energy gap γH (γ is the gyromagnetic ratio), which corresponds to free precession of the magnetic moments, will appear in Eq. (3) which defines the magnon spectrum. In experiments with spin-polarized atomic hydrogen[8,9] it was possible to obtain a long-lived $H\uparrow$ state with $N \approx 10^{16}$–10^{17} cm^{-3} at $T = 0.3$ K and $H = 80$–100 kOe. In this case, the magnetization oscillations with $\Omega_{int}/\gamma H \approx 10^{-5}$ also exist.

2. Undamped spin waves can also propagate via the electronic component in a plasma. Suppose that the parameters of a nondegenerate plasma allow the use of perturbation theory both in the thermodynamic as well as quantum-mechanical sense, i. e.,

$$T >> \epsilon_F \sim \hbar^2 N^{2/3}/m, \qquad T >> N^{1/3} e^2, \quad e^2/\hbar v << 1. \tag{5}$$

Thus, we have instead of Eq. (1)

$$\delta \hat{\epsilon} = - \sum_{p'} \zeta_{p-p'} \hat{n}_{p'}, \qquad \zeta_p = 4\pi e^2 \hbar^2/(p^2 + \hbar^2 \kappa^2), \tag{6}$$

where κ^{-1} is the Debye shielding radius. For a sufficiently high electron density $Na_B^3 > > L$ (such densities are reached in experiments with a laser plasma[10]; a_B is the Bohr radius and L is the Coulomb logarithm) we have a temperature region

$$(1/L)(\hbar\omega_L)^2/\mathrm{Ry} >> T >> \epsilon_F, \tag{7}$$

where ω_L is the Langmuir frequency in which the quantum corrections in the kinematic part of the Boltzmann equation due to Eq. (6) are larger than the nonlocal gradient terms in the collision integral. In this case $\epsilon_F > > \hbar\omega_L > > N^{1/3}e^2 > > \mathrm{Ry}$. If the polarization of electron spins is not achieved by an external magnetic field, then the terms attributable to the Lorentz force will be missing in the kinetic equation, and the magnon spectrum will be determined by the equations.

$$\omega = (\alpha N)^{-1} \sum_{\mathbf{p}} \mathbf{k v} g_{\mathbf{p}} (n^{+}_{\mathbf{p}} - n^{-}_{\mathbf{p}}), \tag{8}$$

$$\hbar \mathbf{k v} + \sum_{\mathbf{p}'} \zeta_{\mathbf{p}-\mathbf{p}'} (n^{+}_{\mathbf{p}'} - n^{-}_{\mathbf{p}'})(g_{\mathbf{p}} - g_{\mathbf{p}'}) = 0.$$

Instead of the conditions (4) we now have

$$\kappa\alpha(\hbar\omega_L/T) >> k >> \alpha^{1/2}\kappa(\hbar\omega_L/T)(\mathrm{Ry}/T)^{1/4}L^{1/2},$$
$$\alpha >> (\mathrm{Ry}/T)^{1/2}L. \tag{9}$$

In this case, $k/\kappa << 1$ and $\lambda\kappa << 1$. Under the experimental conditions of Ref. 10 for $N \approx 10^{24}$ cm^{-3} and $T \approx 1$ keV the spin oscillations can exist for $\alpha >> 0.5$. If $T << \epsilon_F$ and $Na_B^3 >> 1$, then the spin-wave spectrum in a degenerate plasma is also determined by Eqs. (8).

We emphasize that in contrast to the cases examined, it is impossible to calculate the magnon spectrum in terms of the local Fermi-liquid function in polarized Fermi systems with a strong interaction, since the quadratic terms with respect to the magnetization gradients in the free energy also give corrections of the order of k^2 to the spin-wave dispersion law. Detailed results will be published later.

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