Zeeman-like degeneracy of a massive ferromagnetic mode: charge effects in the spin channel.

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Abstract

A study of isotropic single-band ferromagnetism under externally applied magnetic fields reveals that a recently derived massive mode carries a degeneracy with respect to chiral symmetry that may be helpful to identify the presence (or absence) of electrical charge in the spins responsible for ferromagnetism. Calculations for an ESR setup are presented and it is seen that such charge effect maybe essential for the observability of the massive mode.

Key words: Magnetism, ferromagnetism, spin-waves

In isotropic single-band ferromagnetism collective excitations have the spin-wave branch as their paradigm. Such branch is the Goldstone mode that results from broken symmetry and hence it disperses as $\omega \sim q^2$ for small values of the wavevector q. The existence of additional observable spin-wave modes in these systems has been pointed out recently,[1] in particular with the prediction of a gapped mode $\omega \sim \omega_1^+ + \alpha q^2$.

This mode carries a degeneracy that results from chiral symmetry in momentum and coordinate space which can be lifted by an external magnetic field only if the spins that give rise to ferromagnetism are charged,[2]

$$\omega \sim \pm eH + \omega_1^+ + \alpha q^2, \tag{1}$$

where e is the charge attached to the spins that form the magnetized background and $\omega_1^+ \sim |\boldsymbol{m}_0|$, where $\boldsymbol{m}_0$ is the equilibrium magnetization. Although such a Zeeman-like effect is expected to show under quite general conditions, Eq.(1) has been obtained in the small moments, long wavelength, and low field limit.

In this short note we report calculations on an ESR transmission setup for a weak ferromagnet including the effect of an external magnetic field. This illustrates how such an experiment could be used to check for the existence of charge associated to the spins in a given ferromagnetic sample. The setup is represented in Fig.(1).

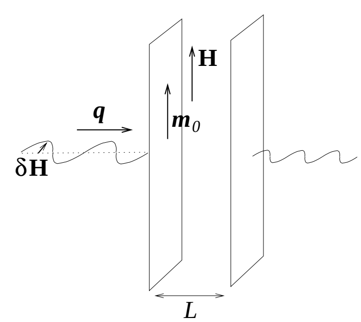

Fig. 1. Suitable geometry for an ESR setup in a metallic sample; transverse field $\delta\mathbf{H}$ due to electromagnetic field (usually in the frequency range of microwaves); $\boldsymbol{m}_0$ is the equilibrium magnetization; One should maximize the ratio between L and the penetration depth δ, while keeping L small enough to ensure that spin will not relax in a trip from one face of the sample to the opposite. Typically $L \sim 200\ \mu$ while $\delta \sim 1\ \mu$.

In order to see how the transmitted field on one side of a metallic slab rates against the insident field, one

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has to solve the boundary value problem for the geometry shown, using Maxwell's equations combined with non-local constitutive relations, in a similar way as in the paramagnetic case.[3] Contrary to the paramagnetic case, in a ferromagnetic metal the equilibrium magnetization is not trivially related to the external magnetic field. Yet the fluctuations do obey a constitutive relation given by

$$\delta m^+(z) = \int_0^L \chi(z,z',\omega)\delta H^+(z')dz', \tag{2}$$

where $\chi(z,z'.\omega)$ is the transverse susceptiblity. The boundary condition of no spin currents flowing through the faces of the slab yields the solution,

$$\chi(z,z',\omega) = \sum_{-\infty}^{+\infty} \cos(q_n z)\cos(q_n z')\chi(q_n,\omega)$$

where $q_n = n\pi/L$ and $\chi(q_n,\omega)$ can be extracted from hydrodynamic equations that govern the fluctuations. Here we use kinetic equations of the Ferromagnetic Fermi liquid theory.[2] The remaining problem is to relate the transmitted and incident fields by eliminating the transverse magnetization, and this is done quite similarly as in the paramagnetic case.[3] Also, in the real experiment, the phase of the field can be controlled through a reference signal, so that the final measured amplitude is given by

$$\frac{H_{\rm out}}{H_{\rm in}} \propto \sum_{-\infty}^{+\infty}(-1)^n S(q_n,\omega),$$

where $S \equiv -\text{Im}[\chi]/\pi$.

Fig.(2) shows the result of a calculation using normalized quantities. The top frame shows the result for a system of charged fermions while the frame below is the same result for uncharged spins. One should note that the existence of side-bands makes it impossible to distinguish whether the higher frequency peaks arise from the Goldstone mode or from the massive mode. Switching the magnetic field on makes it clear, for charged fermions, that in the present example the last peak originates from the gapped mode. This is of course an essential feature in oder to identify the massive branch. The main point we want to stress is that, as seen by comparing the graphs, the existence of a Zeeman-like splitting warrants that magnetism results from charged spins. In MnSi the fields shown correspond to a range $1 < H < 10$ Tesla while the gap is of order of meV. Also, the relation $\sqrt{\alpha/\omega_1^+} = 0.15L/\pi$ has been used, although this choice may represent irrealistically small thicknesses for the particular case of MnSi. Further studies, including other materials will be presented elsewhere.

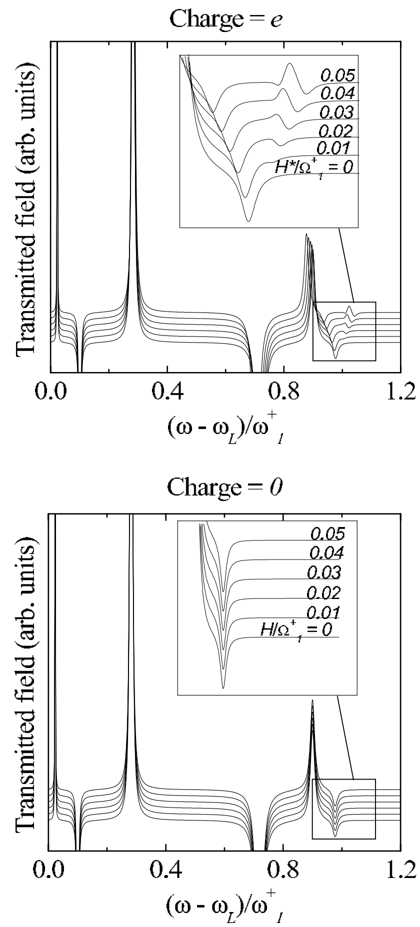

Fig. 2. Transmitted field in the setup represented in Fig(1) The low frequency lines arise from the Goldstone mode, while the gapped mode can only be identified in the higher frequency lines by the action of the external magnetic field. Here $\Omega_1^+ \equiv m^*\omega_1^+/e(1+F_0^a/3)$ where the effective mass and the Landau parameter follow the usual notation.

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