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Abstract

I show that, in commensurate Néel antiferromagnetic conductors with inversion symmetry, the substantial momentum dependence of the Zeeman term survives strong spin-orbit coupling and substantial magnetic anisotropy. I illustrate this by a simple example.

Key words: antiferromagnetic conductors, spin-orbit interaction, Zeeman coupling
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1. Introduction

Recently, peculiarities of the Zeeman coupling in cuprate superconductors have attracted attention, both in relation to the ongoing experiments [1–3] on magnetic quantum oscillations in these materials [4,5], and because of fundamental interest of electron magnetism of antiferromagnetic conductors [6–8].

In spite of the time reversal symmetry being broken by magnetic order, in a commensurate centrosymmetric Néel antiferromagnet the electron Bloch eigenstates are doubly degenerate at all momenta in the Brillouin zone [7]. This is a consequence of the combined symmetry $I\theta\mathbf{T_a}$, where $\mathbf{T_a}$ is a lattice translation, that inverts the local magnetization density $\mathbf{M}(\mathbf{r})$ so that $\mathbf{M}(\mathbf{r}+\mathbf{a}) = -\mathbf{M}(\mathbf{r})$, I is inversion ($\mathbf{r} \to -\mathbf{r}$), and θ is the time reversal. An external magnetic field tends to lift this degeneracy; however, in an antiferromagnet, the presence of a special direction, defined by the staggered magnetization, substantially modifies the Zeeman coupling. A particularly simple picture emerges, when the energy scale E_{SO} of the relativistic spin-orbit coupling is negligible compared with the antiferromagnetic gap Δ in the electron spectrum: in a wide range of magnetic fields H such that $E_{SO} \ll \mu_B H \ll \Delta$, the Zeeman term is sensitive to the orientation of the field relative to the staggered magnetization, but not to the crystal axes; this corresponds to the so-called exchange symmetry approximation. Hence, in this range of fields, the gyromagnetic factor g turns into a tensor with two distinct eigenvalues, $g_\parallel$ and $g_\perp$, corresponding to the longitudinal ($\mathbf{H}_\parallel$) and the transverse ($\mathbf{H}_\perp$) components of the magnetic field $\mathbf{H}$ with respect to the staggered magnetization. The $g_\parallel$ is constant up to small relativistic corrections. By contrast, in d dimensions, the $g_\perp$ vanishes on a $(d-1)$-dimensional manifold $\{\mathbf{p}^*\}$ in the Brillouin zone, due to a conspiracy of the crystal symmetry with that of the antiferromagnetic order [6,7]. Thus, the $g_\perp$ in the Zeeman term $\mathcal{H}_Z$ must depend substantially on the quasiparticle momentum $\mathbf{p}$:

$$\mathcal{H}_Z = -\frac{\mu_B}{2}\left[g_\parallel(\mathbf{H}_\parallel \cdot \boldsymbol{\sigma}) + g_\perp(\mathbf{p})(\mathbf{H}_\perp \cdot \boldsymbol{\sigma})\right]. \quad (1)$$

2. Strong spin-orbit coupling

Here, I would like to point out a different interesting limit: the one of strong spin-orbit coupling. Notice that, in the limit of negligible spin-orbit coupling, described in the Introduction, the subspace of the two directions,

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transverse to the staggered magnetization, is isotropic. In the strong spin-orbit coupling limit, this transverse subspace becomes anisotropic, and the $g_\perp(\mathbf{p})$ in the Eq. (1) splits into two components: $g^a_\perp(\mathbf{p})$ and $g^b_\perp(\mathbf{p})$. The transverse part of the Zeeman term thus takes the form

$$\mathcal{H}^\perp_Z = -\frac{\mu_B}{2}\left[g^a_\perp(\mathbf{p})H^a_\perp\sigma^a + g^b_\perp(\mathbf{p})H^b_\perp\sigma^b\right]. \qquad (2)$$

Degeneracy in a transverse field would require that both the $g^a_\perp(\mathbf{p})$ and $g^b_\perp(\mathbf{p})$ vanish. Because of the anisotropy, the two equations $g^a_\perp(\mathbf{p}) = 0$ and $g^b_\perp(\mathbf{p}) = 0$ are generally independent. If these two equations can be resolved simultaneously, they define the manifold of momenta, labeling the Bloch eigenstates that remain degenerate in a transverse magnetic field. In d spatial dimensions, the dimensionality of this manifold is $d-2$ as opposed to $d-1$, the latter being the result in the isotropic limit, or in the exchange symmetry approximation.

A simple illustration may be given in two dimensions, for the staggered magnetization pointing transversely to the crystal plane (along the z axis), and for the band extremum at the momentum $\mathbf{p}^*$, where $g^a_\perp(\mathbf{p}^*) = g^b_\perp(\mathbf{p}^*) = 0$. Expanding the Eq. (2) around $\mathbf{p}^*$, one finds:

$$\mathcal{H} = \frac{\mathbf{p}^2}{2m} + \mathcal{H}_Z \qquad (3)$$

$$\mathcal{H}_Z = -\frac{\mu_B g}{2}\left[H^z\sigma^z + \frac{\xi^x p_x}{\hbar}H^x\sigma^x + \frac{\xi^y p_y}{\hbar}H^y\sigma^y\right]. \qquad (4)$$

Absorbing $\mu_B g$ into the definition of H and completing the square with respect to p_x and p_y, one finds

$$\mathcal{H} = \frac{1}{2m}\left[p_x - \frac{m\xi}{2\hbar}H^x\sigma^x\right]^2 + \frac{1}{2m}\left[p_y - \frac{m\xi}{2\hbar}H^y\sigma^y\right]^2 - H^z\sigma^z \qquad (5)$$

The spectral properties of Hamiltonians of this type have been explored in a different context by several authors (see, for instance, the Refs. [9,10]), who studied various effects of spin-orbit coupling in inversion layers and quantum dots. The principal difference between their work and the present article resides in the fact, that the Refs. [9,10] studied the intrinsic spin-orbit coupling, whereas, in the present work, the spin-orbit coupling is of the Zeeman origin, and thus is induced by and proportional to the applied magnetic field.

In spite of this difference, the spectra of the two problems manifest important similarities, such as oscillatory behavior of Zeeman splitting as a function of the field orientation with respect to the crystal plane [9,8] and the possibility of electric excitation of spin resonance [11,8]. Therefore, these phenomena, predicted to take place in low-carrier antiferromagnetic conductors, are not an artifact of the exchange symmetry approximation, and shall be equally expected in the limit of developed magnetic anisotropy and strong spin-orbit coupling. This observation constitutes the main point of the present article.

Antiferromagnetic heavy fermion conductor $CePd_2Si_2$ may possibly illustrate the arguments above: with its body-centered tetragonal structure and the staggered magnetization in the ab plane [12], the plane orthogonal to the staggered magnetization is likely to be magnetically anisotropic.

At the same time, one shall note that, in antiferromagnetic conductors, these phenomena would manifest themselves most vividly in low-carrier limit, for carrier concentrations $n \lesssim \xi^{-2}$, where ξ is the characteristic scale of ξ^a and ξ^b. This constraint is imposed by the momentum dependence of the $g^{a,b}_\perp(\mathbf{p})$ being limited to a momentum range of about $\hbar/\xi$ around $\mathbf{p}^*$: as the carrier concentration exceeds ξ^{-2}, a smaller and smaller fraction of carriers become subject to the substantial momentum dependence of the g-tensor.

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