Random spin polarization of carriers in nonequilibrium disordered metal

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The spin of the carriers in a nonequilibrium metal is polarized as a result of quantum interference effects. The spin density varies in a random way from point to point but remains constant in time.

The spin density in a nonmagnetic material is identically zero because of the invariance under time reversal. In a nonequilibrium steady state, dissipation processes lift the requirement of T invariance even if the agent which causes the deviation from equilibrium is T-invariant. In conductors which lack an inversion center, and whose symmetry does not forbid a coupling between a vector and a pseudovector, there can accordingly be a kinetic magnetoelectric effect (Ref. 1 and, more recently, Ref. 2) consisting of the induction of an average spin density by an electric field.

In materials which do have an inversion center, the average density of the induced spin is zero. Nevertheless, the local spin density is nonzero, since the disorder of a material lifts the requirement of a local invarience under inversion.

The polarization at this point is determined by the position of the scatterers and is therefore random. Analysis shows that the polarization is determined by the spin–orbit coupling and by carrier interference effects, so it is correlated over distances on the order of the carrier wavelength.

To calculate the effect, we can use a technique developed for analyzing mesoscopic fluctuations.[3] At low temperatures $T\tau \ll 1$, where τ is the momentum relaxation time, the fluctuations in the spin density are caused primarily by diagrams with two diffusion ladders. Here is the result for a bulk conductor, which will illustrate the structure of the expression:

$$\langle S^a S^b \rangle = \frac{\pi\delta^{ab}}{2} \int \frac{d\epsilon\, d\epsilon'}{(2\pi)^2} \frac{d^3k}{(2\pi)^3} \{ | \Gamma_0(\epsilon, \epsilon')|^2 - | \Gamma_s(\epsilon, \epsilon')|^2 \} B(\epsilon, \epsilon') . \quad (1)$$

Here the Γ's are diffusion propagators, given by

$$\Gamma_0^{-1}(\epsilon, \epsilon') = i(\epsilon - \epsilon') + (2\tau_{in}(\epsilon))^{-1} + (2\tau_{in}(\epsilon'))^{-1} + Dk^2$$

$$\Gamma_s^{-1}(\epsilon, \epsilon') = \Gamma_0^{-1}(\epsilon, \epsilon') + \tau_{so}^{-1};$$

D is the carrier diffusion coefficient, and $\tau_{in}(\epsilon)$ and τ_{so} are the time scales of the energy and spin relaxation. The block $B(\epsilon,\epsilon')$ is expressed in terms of the carrier distribution function f(**n** parametrizes the Fermi surface):

$$B(\epsilon, \epsilon') = \nu \int \frac{d^2n}{4\pi} \{ f(\mathbf{n}, \epsilon) f(\mathbf{n}, \epsilon') \tau^{-1}(\mathbf{n}) - f(\mathbf{n}, \epsilon) \int \frac{d^2n'}{4\pi} W(\mathbf{n}, \mathbf{n}') f(\mathbf{n}', \epsilon') \}. \quad (2)$$

We see from (2) that we have $B \equiv 0$ in the equilibrium state or $B \neq 0$ if the carriers are not at equilibrium in terms of momentum. For $\epsilon - \epsilon' \gg 1/\tau_{so}$, the result in (1) contains a small spin-orbit factor, but at $\epsilon - \epsilon' \ll 1/\tau_{so}$ it does not depend on the spin-orbit strength. This situation corresponds to a complete polarization of the nonequilibrium carriers under the condition $|\epsilon - \epsilon_F| \ll 1/\tau_{so}$.

For a bulk sample we have, in the approximation linear in the field,

$$\langle S^2 \rangle = \frac{\zeta(3/2)}{2^{19/2}\pi^{5/2}} \frac{\mathbf{Ej}}{T^2} (T/D)^{3/2} \quad \text{for} \quad \tau_{in} \gg 1/T \gg \tau_{so}$$

$$\langle S^2 \rangle = \frac{\mathbf{Ej}(D\tau_{so})^{-1/2}}{24\pi^2 TD} \quad \text{for} \quad \tau_{in} \gg \tau_{so} \gg 1/T.$$

Here **j** is the electric current density. At low temperatures one might encounter a situation in which the inelastic length scale $L_{in} = (D\tau_{in})^{-1/2}$ becomes larger than the transverse dimension of the conductor, and the effective dimensionality decreases. In this case we would have

$$\langle S^2 \rangle = \frac{\mathbf{Ej} \ln(\tau_{in} \min(T, 1/\tau_{so}))}{192\pi^3 T d h} \quad \text{for a film of thickness } h,$$

$$\langle S^2 \rangle = \frac{\mathbf{Ej} L_{in}(T)}{48\pi^2 TDA} \quad \text{for a wire with a cross-sectional } A.$$

Here we are assuming $\tau_{in} \gg \min(\tau_{so}, T)$.

The effect which is linear in the field increases without bound with decreasing temperature. Since the effect is determined by the spreading of the Fermi distribution, the nonlinearity in terms of the field becomes important even upon a very slight deviation from equilibrium, while the electric current is still clearly linear in the field. The corresponding condition is

$$\mathbf{Ej} \leqslant \nu T^2 \tau_{e\text{-}ph}^{-1} \tag{3}$$

where τ_{e-ph}^{-1} is the rate of electron–phonon collisions, which carry energy out of the electron subsystem. If, for a given $\mathbf{E}$, condition (3) is violated at a temperature equal to that of the heat reservoir, we can estimate the effective temperature of the electrons from (3). Taking this point into account, we easily see that the random spin density would always be small in atomic units at plausible values of the parameters.

In order-of-magnitude estimates, we should take account of the small factor associated with the numerical coefficient. At $E \sim 1\text{V/cm}$, for example, at liquid-helium temperature, and in the case of a highly disordered metal, we would have (atomic units) $S \sim 10^{-8}$ for a bulk sample, $S \sim 10^{-7}$ for a film a few atomic layers thick, and $S \sim 10^{-5}$ for an extremely thin wire.

The spins of paramagnetic centers and nuclear spins interact directly with the local spin density of carriers, so there is the possibility in principle of observing this phenomenon. In observation of ESR or NMR, a random polarization of the carrier spins would shift the resonant frequency of a localized spin, with the result that the resonance line would broaden. This component of the linewidth might be identified on the basis of its dependence on the deviation from equilibrium, the magnetic field, and the temperature.

Apparently the best bet is to observe the NMR of paramagnetic centers. At $S \sim 10^{-7}$ and liquid-helium temperatures, the component of the linewidth would be ~ 1 G and thus completely observable.

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[2] A. G. Aronov and Yu. B. Lyanda-Geller, Pis'ma Zh. Eksp. Teor. Fiz. **50**(9), 398 (1989) [JETP Lett. **50**, 431 (1989)].

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