PARITY NONCONSERVING CURRENT IN CONDUCTORS OF ELECTRICITY

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Received 30 June 1987; accepted for publication 6 July 1987
Communicated by V.M. Agranovich

The effects due to the weak interaction between the conduction electrons and the lattice nuclei in external magnetic field are considered. It is shown that the continuous current arises under the influence of the rotating magnetic field.

1. Introduction

The parity nonconservation effects due to the interaction of the weak neutral current of electrons and nuclei in atoms, molecules and crystals have been extensively discussed recently (see, e.g., ref. [1]). In particular, in ref. [2] the possibility was discussed that allowance for the weak interaction between the conduction electrons and the lattice nuclei in a metal located in an external constant magnetic field should lead to the appearance of the continuous current. This conclusion, however, was incorrect and in ref. [3] it was shown that only instantaneous current may arise in this situation. In the present paper we show that the continuous current arises under the influence of the rotating magnetic field.

2. Effective hamiltonian

The effective operator for the weak interaction between the electron and the lattice nuclei is

$$\hat{H}_{\rm w} = \frac{G\hbar^2}{\sqrt{2}mc^2} ZgS\Big[\hat{\boldsymbol{p}}, \sum_{\boldsymbol{a}} \delta(\boldsymbol{r}-\boldsymbol{a})\Big]_+ . \tag{1}$$

Here m, $\boldsymbol{S}$, $\boldsymbol{r}$ are the mass, spin and coordinates of the electron, Z, $\boldsymbol{a}$ are the charge and coordinates of the nucleus, G is the Fermi constant, g is the Salam–Weinberg constant, $\hat{\boldsymbol{p}}$ is the operator of electron momentum. In (1) we have discarded the nuclear-spin-dependent part of the interaction which gives a minor contribution to the current. The summation in (1) is over all the nuclei in a crystal.

In the presence of an external magnetic field the operator $\hat{\boldsymbol{p}}$ in (1) should, on the basis of gauge-invariance considerations, be replaced by $\hat{\boldsymbol{p}}+(e/c)\boldsymbol{A}$, where $e=-|e|$ is the electron charge, $\boldsymbol{A}$ is the vector potential of the external field.

The operator (1) describes the contact interaction between the electron and the lattice nuclei. It is convenient to replace (1) by an effective, "diffused" throughout the crystal, interaction, which we determine by the condition

$$\langle\psi|\hat{H}_{\rm w}|\psi\rangle = \langle\psi|\hat{\tilde{H}}_{\rm w}|\psi\rangle . \tag{2}$$

Here ψ is the wavefunction of the electron in a crystal.

Then the total nonrelativistic hamiltonian for the conduction electron in a crystal with the required accuracy may be presented in the form:

$$\hat{H}=\hat{\boldsymbol{P}}^2/2m - eV + \hat{H}_{\rm s} , \tag{3}$$

$$\hat{\boldsymbol{P}}=\hat{\boldsymbol{p}}+(e/c)\boldsymbol{A}+Q\boldsymbol{S} , \tag{4}$$

$$\hat{H}_{\rm s} = (e/mc)\mathscr{H}\cdot\boldsymbol{S} \equiv \mu_{\rm s}\mathscr{H}\cdot\boldsymbol{S} , \tag{5}$$

where V is the total electrostatic potential. The constant Q is determined by (2):

$$Q=(\sqrt{2}G\hbar^2 Zg/c^2)\,|U_{\alpha\boldsymbol{K}}(0)|^2 , \tag{6}$$

where $U_{\alpha\boldsymbol{K}}(\boldsymbol{r})$ is the periodical part (normalized in the unit-cell-volume) of the Bloch wavefunction, α is the band number, $\boldsymbol{K}$ is the quasimomentum.

3. Effective force and the expression for the current

For the computation of the electron velocity $\hat{\boldsymbol{v}}$ and the force $\hat{\boldsymbol{F}}$ acting on the electron we use the formulae

$$\hat{\boldsymbol{v}}=\dot{\boldsymbol{r}}=(\mathrm{i}/\hbar)[\hat{H},\boldsymbol{r}]_{-}=\hat{\boldsymbol{P}}/m\,, \tag{7}$$

$$\hat{\boldsymbol{F}}=m\ddot{\boldsymbol{r}}=(\mathrm{i}/\hbar)[\hat{H},\hat{\boldsymbol{P}}]_{-}\,. \tag{8}$$

The evaluation of the commutators in (8) yields

$$\hat{\boldsymbol{F}}=-e\mathscr{E}+\mu_{\mathrm{s}}\mathscr{H}\times\hat{\boldsymbol{P}}+\mu_{\mathrm{s}}Q\mathscr{H}\times\boldsymbol{S}-\mu_{\mathrm{s}}\nabla(\mathscr{H}\cdot\boldsymbol{S})\,. \tag{9}$$

Here the first term represents the usual electrostatic force ($\mathscr{E}=-\nabla V$) which is equal to zero in the absence of the external electric field, the second term represents the Lorentz force, the third term is the P-odd force, considered in refs. [2,3]. The fourth term in (9) appears only in the case of the inhomogeneous field.

Using the Boltzmann equation [4] we obtain by usual method the expression for the current [2]

$$\boldsymbol{i}=\sigma_{\mathscr{H}}(1/\hbar)\langle\boldsymbol{S}\rangle\times\mathscr{H}, \tag{10}$$

where

$$\sigma_{\mathscr{H}}=(\mu_{\mathrm{s}}\hbar/e)Q\sigma_{\mathscr{E}}\,, \tag{11}$$

and $\sigma_{\mathscr{E}}$ is the usual electrical conductivity. Here we assume that all the conduction electrons have unpaired spins. This assumption is valid, when $kT\approx\mu_{\mathrm{s}}\mathscr{H}$, i.e., for $T\approx10$ K, $\mathscr{H}\approx10^5$ Oe.

The parity nonconservation effects increase when the nucleus charge Z increases (see, e.g. ref. [1]), therefore they will be the largest for the heavy atoms. Noting, that only ns-electrons contribute to $|u_{\alpha\boldsymbol{K}}(0)|^2$ and using the statistical-model estimate for the electron density on the nucleus, we obtain $\sigma_{\mathscr{H}}\approx10^{-16}\sigma_{\mathscr{E}}$ [2].

4. Rotating magnetic field

Let us consider the rotating magnetic field and assume that vector $\langle\boldsymbol{S}\rangle$ behaves as a classical magnetic moment with constant absolute value. For the description of the motion of this moment in the magnetic field we use the Landau–Lifshitz equation [5]:

$$\langle\dot{\boldsymbol{S}}\rangle=\omega_0\langle\boldsymbol{S}\rangle\times\boldsymbol{h}+\frac{1}{\tau_{\mathrm{m}}S}\langle\boldsymbol{S}\rangle\times(\langle\boldsymbol{S}\rangle\times\boldsymbol{h})\,, \tag{12}$$

where $\boldsymbol{h}\equiv\mathscr{H}/\mathscr{H}$, $S=|\langle\boldsymbol{S}\rangle|$, $\omega_0=e\mathscr{H}/mc$ (Larmor frequency), $\tau_{\mathrm{m}}\approx10^{-9}$ s (magnetic relaxation time). Let

$$h_x=\cos\omega t\,,\quad h_y=\sin\omega t\,,\quad h_z=0\,, \tag{13}$$

where ω is the field rotation frequency. The solution of the eq. (12) in accordance with (10) gives the constant current component:

$$i_z=\sin\vartheta\,\sin\varphi\,\sigma_{\mathscr{H}}\mathscr{H}, \tag{14}$$

where

$$\cos\vartheta=\omega_0\tau_{\mathrm{m}}\,\mathrm{tg}\,\varphi\,, \tag{15}$$

$$\mathrm{tg}\,\varphi=-\frac{[1+\tau_{\mathrm{m}}^2(\omega_0^2+\omega^2)-\gamma]^{1/2}}{[1+\tau_{\mathrm{m}}^2(\omega_0^2-\omega^2)+\gamma]^{1/2}}\,, \tag{16}$$

and

$$\gamma=[1-2\tau_{\mathrm{m}}^2(\omega^2-\omega_0^2)+\tau_{\mathrm{m}}^4\,(\omega_0^2+\omega^2)^2]^{1/2}\,. \tag{17}$$

Let us consider the sample in the magnetic field $\mathscr{H}\approx10^5$ Oe, rotating with the frequency 10^9 s^{-1}. Then $\omega_0=10^3\omega$. Introducing the effective intensity of the extraneous force field

$$\boldsymbol{E}_{\mathrm{ext}}^{\mathrm{eff}}=\frac{\sigma_{\mathscr{H}}}{\sigma_{\mathscr{E}}}\frac{1}{\hbar}\langle\boldsymbol{S}\rangle\times\mathscr{H}, \tag{18}$$

and assuming the length of the sample $l=1$ cm, we obtain the extraneous electromotive force $U_{\mathrm{ext}}^{\mathrm{eff}}=E_{\mathrm{ext}}^{\mathrm{eff}}l\approx10^{-12}$ V.

The considered direct current will be much smaller than the alternating current, appearing due to electromagnetic induction. If the magnetic flux is 10^7 Oe cm^2, we have $U_{\mathrm{ext}}^{\mathrm{eff}}/U_{\mathrm{ind}}\approx10^{-19}$. The alternating current may be, however, strongly damped with the help of the frequency filter (see fig. 1). Assuming $L=10^2$ H, $C=1$ F, we obtain $U_{\mathrm{ind}}^{\mathrm{AB}}=10^{-13}$ V, i.e. less than $U_{\mathrm{ext}}^{\mathrm{eff}}\approx10^{-12}$ V.

After this work was finished, a paper [6] came to our attention, where the galvanomagnetic effects in conductors of electricity due to the weak interactions were also investigated. In ref. [6] the absence of the continuous current in the constant magnetic field was

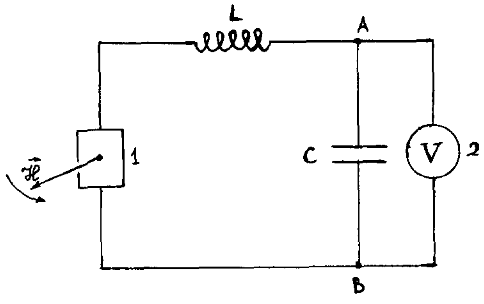

Fig. 1.

stated and the case of alternating magnetic field was discussed. The conclusions in ref. [6] in main features are similar to ours.

Acknowledgement

The authors thank V.G. Gorshkov, D.A. Kirzhnitz, M.G. Kozlov, Yu.E. Lozovik, V.V. Frolov for valuable discussions. They are especially grateful to I.B. Khriplovich for the discussion which led to the right understanding of the role of the magnetic relaxation.

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