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A NEW MECHANISM FOR THE NUCLEAR SPINS DEPOLARIZATION IN A SPIN-DIOD

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We propose a new mechanism for nuclear spin-diffusion via virtual spin-excitons under the conditions of integer quantum Hall effect. The proposed mechanism significantly enhances the range of nuclear spin interaction over the magnetic length, and therefore may explain the nuclear spins depolarization in a spin-diod.

Recently Kane, Pfeiffer and West [1] reported the observation of a remarkable currentvoltage characteristics of a novel device, which they named "spin-diod". In this device the current passes across a junction between two coplanar 2DEG's in which $\nu > 1$ on one side and $\nu < 1$ on the other and the fermi energy E_F crosses between different spin levels at the junction. The 2DEG is highly conducting except for the depletion layer (with width L_{ex} of the order of several hundred angstroms), where $\nu = 1$. Depending on the strength of magnetic field, the ratio L_{ex}/l_B can be of order or larger than unity. Here $l_B = (\hbar c/eB)^{1/2}$ is the magnetic length. Since E_F is in the close vicinity of different spin levels on opposite sides of the junction any passage of an electron across the junction is followed by a spin flip, which can take place due to the hyperfine interaction between the electron spins and the nuclear ones in the depletion layer. Thus the stream of electrons across the junction leads to nuclear spin polarization in the depletion layer. If the rate of nuclear spin relaxation within the depletion layer is sufficiantly low one may reach a situation when the spin polarization inside the junction is saturated and so the electrical current across the junction diminishes.

This current is therefore strongly dependent on the rate of nuclear spin depolarization within the depletion layer. It should be noted that under operation conditions of the diod (i.e. $H \propto 15\,\mathrm{T}$, $T \geq 100\,\mathrm{mk}$) nuclear spin polarization by the external magnetic field is negligibly small so that the entire region outside the depletion layer is depolarized and can be regarded as a spin reservoir.

The nuclear spin relaxation directly to the electronic spin system via the hyperfine interaction was considered in [2]. This mechanism is extremely slow at low temperatures because of the large magnetic energy gap in the electron spectrum as compared to the nuclear one. Experimental feasibility of nuclear spin ralaxation via electron spins was demonstrated in elegant experiments of K. von Klitzing group [3, 4].

In this letter we propose a new mechanism of indirect spin transport from the polarized nuclei within the junction to nuclei outside via the exchange of virtual electron-hole pairs (spin exitions [5, 6]). This mechanism is associated with the hyperfine interaction. In contrast to mechanisms, proposed in [2, 7] the magnetic energy gap is encompassed here by the virtual spin excitions, thus leading to a much more efficient process of nuclear spin flip at sufficiently low temperatures. The virtual character of the spin-excitions, transfering the nuclear spin polarization, removes the problem of the energy conservation in the single flip-flop process.

We consider a region of the heterostructure, in which the nuclear spins are temporarily excited (e.g. the depletion layer in the spin diod of Ref. [1]), and calculate the rate of spin diffusion from this region via the exchange of virtual spin excitions.

The Hamiltonian of the hyperfine interaction between a nuclear spin at a given position R and the electron spins can be written in terms of spin exciton operators $\hat{A}_{\mathbf{k}}$, [7], as follows:

$$\hat{H}_{e-n}(\mathbf{R}) \propto \sum_{\mathbf{k}} W(k^2)(\hat{A}^{+}_{\mathbf{k}}\hat{I}^{+} + \hat{A}_{\mathbf{k}}\hat{I}^{-})\exp[i(k_x X - k_y Y)] \tag{1}$$

where $\hat{I}^{\pm}$ are the transvers components of the nuclear spin operator, and $W(\tilde{k}) = e^{-\tilde{k}^2/4}$, with $\tilde{k} \equiv k l_B$. This fotm of $W(\tilde{k})$ corresponds to electrons in the ground Landau level.

The spin diffusion rate from a given nuclear site $\mathbf{R}_a$ within the polarized region is proportional to the rate of transition probability $P(\mathbf{R}_a)$ for the polarization of the nuclear spin $\Downarrow$, located at $\mathbf{R}_a$, to be transfered to a nuclear spin $\Uparrow$, positioned at $\mathbf{R}_b$, outside the polarized region, via the exchange of virtual exchange of virtual spin excitions.

Using second order perturbation theory with respect to $\mathbf{H}_{e-n}$, the desired rate of transition probability can be written in the form:

$$\frac{d}{dt}P(\mathbf{R}_a) \propto |\sum_{\mathbf{R}_b} <\Downarrow,\Uparrow|\hat{T}(\mathbf{R}_a,\mathbf{R}_b)|\Uparrow,\Downarrow>|^2 \delta(\epsilon^a_{\downarrow} + \epsilon^b_{\uparrow} - \epsilon^a_{\uparrow} - \epsilon^b_{\downarrow}) \tag{2}$$

where

$$\hat{T}(\mathbf{R}_a,\mathbf{R}_b) \equiv -(\hat{I}^{+}_a\hat{I}^{-}_b + \hat{I}^{-}_a\hat{I}^{+}_b)\int_0^{\infty} \frac{J_0(kR_{ab})}{E^{sp}_{ex}(\tilde{k})} e^{\frac{-\tilde{k}^2}{2}} \tilde{k}\, d\tilde{k} \tag{3}$$

with

$$R_{ab} \equiv |\mathbf{R}_a - \mathbf{R}_b|$$

and

$$E^{sp}_{ex}(\tilde{k}) \equiv |g|\mu_B B + \frac{e^2}{\kappa l_B}\sqrt{\frac{\pi}{2}}\left[1 - e^{-\tilde{k}^2/4} I_0\left(\frac{\tilde{k}^2}{4}\right)\right] \tag{4}$$

is the spin-exciton energy dispersion. In these expressions g is the effective electronic g-factor, μ_b is the Bohr magneton and k is the dielectric constant in the 2DEG region.

Ideally the conservation of energy between the initial and the final states imposed by the delta function in Eq.(2) is strictly satisfied. In reality, however, as a result of the difference in local magnetic fields at the various nuclear positions, the initial and final states energies $(\epsilon^b_{\uparrow}, \epsilon^b_{\downarrow})$ of the nuclei located outside the excited region fluctuate with respect to the corresponding energies $(\epsilon_\downarrow^a, \epsilon_\uparrow^a)$ of the relaxing nuclei within this region.

The transition operator $\hat{T}(\mathrm{R}_a, \mathrm{R}_b)$ corresponds to an effective nuclear spin-spin interaction, analogous to the well known Ruderman - Kittel - Yosida interaction [8] in metals, which exhibit the Friedel oscillations. In our case the interaction between the nuclear spins, given by the integral in Eq. (3), is a monotonic function of the distance between two nuclei, interacting via the spin-excitons. The negative sign in Eq. (3) indicates an attraction between the nuclear spins which may result in a ferromagnetic nuclear state.

Assimptotically, at large distances between interacting nucleas, $R_{ab} \gg l_B$, the important values of $\tilde{k}$ are of the order of l_B/R_{ab} and are, therefore, much smaller than unity so that both $e^{-\tilde{k}^2/2}$ and $E_{ex}^{sp}(\tilde{k})$ can be expanded to the lowest significant order in $\tilde{k}$ (i.e. to zero and to second order respectively). Using the parabollic approximation for the spin-exciton dispersion:

$$E_{ex}^{sp} \simeq \epsilon_{sp} + \frac{1}{4}\epsilon_c \tilde{k}^2 \tag{5}$$

where $\epsilon_c = (e^2/kl_B)(\pi/2)^{1/2}$ is the characteristic coulomb energy, and the asymptotic behavior of effective interaction, Eq. (3), is:

$$T(\mathrm{R}_a, \mathrm{R}_b) \propto -\sqrt{\frac{d}{R_{ab}}} e^{-R_{ab}/d} \tag{6}$$

where

$$d \equiv \frac{l_B}{2}\sqrt{\frac{\epsilon_c}{\epsilon_{sp}}}. \tag{7}$$

It is the well known behavior characterizing the interaction potential, mediated by the exchange of quasiparticles having a dispersion law such as in Eq. (5). The range ΔR of this potential is determined by the critical wave number $k_0 = (2/l_B)(\epsilon_{sp}/\epsilon_c)^{1/2}$ as it follows from the uncertainty principle: $\Delta R \cdot k_0 \simeq 1$. The spin-diffusion process is therefore governed by two characteristic length scales: the width, L_{ex} of the polarized region and the range d of the effective interaction.

Thus, using Eq. (5) for $E_{ex}^{sp}(\tilde{k})$, then integrating over $\tilde{k}$ and finally using the asymptotic form of the modified Bessel Functions while integrating over the unpolarized part of the sample, we obtain a rather simple expression for the nuclear spin diffusion rate:

$$\frac{1}{\tau_{sd}} \propto \left(\frac{\hat{n} l_B^2}{\epsilon_{sp}}\right)^2 e^{-L_{ex}/d} \cos h^2 \left[\frac{(R - \frac{1}{2}L_{ex})}{d}\right] \tag{8}$$

where $\mathrm{R} \equiv \mathrm{R}_2 - \mathrm{R}_a$. Here R_2 and R_a are the positions of the nuclei in the unpolarized region and in the strip L_{ex} respectively.

To conclude, we have considered the depolarization of nuclear spins in spin-diod, [1]. The proposed mechanism for nuclear spin-diffusion, via virtual spin=excitons, yields the possibility of transferring nuclear spins over a distance longer than the magnetic length l_b. The long range naturé of this mechanism is of a considerable importance when the size of the region of excited nuclear spins, L_{ex}, is larger than the the magnetic léngth l_B, which is the case in recent experiment [1].

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