Photo-induced Magnetic Solitons and the Slow Relaxation Mechanism in Diluted Magnetic Semiconductors

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Abstract. Taking into account the correlation effect among photo-induced magnetic solitons, the mechanism of the slow relaxation of the spin dynamics in diluted magnetic semiconductors has been discussed by the long-range p-spin spherical model.

1. Introduction
The photo-induced dynamic magnetic effect has been studied in the II-VI-based diluted magnetic semiconductors (DMS) and III-V-based DMS, and interesting phenomena such as photo-induced magnetic polaron have been discovered [1,2]. These experiments stimulated us to the study of the carrier-induced magnetic soliton, which is an interesting and challenging subject. The microscopic-formation mechanism of the hole-induced magnetic soliton is very difficult to understand, because of cooperation phenomena such as the remarkable change of spin exchange interaction among Mn ions by the hole [3]. In addition, III-V-based DMSs [4,5], especially ferromagnetic p-type (In,Mn)As [6], offer an opportunity to explore various aspects, localization and negative magnetroresistance of carrier transport in the presence of cooperation phenomena [7]. Recently Mitsumori et al. [8] have found the important result for the spin dynamics in III-V-based DMS with a femtosecond time-resolved magnetic circular dichroism spectroscopy. That is, the relaxation time of the spin excited by optical pulse shows the strong dependence on the intensity of the pump pulse below Curie temperature. For example, the decay time varies from 0.2 to 20 ps as intensity of the pump pulse increases from $5.5 \times 10^{12}$ to $3.3 \times 10^{13}$ photons/cm²/pulses. Recently the present author [9] has proposed the mechanism of the long relaxation of spin dynamics in diluted magnetic semiconductors, using the ferromagnetic domain dynamics. In this study, taking into account the correlation effect among photo-induced magnetic solitons, we discuss the mechanism of the long relaxation of spin dynamics in diluted magnetic semiconductors from a different standpoint.

2. A model system and the slow relaxation mechanism of spin dynamics
It has been suggested that the ferromagnetic interaction induced by the hole seems to be cooperative and non-linear. In order to argue in the gauge-invariant formula, we shall introduce the non-linear gauge fields (Yang-Mills fields) $A^\mu_a$, which mediate the effective ferromagnetic...
interaction induced by the hole. It has been proposed that the hedgehog-like soliton in three-dimensional system is specified by rigid-body rotation, which is related to gauge fields of SO(4) symmetry for $S^3$ [10-13]. Thus it is thought that the non-linear gauge fields $A^a_\mu$ introduced by the hole have a local SO(4) symmetry. Then it is assumed that the SO(4) quadruplet fields, $A^a_\mu$, are spontaneously broken around the doped hole through the Anderson-Higgs mechanism, in the III-V-based DMS with magnetic manganese ion-doping. After the symmetry breaking $(0|\phi_a|0) = \langle 0, 0, 0, \mu \rangle$, we can obtain the effective Lagrangian density,

$$ L_{\text{eff}} = \frac{1}{2} \left( \partial_i S^j - g_3 \varepsilon_{ijk} A^b_i S^k \right)^2 + \psi^+ \left( i \partial_0 - g_2 T_a A^a_0 \right) \psi - \frac{1}{2m} \psi^+ \left( i \nabla - g_2 T_a A^a_0 \right) \psi \\
- \frac{1}{4} \left( \partial_\mu A^a_\mu - \partial_\nu A^a_\nu + g_3 \varepsilon_{abc} A^b_\mu A^c_\rho \right)^2 + \frac{1}{2} \left( \partial_\mu \phi_a - g_4 \varepsilon_{abc} A^b_\rho \phi_c \right)^2 \\
+ \frac{1}{2} m_1^2 \left( A^4_\mu \right)^2 + \left( A^2_\mu \right)^2 + \left( A^3_\mu \right)^2 + m_1 \left[ A^4_\mu \partial_\mu \phi - A^2_\mu \partial_\mu \phi_1 \right] + m_1 \left[ A^2_\mu \partial_\mu \phi_3 - A^3_\mu \partial_\mu \phi_2 \right] \\
+ m_1 \left[ A^3_\mu \partial_\mu \phi - A^1_\mu \partial_\mu \phi_4 \right] + g_4 m_1 \left\{ \phi_4 \left[ (A^4_\mu)^2 + (A^2_\mu)^2 + (A^3_\mu)^2 \right] \right\} \\
- g_4 m_1 \left\{ A^4_\mu \left[ \phi_1 A^2_\mu + \phi_2 A^3_\mu + \phi_3 A^4_\mu \right] \right\} - \frac{m_2^2}{2} (\phi_4)^2 - \frac{m_2^2 g_4}{2 m_1} (\phi_4)(\phi_a)^2 - \frac{m_2^2 g_4}{8 m_1} (\phi_a)^2, $$

(1)

where $S^j$ is the spin of Mn, $\psi$ is the Fermi field of the hole, $m_1 = \mu \cdot g_4$, $m_2 = 2(2)^{1/2} \lambda \cdot \mu$. $\phi_a$ is the Bose field for the Anderson-Higgs mechanism. Recent study [14] shows that carriers of the hole seem to be coupled to Mn spins by an antiferromagnetic Heisenberg exchange interaction. Thus $j$ corresponds to the reverse direction of the spin one of the hole. The effective Lagrangian describes three massive gauge fields $A^1_\mu$, $A^2_\mu$, and $A^3_\mu$, and one massless gauge field $A^4_\mu$. The generation function $Z[J]$ for Green functions is shown as follows,

$$ Z[J] = \int \mathcal{D}A^a \mathcal{D}B^a \mathcal{D}C^a \mathcal{D}D^a \mathcal{D}\psi^+ \mathcal{D}\psi \mathcal{D}\phi \cdot \exp i \int d^4x \left( L_{\text{eff}} + L_{\text{GF+FP}} + J \cdot \Phi \right), $$

(2)

$$ L_{\text{DF+FP}} = B^a \partial^\mu A^a_\mu + \frac{1}{2} \alpha B^a B^a + i \tilde{C}^a \partial^\mu D^a C^a, $$

(3)

where $B^a$ and $C^a$ are the Nakanishi-Lautrup(NL) fields and Faddeev-Popov fictitious fields, respectively.

$$ J \cdot \Phi \equiv J^{ab} A^a_\mu + J^B B^a + J^S \cdot S + J^C \cdot C^a + J^\tilde{C} \tilde{C}^a + \eta \tilde{\psi} + \eta \tilde{\psi}^+ + J^\phi \phi_a $$

(4)

BRS-quartet [15] in the present theoretical formula are $(\phi_1, B^1, C^1, C^1)$, $(\phi_2, B^2, C^2, C^2)$, $(\phi_3, B^3, C^3, C^3)$, and $(A^4_{1\mu}, B^4, C^4, C^4)$. Where $A^4_{1\mu}$ is the longitudinal component of $A^4_\mu$. Thus we need these fields for the unitarity condition, although these fields are unobservable and fictitious ones. Because masses of $A^1_\mu$, $A^2_\mu$, and $A^3_\mu$ are created through the Anderson-Higgs mechanism by introducing the hole, the fields $A^1_\mu$, $A^2_\mu$ and $A^3_\mu$ exist around the hole within the length of $\sim 1/m_1 \equiv R_C$. From the first term in Eq. (1), the spins $S$ of Mn atoms are induced in the ferromagnetic state, where the average spin is parallel to $\vec{j}$ direction, within the length of $\sim R_C$ around the hole. That is, the effective Lagrangian represents that the ferromagnetically aligned Mn spins form clusters, in which the hole is trapped, with the radius, $R_C \sim 1/m_1$. Especially
Katsumoto et. al. [16] indicated that the finite localization length $l_c$ of the wave functions of holes plays a crucial role in MIT in (Ga,Mn)As. It looks like that the $l_c$ might correspond to $R_C \sim 1/m_1$. In order to discuss the spin dynamics, we envisage an effective hamiltonian, $H$, for the magnetic-soliton, $O(r_i)$, which is introduced in eq.(1),

$$
H = -J \sum_{<i,j>} \frac{S_i \cdot S_j}{|S_i||S_j|} O(r_i) \cdot O(r_j) + \frac{1}{2} K \sum_{i\neq j} \frac{O(r_i) \cdot O(r_j)}{|r_i - r_j|} 
$$

$$
= -J \sum_{<i,j>} \frac{S_i \cdot S_j}{|S_i||S_j|} O(r_i) \cdot O(r_j) + \sum_{i\neq j} K_{ij} O(r_i) \cdot O(r_j) 
$$

(5)

with $J > K > 0$ and the first sum taken only over nearest neighbor (the distance between each magnetic soliton is $\leq 2R_c$) and the second taken over all pair ($i \neq j$ means $|r_i - r_j| \gg 2R_c$).

$S_i \equiv \sum_{\tilde{i} \in \frac{1}{4\pi R_c^3}} S_{\tilde{i}}$. That is, $S_i$ is the summation of the ferromagnetic spin, $S_{\tilde{i}}$, of Mn within $\sim \frac{4}{3} \pi R_c^3(\tilde{i})$ around the photo-induced hole at the site $r_{\tilde{i}}$. $S_i$ represents the effective spin of the soliton $O(r_i)$. The first term corresponds to short-range ferromagnetic ordering interaction and the second corresponds to long-range frustration. In addition, $K_{ij} = \frac{1}{2} \frac{K}{|r_i - r_j|}$. Although the first term of the effective Hamiltonian in eq.(5) cannot be derived immediately from the effective Lagrangian in eq.(1), this term can be introduced approximately as follows. When the magnetic soliton, $O(r_i)$, with the effective spin $S_i$ is located in the nearest neighbors of the magnetic soliton, $O(r_j)$, with the effective spin $S_j$, holes are hopping between two solitons $O(r_i)$ and $O(r_j)$. If $S_i$ is parallel to $S_j$, p-d exchange interaction induces much reduction of the kinetic energy. This introduces the ferromagnetic short-range interaction such as the first term of eq.(5).

Also, $\sqrt{\frac{\pi}{K}}$ corresponds to $g_3$ in eq.(1) [9]. In order to discuss the correlation among spins $S_i$, we shall consider by the effective Hamiltonian with the p-spins interaction term,

$$
H_{eff} = - \sum_{i_1 < \ldots < i_p} K_{i_1 \ldots i_p} S_{i_1} \ldots S_{i_p} + \sum_i h_i S_i 
$$

(6)

The spherical spin-constraint is $\sum_{i=1}^{N} S_i^2 = lN$, using $\sum_{i=1}^{N} (S_i^2 - l) = 0$. The couplings are Gaussian variables with zero mean and average $K_{i_1 \ldots i_p} = \frac{p!}{2^l (lN)^{l-1}}$. The relaxation dynamics is given by the Langevin equation,

$$
\partial_t S_i(t) = -\beta \frac{\delta H_{eff}}{\delta S_i(t)} - z(t)S_i(t) + \eta_i(t) 
$$

(7)

$\beta$ is $1/T$. Where $\eta_i(t)$ are Gaussian random variable, with zero mean and variance 2. The second term on the right-hand side enforces the spherical constraint. The two-time correlation and the linear response functions are represented as,

$$
C(t, t') = \frac{1}{N} \sum_{i=1}^{N} < S_i(t)S_i(t') > 
$$

$$
R(t, t') = \frac{1}{N} \sum_{i=1}^{N} \frac{\partial}{\partial h_i(t')} < S_i(t) > 
$$

(8)

(9)
The dynamical equations for them can be obtained from eq.(7) through standard function methods[17].

\[
\partial_t C(t, t') = -[1 - p\beta \varepsilon(t)]C(t, t') + 2R(t', t) + \frac{p\beta^2}{2} \int_0^t dt'' C^{p-1}(t, t'') R(t', t'') + \frac{p\beta^2(p-1)}{2} \int_0^t dt''' R(t, t''') C^{p-2}(t, t''') C(t'', t').
\] (10)

\(\varepsilon(t)\) can be identified as the energy per spin multiplying eq.(7) by \(S_{i}(t')\), averaging over the noise and the couplings and taking the limit \(t' \to t\). From the first term in eq.(10) in the condition of \(p\beta \varepsilon(t) < 1\), it is seen that the relaxation time is \(\propto \frac{1}{1 - p\beta \varepsilon(t)}\) approximately. When the intensity of the optical pulse increases, number of hole-induced magnetic solitons increases. As a result, \(p\) increases and then the relaxation time increases. This is consistent with the recent experiment[8].

3. Conclusion
The mechanism of the slow relaxation of the spin dynamics in diluted magnetic semiconductors has been proposed, by using the long-range p-spin spherical model. It is shown that the correlation effect among photo-induced magnetic solitons is significant for this phenomenon.

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