Strong interaction between light and electrons (2) "Four states of interaction between photon and spins"

Product used : Electron spin resonance spectrometer (ESR)

A conventional ESR spectrometer uses a cavity for microwave irradiation and detection of ESR absorption. On the resonance state, it can be considered as a model that spins absorb energy of $h\nu = g\mu_B B$ and then release it to the lattice system one way, where *h:* Planck constant, *v*: frequency, *g*: *g-value,* μ_B: Bohr magneton, and *B*: magnetic flux density. However, the interaction between photon of microwave and spins of electrons is a little more complex in fact.

Figure 1 is a modelized drawing that expresses energy flow of microwave photon and spins. The cavity resonates with angular frequency ω_c, relaxes with velocity of $\kappa_c = \omega_c/Q_u$, which is inversely proportional to unloaded Q value of the cavity. On the other hand, spins do precess with an angular frequency of $\omega_m = \gamma_e B_m$ under the static magnetic field B_m. When the resonant condition of $\omega_c = \omega_m$ is satisfied, excited electron spins that absorbed microwave energy relax with the velocity of γ_m(half width: half width at half maximum (HWHM)), which corresponds to spectral line width. At this time, photon and electron spins exchange energy with a coupling constant g_m. The coupling constant g_m is expressed as[1]

$$g_m = \frac{\eta_m^{sqrt}}{2}\gamma_e\sqrt{\frac{\hbar\omega_c\mu_0}{V_c}}\sqrt{2NS} \quad , \qquad (1)$$

where η_m^{sqrt} is the square root of the filling factor of the cavity, γ_e is gyromagnetic ratio of the electron, $\hbar$ is reduced Planck constant ($h/2\pi$), μ_0 is vacuum permeability, V_c is the volume of the cavity, *N* is number of magnetic ions, and *S* is spin quantum number.

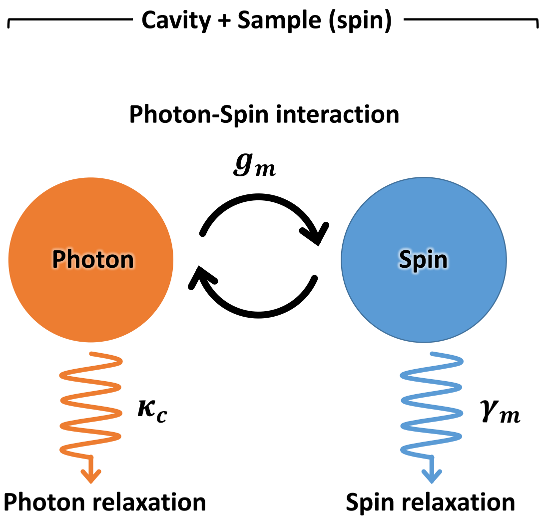


Fig.1 Energy flow in spin–cavity system.

Four states of interaction between photon and spins

Interaction between photon and spins can be categorized to four states according to the relation between the coupling constant (g_m), relaxation velocity (κ_c) of photon, and relaxation velocity (γ_m) of spins[1].

① 『weak coupling』 : A state that corresponds to the condition of $g_m < \kappa_c$ and $g_m < \gamma_m$. Normal ESR measurement is done in this state.

② 『Purcell effect』 : A state that corresponds to the condition of $g_m < \gamma_m$ and $g_m > \kappa_c$.

③ 『strong coupling』 : A state that corresponds to the condition of $g_m > \gamma_m$ and $g_m > \kappa_c$. It behaves as a "quasi particle" that is unified by photon and spins.

④ 『magnetically induced transparent (MIT)』 : A state that corresponds to the condition of $g_m < \kappa_c$ and $g_m > \gamma_m$.

Special care should be taken to the state of "Purcell effect" and "strong coupling", in practical ESR measurements.
Extraordinary spectral line shape, as shown in Application Note ER200006, might be due to the interaction between microwave photon and spins. An excess sample amount would produce an unexpected effect according to this photon- spin interaction, because equation 1 indicates that coupling constant is proportional to the square root of spin numbers. As shown in Fig. 2, resonant frequency shift of the cavity (dotted lines corresponded to AFC balance) on measuring spectrum can help to check the abnormal interaction.

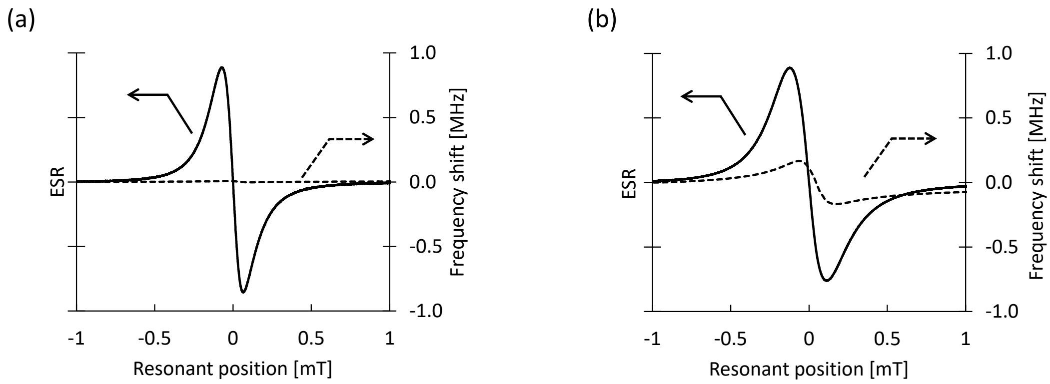
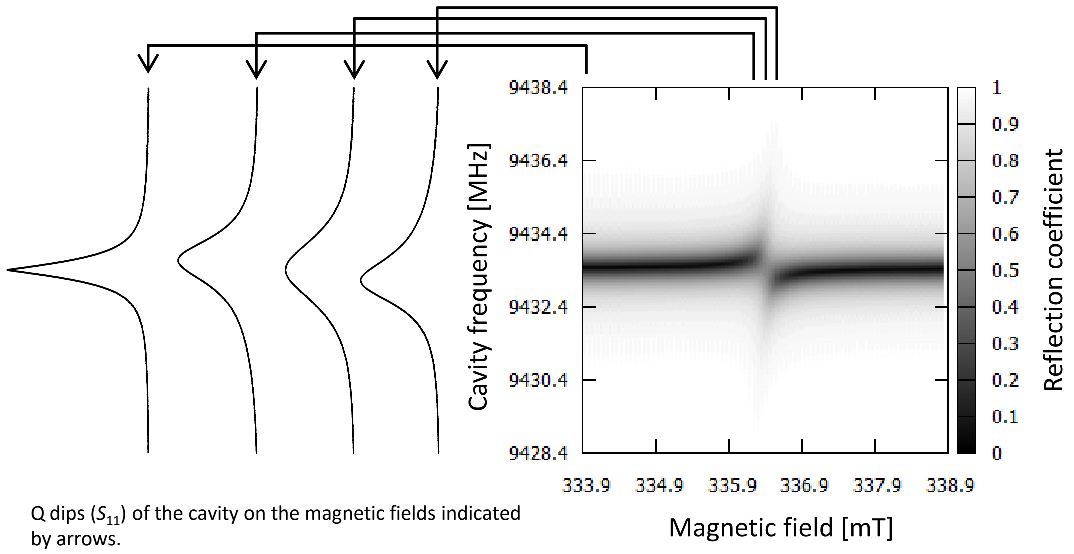


Fig. 2 Frequency shift of the cavity on measuring ESR spectra (*conf.* Application Note ER200006).

(a) Normal (Set_B). AFC balance does not almost move. (b) Excess sample (Set_A). AFC balance moves hard.

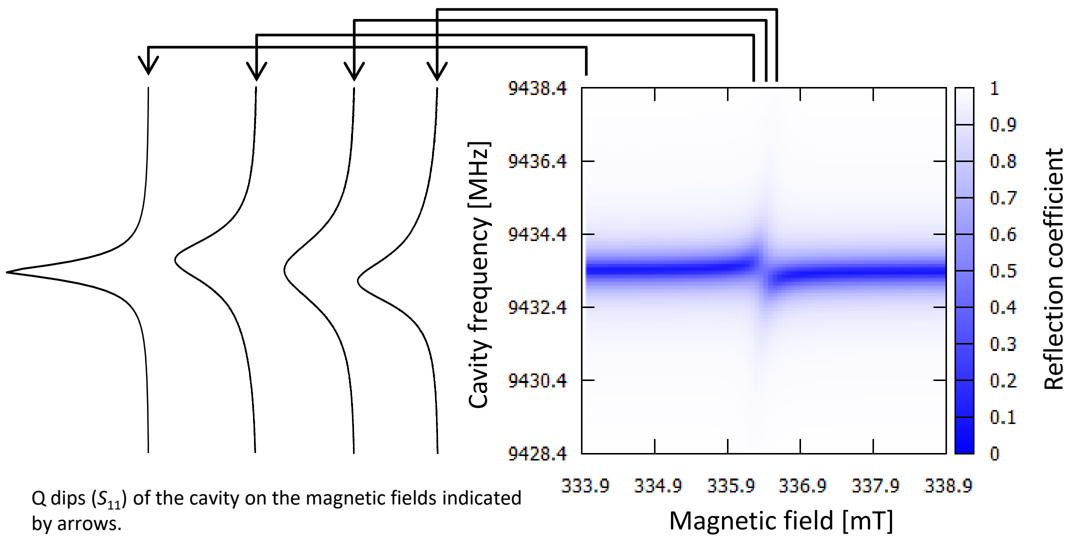
Investigating the frequency shift of the cavity around the resonant region, we can estimate what kind of interaction the syst em can be categorized to. Figure 3 is a mapping graph that the frequency spectra of the cavity ("Set_A" configuration as shown in Application Note ER200006) is arrayed on the respective magnetic fields. Based on the simulation using the equation of Q-dip (S_{11} parameter) shown in references[2][3], coupling constant was estimated to ca 1.2 MHz. This situation is inferred to the state of "Purcell effect", because it is under the condition of $\frac{g_m}{2\pi} < \frac{\gamma_m}{2\pi}$ and $\frac{g_m}{2\pi} > \frac{\kappa_c}{2\pi}$, where spectral half width (HWHM (half width at half maximum) is ca 121 μT ($\frac{\gamma_m}{2\pi} = 3.39$ MHz), Q_u value of the cavity is ca 18,000 ($\frac{\kappa_c}{2\pi} = 0.52$ MHz). Such a situation, normal ESR spectra can not be obtained. Especially, using high Q cavity that includes an excess sample migh t induce "Purcell effect", and it should be taken care of in the interaction. Furthermore, when the sample is not a paramagnet, but a ferromagnet, and i ts line width is narrow, we might encounter the state of "strong coupling" (continued to Application Note ER200008E).

(a)



Q dips (S_{11}) of the cavity on the magnetic fields indicated by arrows.

(b)



Q dips (S_{11}) of the cavity on the magnetic fields indicated by arrows.

Fig.3 Field dependence of the frequency spectra (Q-dips) . (a) Observed. (b) Simulation results based on the equation in the literature[3].

Reference: [1] X. Zhang, C-L. Zou, L. Jiang, and H. X. Tang, Phys. Rev. Lett. **113**, 156401 (2014).
[2] E. Abe, H. Wu, A. Ardavan, and J. J. L. Morton, Appl. Phys. Lett. **98**, 251108 (2011).
[3] Patent, US10288707B2 "Relaxation time measuring method and magnetic resonance measuring apparatus".

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