EFFECT OF SECONDARY NUCLEAR SPIN ECHO IN MAGNETICALLY ORDERED CRYSTALS

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There are known reports [1 - 5] of observation of additional nuclear-echo signals in magnetically ordered substances. The additional (secondary) echo is observed when the sample is acted upon by two radio-frequency (RF) pulses and follows the usual echo signal at a distance equal to the delay between the RF pulses (see the figure). The intensity of the secondary echo is smaller and decreases more rapidly with increasing delay than in the case of the ordinary echo. It was proposed in [2, 5] that the secondary echo appears because the precessing nuclear magnetization acts on the nuclear system during the time of appearance of the ordinary echo like some additional RF pulse. The magnitude of the alternating field at the nuclei is governed in this case by the hyperfine electron-nuclear interaction.

We consider in this article concrete mechanisms that lead to the appearance of the secondary echo.

We recall that in magnetically ordered substances the RF field acting on the nuclei is enhanced η times by the hyperfine-interaction [6]. (For the simplest one-domain ferromagnet, $\eta = H_{loc}/(H_0 + H_A)$, where H_{loc} is the hyperfine field at the nucleus, H_A the anisotropy field, and H_0 the external field.) In addition, the transverse precessing component of the sample magnetization is increased by the same number of times. Therefore the induction (echo signal) is due not directly to the transverse component of the nuclear magnetization m, but to the electronic magnetization $M_\perp = \eta m_\perp$. However, the appearance of $M_\perp$ produces at the nuclei an alternating hyperfine field $\tilde{H}^{hfi} = A_0 M_\perp$ (where A_0 is the hyperfine interaction constant), which is "sensed" by the nuclear system as an additional RF action and which leads in certain situations to an additional echo signal.

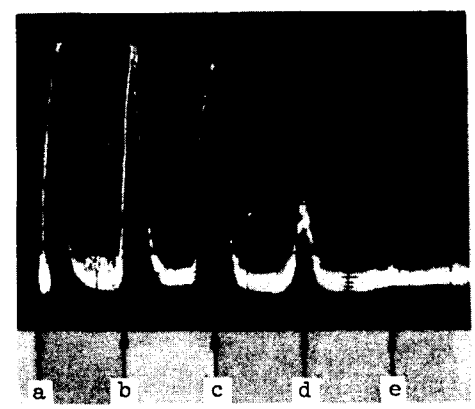
Let us consider the most effective concrete mechanisms. It is known [7] that application of two RF pulses produces an ordinary echo proportional to the nuclear magnetization

$$m_1 = m_0 \sin\theta_1 \sin^2\frac{\theta_2}{2} e^{-2\tau/T_2}, \qquad (1)$$

where m_0 is the equilibrium value of the nuclear magnetization (or of that part of the magnetization which participates in the formation of the echo)

$$\theta_1 = \gamma_n \eta H_1 t_1; \quad \theta_2 = \gamma_n \eta H_1 t_2 \qquad (2)$$

γ_n is the nuclear gyromagnetic ratio, H_1 the amplitude of the alternating circular RF field acting on the sample, t_1 and t_2 the durations of the first and second pulses, respectively, τ the distance between the pulses, and T_2 the time of nuclear transverse relaxation.



Photograph of signals of ordinary and secondary echo of Fe^{57} nuclei in $FeBO_3$ at T = 4.2°K; a and b - RF pulses, c - ordinary echo (the amplitude is limited by the oscilloscope), d - secondary echo, e - echo of next order.

As already indicated, owing to the hyperfine interaction, the transverse field at the nuclei, due to $m_\perp$, is equal to

$$\vec{H}^{hfi} = A_0 \eta \vec{m}_\perp$$

$H^{hfi}_\sim$ is directed along $m_\perp$, i.e., it is shifted 90° in phase relative to H_1. We assume for simplicity that the ordinary echo has the form of a rectangular pulse of duration t_e. We can then consider the problem of occurrence of a secondary echo signal if three RF pulses act on the sample (the two external-field pulses mentioned above and a pulse of amplitude H^{hfi} and duration t_e).

Such an approach yields the amplitude of the secondary-echo signal at the instant of time 3τ, in relative units:

$$U_{sec} = \frac{1}{2}\sin\theta_1 \sin\theta_2 \sin\theta_3 e^{-\left(\frac{2}{T_2}+\frac{1}{T_1}\right)\tau} + \left[1-(1-\cos\theta_1)e^{-\frac{\tau}{T_1}}\right]\sin\theta_2 \sin^2\frac{\theta_3}{2} e^{-\frac{2\tau}{T_2}}. \quad (3)$$

Here $\theta_3 = \gamma_n t_e \eta A_0 m_\perp$.

Formula (3) is valid if $\theta_3 \ll \pi/2$. The two terms in (3) have simple physical meanings. The first describes a case analogous to the so-called stimulated echo, which appears if three RF pulses are applied to the sample. The second corresponds to ordinary echo, if only the second RF pulse and $H^{hfi}_\sim$ are considered and the initial equilibrium value m_0 is replaced by the value m_z existing in the nuclear system at the instant when the second RF pulse is turned on.

At values typical of 100% concentration of the Fe^{57} nuclei in ferrites at $T = 4.2°K$ we have $Am_0 = 5 \times 10^{-3}$ Oe, $\gamma_n = 2\pi \cdot 137.7$ Hz/G, $\eta = 10^3$, $t_3 = 10^{-5}$ sec, and $\theta_3 \simeq 0.5 \times 10^{-1}$ rad. In this case the ratio of the amplitudes of the secondary and ordinary echoes at $\tau \ll T_2$, T_1 is $U_{sec}(0)/U_{ord}(0) \simeq 10^{-2}$. At $\theta_3 \ll \pi/2$ and $\theta_2 \neq \pi$, the first term makes the largest contribution in most cases. Then

$$\frac{U_{sec}}{U_{ord}} = \frac{1}{2}\sin\theta_1 \sin\theta_2 \gamma_n \eta m_0 A t_e \exp\left[-\left(\frac{2}{T_2}-\frac{1}{T_1}\right)\tau\right].$$

The case $\theta_3 = \pi/2$ corresponds to a number of additional complications, which will be considered elsewhere. It should be noted that the additional echo signals appear not only at the instant 3τ, but also at $(3+n)\tau$, where n is an integer. The intensity, however, decreases at least like $(U_{sec}/U_{ord})^n$, so that these echoes will not be considered here.

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PULSED CHEMICAL HIGH PRESSURE LASER USING THE MIXTURE $D_2 + F_2 + CO_2$

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The chemical lasers most widely developed by now are based on reactions of halogens with hydrogen, the first being the hydrogen-chloride laser [1]. Most investigators gave preference to reactions with fluorine, which has the largest energy content [2 - 4]. A logical consequense of this trend is the use of the chemical reaction of hydrogen with fluorine for lasers [5, 6], wherein the chain effective for the laser operation is considerably longer than the chain of the reaction of hydrogen with chlorine. Work with such lasers, however, has revealed their principal shortcoming, namely the rapid relaxation of the excited molecules by interacting with deactivated molecules of the same type. A very fruitful approach to overcoming this difficulty was the idea of obtaining inverted population by transferring energy from the "hot" molecules obtained in the chemical reactions to the "cold" molecules. This idea, first suggested for chemical lasers in [7], was successfully realized by a number of workers [8 - 11]. The procedure of introducing the polyatomic molecule CO_2 into the $D_2 + F_2$ mixture turned out to be very fruitful: it made it possible to increase the chemical efficiency and the output energy of a pulsed chemical laser by approximately 10 times [12]. The success of the experiments performed with the mixture at low pressures [12] has enabled us to advance to experiments at higher pressures of the reagents. By introducing the CO_2 molecules we were able to obtain a working mixture in which the partial pressures of the deuterium and of the technically pure fluorine exceeded the second chain limit of ignition of the pure stoichiometric $D_2 + F_2$ mixture. CO_2 apparently eliminates the energy branching in the reaction between deuterium (hydrogen) and fluorine, without noticeably affecting the length of the direct chain[1)]. A typical ratio of the partial pressures of the main components of the gas mixture (fluorine, deuterium, carbon dioxide, and helium) was respectively 1:1:4:11; the total pressure varied in a range of several hundred Torr.

The experiments were performed in a stainless steel reaction vessel. The reaction was initiated by radiation from a straight flash lamp with brightness temperature 20000 - 25000°K, wherein an electric discharge (20 μF, 30 kV) was initiated in a quartz tube by an exploding wire [13, 14]. The radiation was extracted through windows of sodium chloride, located in flanges of the reaction tube. The optical resonator was made up of a gold-coated flat mirror and one of the windows of the reaction vessel. Light passing through a sodium-chloride plate was directed to a calorimeter, and part of the light, after attenuation, to a gold-doped germanium photoreceiver operating at liquid-nitrogen temperatures.

[1)] We disregard here the possible role of CO_2 as a third body in reactions of the type $F + F + M \rightarrow F_2 + M$ and $D + D + M \rightarrow D_2 + M$.