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STIMULATED SPIN ECHO STUDIES OF $^{60}$Co NUCLEI ORIENTED IN IRON


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Résatm.- Une technique utilisant quatre impulsions résonnantes est utilisée afin de produire des échos de spin stimulés qui sont détectés à l'aide du rayonnement nucléaire. Ces échos présentent une période d'extinction, fonction de la relaxation spin-réseau, au contraire de l'effet observé dans les expériences à trois impulsions seulement.

Abstract.- A four-pulse resonance technique has been developed to produce stimulated spin echoes which are then observed by radiative detection. These echoes show a decay time which depends on the spin-lattice relaxation ; this is not the case for the echoes produced by the triple-pulse sequence.

INTRODUCTION AND THEORY.- Recently we reported/1/ observations by radiative detection of spin echoes, produced by triple-pulse sequences, for $^{60}$Co nuclei oriented in iron. Studies/2/ of the dependence of the echo amplitude upon pulse interval showed that, after an rf pulse, the nuclear spins irreversibly lose their coherence in the transverse plane with a decay time $T_2 \sim 1$-2 ms. This is a very short time for a dilute alloy when compared to the spin-lattice relaxation time $T_1 \approx 75$ s/3/ for the conditions of reference/2/. To study further the application of pulsed resonance techniques in nuclear orientation, we have applied a four-pulse sequence, with intervals $T', T''$ and $T'''$, to the same sample. Whereas the echo decay time for a triple-pulse sequence should relate to $T_2$, the decay time for a four-pulse (stimulated echo) sequence, should, under the correct conditions, relate to $T_1$. In nuclear orientation experiments, the fourth pulse is used to return a component of the transverse magnetization to the z-axis and the $\gamma$-anisotropy is then measured as a function of $T'''$. The stimulated echo will appear as a change in this anisotropy when $T''' = T'$.

To calculate the amplitude of the expected echo signal it is necessary to integrate over all spins since rf fields $H_1$ which are comparable in magnitude only with the inhomogeneous broadening have been used. For $T'$, $T'' < T_1$, $T_2$ and a system in which the major term in the $\gamma$-anisotropy is $P_2(\cos \theta)$, the fractional change in that anisotropy after the pulse sequence is given by

$$S_2 = 1 - P_2(\cos \theta) = 1 - \int_{\infty}^{\infty} \rho(\omega) P_2(\cos \theta) d(\omega - \omega_0)$$

where $\omega_0$ is the centre of the distribution (assumed to be Gaussian) of resonant angular frequencies $\theta$ is the final angle between a spin and the z-axis, after allowing for rotations during each pulse and rotation about the z-axis during each pulse interval. Also we define a parameter $R$ as $\omega_1/\Delta \omega$ where $\Delta \omega$ is the half-width at half-maximum of the inhomogeneously broadened resonant frequency and $\omega_1$ is the rf angular frequency.

Calculated spin echo line shapes for equal 90° pulses at values of $R$ of 0 and 0.45 are given in figure 1 : $R = 0.45$ corresponds to our experimental conditions. For a true 90° pulse sequence ($R = \infty$), harmonic sub echoes are absent. For more general turn angles, $S_2$ has twenty echoes at times $T''' = 2/\Delta \omega = 16$ ms. The arrows indicate the principle stimulated echo.
later than the third rf pulse/4/. Even for 
\( R = 0.45 \) the stimulated echo remains prominent des-
pite the additional competing structure due to the 
harmonic sub echoes and their broadening due to 
other effective angles of rotation centred on 90°.

EXPERIMENTAL DETAILS AND RESULTS.- The sample used 
was that of references/1/ and /2/ with a calcula-
ted fractional concentration of \( ^{60}Co \) atoms \( \approx 5 \times \)
\( 10^{-5} \) in the diffusion layer. A 0.1 T polarizing 
field was used, corresponding to a resonant fre-
quency of 165.5 MHz; the linewidth, \( \Delta \omega / 2\pi \), was 
0.5 MHz. No evidence for \( ^{60}Co \) satellite structu-
re or for a \( ^{60}Co \) resonance could be found in 
this heavily doped sample.

After each four-pulse sequence, the time de-
pendence of the \( \gamma \)-anisotropy was determined for 
250s. The "signal" was obtained by computer extra-
polation of the anisotropy back to a time immedia-
tely after the fourth pulse. No signals were obser-
vied when rf frequencies a few MHz either side of 
resonance were used, indicating that off-resonant 
heating was negligible.

For \( \tau' = 5 \) \( \mu \)s stimulated echoes were observed 
for values of \( \tau'' \) of 1, 10, 25 and 40 s (figure 
2). For these values of \( \tau' \) and \( \tau'' \) and the estab-
lished short \( \tau_2 \), the baseline of the stimulated echo 
appears well defined, being subject only to inter-
ference from negligible weaker harmonics of this 
echo. Comparison of the calculated and observed li-
neshapes for \( \tau'' = 1 \) s shows the same general beha-
viour though the amplitude of the observed shape is 
somewhat lower, as in/1/. This reduction is proba-
bly associated with inhomogeneous broadening of 
the rf field \( H_1 \).

A simple spin-temperature analysis of the 
time dependence of the \( \gamma \)-anisotropy after removal 
of a frequency modulated c.w. rf field yielded a 
value \( \tau_1 = (80 \pm 5) \) s at 12 mK for a 0.1 T applied 
field. This is comparable with the decay time of 
the amplitude of the stimulated echo. Hence we can 
conclude that the four-pulse nuclear orientation 
stimulated echo technique does lead to a relaxation 
time which is related to \( \tau_1 \), rather than the much 
faster \( \tau_2 \). The previously observed short value for 
\( \tau_2 \) appears to validate the use of the spin tempera-
ture concept in the analysis of spin-lattice rela-
xation. Further experiments on \( ^{60}Co \) samples of 
varied concentration are in progress. These should 
establish whether a grain boundary diffusion mecha-
nism exists, causing an anomalously high local con-
centration in this sample, or whether the results 
presented here indicate a general property of the 
very dilute \( ^{60}Co \) system.

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Fig. 2 : Observed stimulated echo lineshapes for 
\( \tau' = 5 \) \( \mu \)s and various values of \( \tau'' \).