ELECTRIC QUADRUPOLE INDUCTION EFFECT IN ELECTRON RESONANCE

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It is well known that under certain conditions precessing components of the magnetization arise in paramagnetic resonance. The alternating magnetic field created by them carries much information about the structure of the sample.

If the resonance magnetic field causes transitions between levels whose magnetism is not due purely to spin, then besides the motion of the orbital magnetic moment, changes in the distribution of electronic charge occur. In particular, the motion of the electric quadrupole moment of the electron shell induces an electromagnetic field which, as estimates show,[1] is completely accessible in present-day experiments.

Let us take the Fe^{2+} ion in MgO[2] as an example. In a magnetic field a resonance line is observed from the three lowest equidistant levels described by the spin Hamiltonian $\mathcal{H} = g^*\beta \mathbf{H}\cdot\mathbf{S}$ $(S=1)$; the line is 8 to 10 G wide. By making use of the transformation properties of the wave functions ψ_m of these levels, it can be shown that the matrices of the operators that transform in the same way in the ψ_m basis and in the basis of the eigenfunctions χ_m of the spin $S = 1$ are the same to within a multiplicative constant (Γ).[3] For the operators S_x, S_y, S_z this factor equals $g^* = 3.5$, the effective g factor, but needs to be calculated for the other operators. Proceeding as in [4], we find that following an electromagnetic pulse of length t_0, in which the resonant alternating magnetic field $(2H_x \cos \omega t)$ is perpendicular to the constant field (H_z), the average values of the effective spin components are

$$\langle S_{+1}\rangle \equiv \langle S_x + iS_y\rangle = iP_1 f_{\omega_0}(t)\sin\xi_1, \qquad (1)$$

$$\langle S_{+1}S_z + S_zS_{+1}\rangle \equiv \langle\{S_{+1}S_z\}\rangle = \frac{i}{2}P_2 f_{\omega_0}(t)\sin 2\xi_1, \qquad (2)$$

$$\langle S_{+1}^2\rangle = P_2 f_{2\omega_0}(t)\sin^2\xi_1; \qquad (3)$$

where*

$$P_1 = \frac{\operatorname{sh}\delta}{\operatorname{ch}\delta + 1/2}, \qquad P_2 = \frac{\operatorname{ch}\delta - 1}{\operatorname{ch}\delta + 1/2},$$

$$f_{k\omega_0}(p) = \exp\left\{-ik\omega_0 p - \frac{k^2\sigma^2p^2}{2}\right\},$$

$$\xi_1 = g^*\beta H_x\hbar^{-1}t_0, \qquad \delta = \hbar\omega_0/kT, \qquad \hbar\omega_0 = g^*\beta H_z,$$

and σ^2 is the mean square deviation of the resonance frequency from ω_0. It is well known that Eq. (1) determines the magnetic dipole induction (MDI) signal which arises from the precession of the magnetization components of the sample $M_+ = g^*\beta N\langle S_{+1}\rangle$ (N is the number of Fe^{2+} ions). Equations (2) and (3) give the electric quadrupole precession (EQP) signal evoked by the components of the quadrupole moment of the d shell of the Fe^{2+} ion. The amplitude of the electric field induced by these components in the wave zone and at distances $\mathbf{R}$ of the order of the wavelength λ, is accordingly[5] $(\mathbf{n} = \mathbf{R}/R)$:†

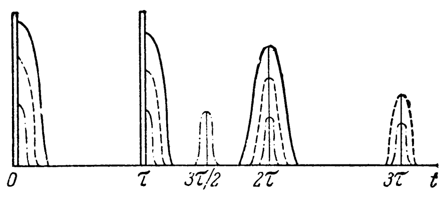
$$E_1 = \frac{1}{2Rc^3}\sum_{i=1}^{N}\left[\left[\frac{d^3}{dt^3}\langle e\mathbf{x}_\alpha\mathbf{x}_\beta\rangle\mathbf{n}\right]\mathbf{n}\right]$$

$$\approx\left(\frac{2\pi}{\lambda}\right)^3\frac{e\Gamma_{\alpha\beta}N}{2R}\left[\left[\langle\{S_\alpha S_\beta\}\rangle\mathbf{n}\right]\mathbf{n}\right], \quad E_2\sim\eta E_1.$$

The quantity η plays the role of a filling factor; for MDI $\eta = 0.1$–0.5. Calculations give $2\Gamma_{xz} = 2\Gamma_{yz} = \Gamma_{xx} = \Gamma_{yy} = 2\overline{r^2}/35$, where $\overline{r^2}$ is the mean square radius of a d electron. For example, for $\eta = 0.1$, $\xi_1 = 90°$, $T = 1°K$, $\omega_0 = 2\pi \times 10^{10}$ rad/sec, we find $E_1 \sim 55\,R^{-1} \times 10^{-6}$ V/cm and $E_2 \sim 2 \times 10^{-6}$ V/cm. Signals of this magnitude can be detected.

Besides this radiation, there is also radiation from MDI, which is about 10^6 times larger. Hence, after a single pulse only the signal from component (3), which precesses at twice the resonance frequency can be distinguished. After two pulses, there occurs a difference in the signals not only in frequency but also in time. The signals evoked by two pulses applied at an interval τ are shown in the figure, and their amplitudes are given in the table. In particular, it follows from the table that if the first pulse is a 90° pulse $(\xi_1 = \pi/2)$, then at $t = \tau$ the MDI signal does not show up and only the EQP signal will be observed.

Observation of EQP allows the direct investigation of the quadrupole moments of the electron shells of paramagnetic atoms. Since spin-lattice relaxation in paramagnetic substances is brought about by interaction between the quadrupole mo-



Signals evoked by two pulses applied at an interval τ; solid line – $\langle S_+\rangle$, broken line – $\langle\{S_+S_z\}\rangle$, dot-dash line – $\langle S_+^2\rangle$.

	Amplitudes of the signals shown in the figure			
	units $f_k\ (t-\tau)$	units $f_k\left(t-\frac{3\tau}{2}\right)$	units $f_k\ (t-2\tau)$	units $f_k\ (t-3\tau)$
$\frac{\langle S_{+1}\rangle}{P_1}$	$i\cos\xi_1\sin\xi_2$	0	$-i\sin\xi_1\sin^2(\xi_2/2)$	0
$\frac{\langle\{S_{+1}S_z\}\rangle}{P_2}$	$i\sin 2\xi_2 \times [1-{}^3/_2\sin^2\xi_1]$	0	$-i\sin 2\xi_2\sin^2(\xi_2/2) \times [3-4\sin^4(\xi_2/2)]$	$i\sin^2\xi_1\sin\xi_2 \times \sin^2(\xi_2/2)$
$\frac{\langle S_+^2\rangle}{P_2}$	$-\sin^2\xi_2 \times [1-{}^3/_2\sin^2\xi_1]$	$\sin 2\xi_1 \times \sin\xi_2\sin^2(\xi_2/2)$	$-\sin^2\xi_1\sin^4(\xi_2/2)$	$-\sin^2\xi_1\cos^4(\xi_2/2)$

ment and the crystal field, this effect furnishes a more accurate method for the investigation of transition processes. Finally, the shape of the EQP line will yield information about the local crystal field.

It is to be noted that EQP can also be excited by acoustic pulses.[3]

*sh = sinh, ch = cosh.
†[**ab**] = **a** × **b**.

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RECOMBINATION RADIATION OF GaAs AND Ge ON EXCITATION WITH FAST ELECTRONS

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It has been proposed earlier[1] to use the interband carrier transitions in semiconductors to obtain states with population inversion for the purpose of constructing an optical maser. Later a hypothesis was put forward on the possibility of obtaining a state with population inversion in semiconductors by irradiation with a flux of fast electrons.[2]

From this standpoint it was of definite interest to investigate the recombination radiation of semiconductors excited by fast-electron bombardment. Until now this radiation has not been investigated at all.

When semiconductors are irradiated with fast electrons there is a volume excitation of carriers and the influence of surface effects can be reduced to minimum.

In the present work we detected the recombination radiation of germanium and n-type gallium arsenide on irradiation with a beam of electrons of ≈ 0.6 MeV energy, obtained from a linear electron accelerator.

GaAs and Ge samples in the form of single crystals of 4×4×10 and 10×10×2 mm dimensions, respectively, were placed on a cold duct in a cryostat and cooled to the temperature of liquid nitrogen. The electron beam entered the cryostat through a window covered with aluminum foil 50 μ thick. Through another window the image of the sample was projected onto the slit of an IKS-12 spectrometer. The electron accelerator produced pulses of 2 μsec duration and 400 cps repetition frequency. The average current in the electron beam incident on the sample was ≈ 1 μA. An FÉU-28 photomultiplier (in the case of GaAs) and a PbS photoresistor (in the case of Ge) were used as radiation detectors.

The intensity of radiation from the samples in-