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CONCERNING DISCRETE SATURATION IN INHOMOGENEOUSLY BROADENED EPR LINES

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In. [1, 2] there was described the discrete saturation (DS) observed when a short-time saturating pulse of microwave power acts on an EPR line whose width is governed by the nuclei surrounding the paramagnetic center. It was proposed that a possible mechanism causing the DS is one in which the quantum of the microwave field causes simultaneous reorientation of the spin of the electron and of the nucleus located in the environment of the neighboring paramagnetic center. Such a process should depend strongly on the concentration of the magnetic centers. By investigating DS in samples in which the concentration was varied in a wide range, we have established that the DS picture hardly varies with the concentration. It follows therefore that the DS mechanism should be local. A similar statement was made recently in [3].

The Hamiltonian of the paramagnetic center and the nuclei surrounding it can be written in the form

$$\mathcal{H} = g\beta H_0 \mathbf{S}\mathbf{n} + \sum_i \mathcal{H}_i ,$$
$$\mathcal{H}_i = \hbar\gamma H_0 \mathbf{I}^i\mathbf{n} + \mathbf{S}A^i\mathbf{I}^i ,$$

where the index i labels the nuclei, $\vec{n}$ is a unit vector along the external field H_0, $\vec{S}$ is the electron spin operator, $\vec{I}'$ is the spin operator of the i-th nucleus, and A^i is the tensor of hyperfine interaction of the i-th nucleus with the electron spin.

It was shown in [4] that in the case when the energy of the hyperfine interaction A is of the order of the Zeeman energy of the nucleus in the external field, $\hbar\gamma H_0$, the EPR spectrum may become complicated by the presence of "forbidden" transitions with simultaneous reorientation of the spins of the electron and of the nuclei. This occurs in the electronic transition because of the change of the orientation of the effective magnetic field $\vec{H}^i_m = H_0\vec{n} + (m/\hbar\gamma)A^i\vec{n}$ in which the nuclear spin is quantized. The problem of a complex super-hfs was solved completely, in principle, for any number of non-equivalent nuclei with spin 1/2 in the environment of the paramagnetic center.

In the general case the number of components of the complex super-hfs is 4^ℓ, where ℓ is the number of nuclei in the environment of the paramagnetic center. For ℓ equivalent nuclei, the number of observed lines decreases to $(\ell + 1)^2$. We recall that for a simple spectrum this number equals $\ell + 1$. Individual lines in the complex super-hfs may overlap, and in this case each line in the observed EPR spectrum represents an aggregate of different transitions. When this component is saturated by a short-duration powerful microwave pulse, the neighboring hfs components are also saturated. In the case of an unresolved super-hfs spectrum this will present the appearance of resolution of the structure.

We shall illustrate the foregoing using a simple example of four equivalent nuclei in

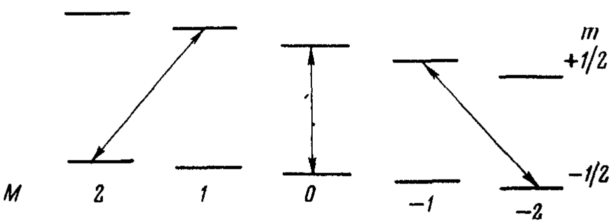

Fig. 1. Level scheme for four equivalent nuclei m and M (projections of electron and total nuclear spin). The arrows indicate the set of transitions following saturation of the central transition (+1/2, 0) ↔ (-1/2,0).

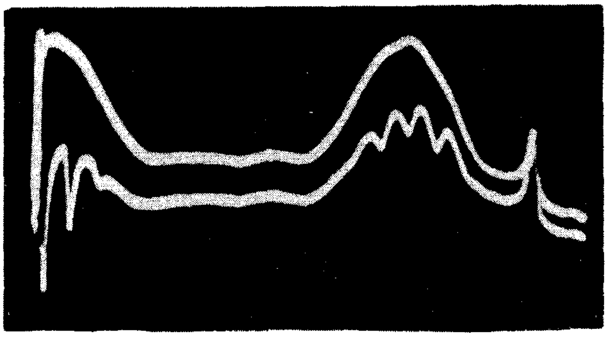

Fig. 2. DS on one of the six hfs components, observed in irradiated isotropic polyethylene, due to long-range-order protons in the polymer chain. The top trace shows the same section of the spectrum covered twice during the modulation period without saturation. An anthracene reference line is shown on the right.

the environment of a magnetic center with effective spin $S = 1/2$. Such a case takes place, for example, for a paramagnetic center in irradiated polyethylene $- CH_2 - CH_2 - \dot{C}H - CH_2 - CH_2 -$. The unpaired electrons interact with five nearest almost-equivalent protons and, as is well known, produce a hfs spectrum of six lines with a binomial intensity ratio 1:5:10. The distance between the components is approximately 30 Oe. For these protons there is observed in the 3-cm band a simple spectrum, since $A >> \hbar\gamma H_0$. The large width of the components of this spectrum is due to the interaction of the unpaired electron with the next four protons, for which a complicated super-hfs spectrum is expected. The level scheme for these four protons is shown in Fig. 1. The total number of expected components is 25. Some of these transitions may coincide in energy. Obviously, in order for the DS to be possible, it is necessary to have an overlap of different transitions from the total number of super-hfs components. This will occur, in particular, if the approximate equality $\varepsilon_{1/2} \approx 2\varepsilon_{-1/2}$ holds, where $\varepsilon_{1/2}$ and $\varepsilon_{-1/2}$ are the distances in the upper and lower levels, respectively. This is indicated by the weak resolution of the parameter 6 Oe in isotropic and particularly in oriented polyethylene (in which the polymer chains stretch along one axis), and the agreement between this parameter and the observed DS parameter in these samples (see Fig. 2). In this case the number of expected super-hfs components decreases to 13. Saturation of the central transition (+1/2, 0) ↔ (-1/2, 0) by a short-duration microwave power pulse obviously leads to saturation of the transitions (+1/2, 1) ↔ (-1/2, 2) and (+1/2, -1) ↔ (-1/2, -2), since the intensity of the central hfs line is the sum of these transitions. When the magnetic field is shifted to the neighboring hfs component, the latter becomes saturated because it is an aggregate of the transitions (+1/2, -1) ↔ (-1/2, -1) and (+1/2, 0) ↔ (-1/2, 1). The same will also be observed for the component (+1/2, -2) ↔ (-1/2, -2) observed in conjunction with the transitions (+1/2, -1) ↔ (-1/2, 0) and (+1/2, 0) ↔ (-1/2, 2). The picture is perfectly symmetrical for the left wing of the central saturable transition. Thus, when the central transition is saturated there will be observed DS consisting of 5 lines with parameter $\varepsilon_{-1/2} \approx 5$ Oe. When the neighboring transition is saturated, the DS picture should be asymmetrical relative to a change of the magnetic field, as is indeed observed in oriented polyethylene.

Simple calculations were made of the intensities, in accordance with [4], for all 13 x 6 = 78 lines, and the plotted envelope of these lines is in good agreement with the shape of the observed EPR spectrum.

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PRODUCTION OF HIGH-ENERGY PARTICLES BY ACCELERATION OF A PLASMA SCATTERING A STRONG BEAM OF FAST ELECTRONS

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The development of powerful pulsed electron accelerators with currents 10^5 - 10^6 A and voltages 0.3 - 10 MV, with pulse durations of several dozen nanoseconds [2-4] has made it possible to employ now the previously proposed [1] method of accelerating a plasma with a frozen-in magnetic field, scattering an electron current, to accelerate the plasma to relativistic velocities and to obtain high-energy particles (in [1] we considered the nonrelativistic case).

Let us consider a beam of relativistic electrons incident on a plasmoid of sufficiently high density, whose scattering ability is enhanced by a frozen-in magnetic field. When the electrons are scattered by the magnetic field, the plasma receives the momentum of the electron current, and the plasma will be accelerated as a whole, provided a sufficiently strong coupling obtains between the electronic and ionic fractions of the plasma, i.e., if the resultant accelerating field E_{acc} does not exceed the maximum Coulomb field that can arise as a result of the separation of the plasma charges, $E_p \approx 4\pi n_e ed$, where n_e is the plasma density and d is the length of the plasmoid. (For example, if $E_{acc} = 10^9$ V/m we need $n_e \gtrsim 10^{12}$ cm^{-3} at a plasmoid length d = 5 cm.)

The magnetic field frozen in the plasma should have an intensity sufficient for strong scattering or reflection of the electron current: from the condition $eH\rho \approx mvc \approx \mathcal{E}$ we find the required $H \approx \mathcal{E}/ed \approx 0.6 \times 10^3 \mathcal{E}_{MeV} \approx 10^3$ Oe at an electron energy $\mathcal{E} = 3$ MeV. If the force lines of the frozen-in magnetic field emerge from the plasmoid, then the cross section of the plasmoid can be much smaller than the cross section of the electron beam and the efficiency of momentum transfer can still remain adequate. The duration of the acceleration should not exceed noticeably the skin-effect damping time of the currents in the plasma ($t \approx 4\pi\sigma d^2/c^2$, where σ is the electric conductivity of the plasma), if no special measures are taken to maintain the currents (say by means of a varying external magnetic field or by deformation of the plasmoid), or else should not exceed the time of spreading of the plasma