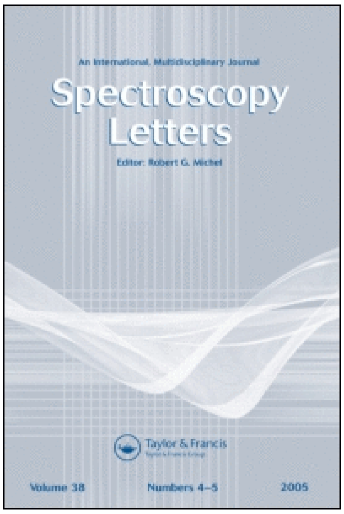

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Magnetic Field Profiling for Selected-States Magnetic-Resonance Spectroscopy (Ssmrs) and Stern-Gerlach Spectroscopy (Mgrs) In Condensed Matter

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MAGNETIC FIELD PROFILING FOR SELECTED-STATES MAGNETIC-RESONANCE SPECTROSCOPY (SSMRS) AND STERN-GERLACH SPECTROSCOPY (MGRS) IN CONDENSED MATTER

Key words: nuclear magnetic resonance and relaxation, Stern-Gerlach effect, other topics in magnetic resonances and relaxations, EPR and NMR spectroscopy.

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Abstract: - *A method was presented of profiling the magnetic field, with a zero vector of magnetic flux density B_r and strong gradient G, enabling conditions for the Stern-Gerlach spectroscopy to be accomplished in condensed matter (the method has been called magnetic field gradient spectroscopy - MGRS), as well as the previously proposed magnetic resonance spectroscopy for selected energy states (SSMRS). Magnetic field distribution in a model electromagnet were shown when condition $B_r = 0$ for the resultant magnetic field was satisfied within the sample.*

INTRODUCTION

In recent years the authors of many papers [1-13] pointed out the necessity to undertake, in magnetic resonance (MR) spectroscopy, the investigations on the possibilities of the employment of the Stern-Gerlach (SG) interaction [14,15], i.e. the interaction of the magnetic dipole moment with the magnetic field gradient

In the currently used MR methods, the magnetic field gradient has found wide applications such as the transformation of spatial coordinates to frequency coordinates [16,17], the measurement of the diffusional [18] and continuous [19] spin transport, or the measurement and imaging of periodical spin displacements evoked by an elastic wave originating either from external [20-27] or internal [25-27] sources and by the electric field [28,29].

During the 1990s, several methods were worked out which have shown new interesting capabilities of the MR methods created by the use of a strong magnetic field gradient, thus revealing the effect of the SG interaction. Sidles et al. [2-8] have worked out a technique of atomic force microscopy (AFM) enabling the nuclear or electronic MR signal from a single spin in condensed matter to be detected. Thus, owing to the SG interaction and force detection, marked improvement in the resolution of the MR methods was attained. The principles of the selected states magnetic resonance spectroscopy (SSMRS) were also presented [9-13]. This spectroscopy is based on the spatial separation of spin groups from different Zeeman energy states in a fluid medium caused by the SG interaction. As a result it is possible to obtain an MR signal proportional to the population of the energy states, i.e. the improvement of the sensibility of the MR methods by many orders of magnitude compared with the methods based on the postulate of Bloch [30] and Purcell et al. [31], in which the signal is proportional to the difference in the population of the Zeeman energy states.

There is also another interesting and promising hypothesis concerning the MR methods of employing the SG spectroscopy [32-36] in condensed matter

[37,38]. It was temporarily called the magnetic field gradient resonance spectroscopy (MGRS) [37,38].

In the authors' opinion, the accomplishment of the MR spectroscopy in the magnetic field gradient (and not as previously in a homogeneous field with a possible superimposition of a programmed sequence of magnetic field gradient pulses) will facilitate an essential development of the MR technique in respect to both its research potential and technical solutions in regards to the MR apparatus [37]. This is a logical consequence of the SG experiment. The AFM, SSMRS and MGRS methods are the first promising signs of this trend in the MR development.

The main obstacle in carrying out the experiments in which the effect of the SG interaction is observed, consists in generating and profiling a suitable magnetic field. Such a field should have the following properties: (i) strong and linear heterogeneity, (ii) a possibly low absolute value of the magnetic flux density vector, $\boldsymbol{B}$, (iii) it should make possible the time changes in both magnetic flux density, $\boldsymbol{B}_o$, and the direction and value of the magnetic field gradient, $\boldsymbol{G}$, and (iv) it should create possibilities of changing the mutual orientation of vectors $\boldsymbol{B}_o$ and $\boldsymbol{B}_G$, where $\boldsymbol{B}_G$ denotes the vector of the magnetic flux density of the generated magnetic field gradient, $\boldsymbol{G}$.

The progress made in recent years in the technology of superconducting materials and ferromagnetic materials with high magnetic susceptibility seems to encourage the attempts to undertake such a direction of investigations. In the case of small volumes, a gradient, $\boldsymbol{G}$, of the order of 10^6 T/m has already been obtained [4]. Values of the order of 10^8 T/m are anticipated in the near future [4].

The present paper outlines the direction of the search in the domain of generating a magnetic field suitable for both SSMRS and MGRS and shows one of the constructed models of an electromagnet [37] to be used in the accomplishment of the above requirements.

METHOD OF PROFILING THE MAGNETIC FIELD

An attempt was undertaken to find possibilities of: (a) obtaining a space with a zero vector of magnetic flux density, $\boldsymbol{B}$, and a strong magnetic field gradient, $\boldsymbol{G}$, or (b) suppressing the effect of the Zeeman interaction. It was proposed to superimpose, on a constant and homogeneous magnetic field gradient $\boldsymbol{G}$, a homogeneous field with the magnetic flux density $\boldsymbol{B_o}$ (|| z) anti-parallel to the vector $\boldsymbol{B_G}$ (|| -z) of the generated gradient $\boldsymbol{G}$ ($\equiv \delta \boldsymbol{B_G}/\delta$i, where i denotes the components of the Cartesian system). Figure 1 shows two cases in which areas with a zero magnetic flux density can be obtained with the use of a transverse [part (a) - $\boldsymbol{G}$ in the xy-plane] and longitudinal [part (b) - $\boldsymbol{G}$ parallel to the z-axis] magnetic field gradient.

The following cases can be distinguished depending on the value of $\boldsymbol{B_o}$ and $\boldsymbol{B_G}$:

(α) When the absolute value of the magnetic flux density $\boldsymbol{B_o}$ is within the limits

$$\boldsymbol{B}_{Gmax} > /\boldsymbol{B}_o/ > \boldsymbol{B}_{Gmin}, \qquad (1)$$

where $\boldsymbol{B_{Gmax}}$ and $\boldsymbol{B_{Gmin}}$ denote the maximum and minimum value of $\boldsymbol{B_G}$ within the sample, respectively, then there exists an area in the sample with a zero resultant magnetic flux intensity

$$\boldsymbol{B}_r = \boldsymbol{B}_o + \boldsymbol{B}_G = 0. \qquad (2)$$

For a transverse magnetic field gradient condition (2) is satisfied in a thin flat layer (clear in Fig. 1a), whereas in the case of the longitudinal gradient the area is a small 3D volume one (clear in Fig. 1b). Areas with an opposite magnetic flux density $\boldsymbol{B_r}$ are distributed symmetrically about the above areas. Thus, three areas can be distinguished within the sample: the central one with $\boldsymbol{B_r} = 0$ (i) and two stretched areas symmetrical relative to the central one, with an opposite

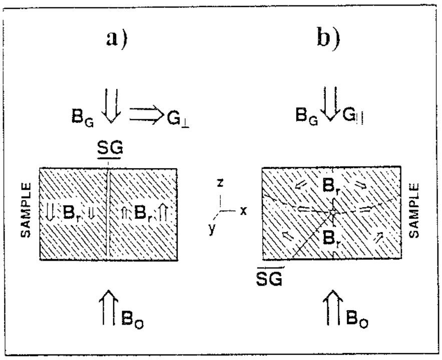

Fig. 1. The schema of magnetic field profiling with: transverse (a) and longitudinal (b) magnetic field gradient, $\boldsymbol{G}$.

magnetic flux density $\boldsymbol{B_r}$, increasing with the distance from the point where $\boldsymbol{B_r} = 0$ [the right-hand side (ii) and left-hand side (iii) parts of the sample in Fig. 1].

(β) For $/\boldsymbol{B_o}/ < \boldsymbol{B}_{Gmin}$ or $/\boldsymbol{B_o}/ > \boldsymbol{B}_{Gmax}$ only the area (ii) or (iii), respectively, will occur in the sample.

In all the above distinguished sample areas there exists a homogeneous and equal magnetic field gradient, $\boldsymbol{G}$.

MODEL OF THE ELECTROMAGNET

In order to verify the above assumptions, a model of a resistance electromagnet was constructed with a ferromagnetic core, a pole piece diameter of 40 mm and a slit adjusted from 10 to 20 mm. Figure 2 shows a schematic cross-section of the pole pieces of the model. Such an electromagnet enables a longitudinal magnetic field gradient to be generated. The windings were coiled with a copper wire. Physical parameters of the model electromagnet were thoroughly verified. The usefulness of such an electromagnet in the SSMRS and MGRS methods was also analysed [37]. The relevant results concerned the possibilities of obtaining a space with a zero magnetic flux density and a strong

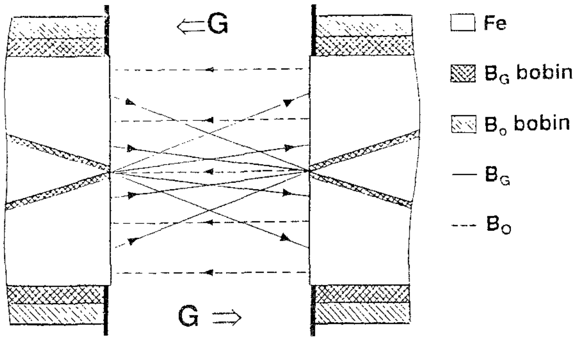

Fig. 2. Cross-section of the pole pieces of the model electromagnet and magnetic field distribution for two orientations of gradient $\boldsymbol{G}$ with preserved direction of magnetic flux density $\boldsymbol{B_G}$.

magnetic field gradient. Figure 3 shows the longitudinal magnetic field distribution obtained in the case when condition (1) is satisfied. The significant values of magnetic field gradient were obtained. The maximum value of $\boldsymbol{G}$ obtained in the centre of the space between the pole pieces amounts to 3.6 T/cm which, when referring to the GNT values given in table 1 [see ref. 12], shows that it exceeds the values indispensable for the accomplishment of the SSMRS method. The calculations carried out indicate also that with the use of such an electromagnet it is possible to commence preliminary investigations on the MGRS method.

Although the model of the electromagnet discussed does not ensure full homogeneity of the magnetic field gradient, it satisfies the main assumptions of the design.

DISCUSSION

Let us consider the MR processes in the areas distinguished by such a magnetic field. The concept is easily understood in the classical terms.

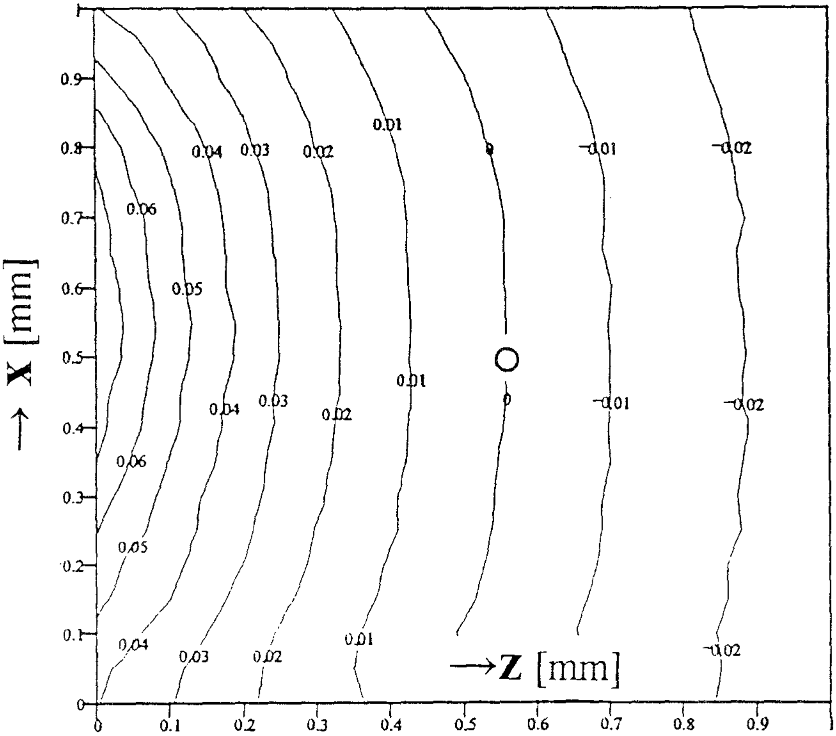

Fig. 3. Magnetic field distribution with the satisfied condition $B_{Gmax} > /B_o/ > B_{gmin}$. The longitudinal magnetic field component, (B_{rz} | z), was measured. The area with a zero field, $B_r = 0$, and a non-zero gradient, $G \neq 0$, is marked with a dot.

1. The pure SG effects. In area (i) a space with a zero magnetic flux density $B_r = 0$, and a nonzero gradient G was obtained. This creates possibilities to study the effects caused by the SG interaction effects and devoid of the features of the Zeeman effect [37,38]. Thus, in this space, the paramagnetic elements of the sample interact only with the magnetic field gradient, G. This area can be displaced in space by changing the value and/or the direction of the magnetic flux density vector, B_o or B_G. Hence, as in the MR Imaging methods, the spatial sweeping, i.e. the creation of the images of the SG effect in the stretched sample of the condensed matter is possible.

II. The SG effect with suppressed Zeeman effect. In areas (ii) and (iii) the paramagnetic elements are affected by the magnetic field gradient ***G*** identical in value and direction to those in the area (i) and, additionally, by the resultant magnetic field flux $\boldsymbol{B_r}$. They differ in the opposite direction of the magnetic flux density $\boldsymbol{B_r}$, i.e. that of the Zeeman interaction, which results in the opposite direction of the Larmor precession. The values of these frequencies increase linearly with the distance from the symmetry surface, i.e. from the center of area (i). Hence, by superimposing the signals originating from the mirror fragments of areas (ii) and (iii), one can suppress the effects inherent in the Zeeman interaction which, as a result, makes possible the observation of the pure response from the SG interactions [38].

III. The combination SG and Zeeman effects. If the paramagnetic elements undergo the spatial displacement under the influence of the SG forces, the employment of the method of magnetic field forming enables the SSMRS [9-13] to be accomplished by observing the effects of the exchange of the paramagnetic elements between the distinguished areas [37], or the satisfaction of one of the conditions (β), i.e. according to the previous proposition [9,12,13].

Of particular importance seems the exchange of the paramagnetic elements in the space close to the area (i). For example, for I = 1/2 and the magnetic field gradient parallel to the direction of the magnetic field, $\boldsymbol{B_o}$, the spins occupying the excited state will be introduced in the area (i) with a simultaneous elimination of the spins in the ground state. Thus this area undergoes polarization, the degree of which depends on the experimental conditions and the properties of the sample [37,38].

The accomplishment of the methods named above seems promising for many aspects of the development of the MR technique, as well as for fundamental research and technical applications. We shall name several potential advantages of these methods:

(a) The SG spectroscopy in condensed matter can afford interesting research possibilities (e.g. in the field of inter-molecular interactions and molecular dynamics in condensed matter) and technical solutions. For example, the proposed realization with point detection creates new chances for the microscopy of paramagnetic elements [4].

(b) The MR response obtained from pure quantum states [11,12,37,38], apart from other advantages, leads to the increase by many orders of magnitude of the MR methods' sensitivity. It will also open up perspectives for such methods as quantum computation [39-41] or MR microscopy [2-8,42]. It has become possible to realize in practice the solution sought for in many earlier papers [39-41] for the problem of quantum computation in the case of volumetric spin ensembles, that would be devoid of shortcomings occurring in the existing realizations of quantum computers [39,41]. This disadvantage is related with the necessity of refined separation of chosen states from the state mixture characteristic of spin distribution in thermodynamical equilibrium.

(c) The accomplishment of MR in a constant magnetic field gradient (MGRS) should result in new and possibly simpler technical solutions of MR and MRI. The generation of the pulse magnetic field gradients used so far is difficult due to the resistance of the materials used to carcass, linearity and magnitude of the gradient etc. These gradients also evoke many undesirable side effects, among other things,by the generation of Foucault currents, thus considerably limiting the range of application of these methods.

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