[8] L. Page, M. N. Roy. Astron. Soc. 99, 385 (1939).
[9] A. Unzol'd, *Physics of Stellar Atmospheres*, IIL, 1948.
[10] Ia. B. Zel'dovich and O. I. Leipunskii, J. Exptl. Theoret. Phys. (U.S.S.R.) 13, 183 (1943).
[11] Ia. B. Zel'dovich, J. Exptl. Theoret. Phys. (U.S.S.R.) 32, 1028 (1957). [sic!]
[12] G. Glaser, ZS. Naturforsch. 6a, 706 (1951).
[13] Vul'fson, Libin and Charnaia, Izv. Akad. Nauk SSSR, Ser. Fiz. 19, 61 (1955).

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Paramagnetic Absorption at High Frequencies in Gadolinium Salts in Parallel Fields

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Measurements were carried out at room temperature on the dependence of paramagnetic absorption on the intensity of a stationary field parallel to a high frequency ($\nu = 9.377 \times 10^9$ cps) field. The experimental absorption curves are in good agreement with Shaposhnikov's spin absorption theory[1]. This made it possible to determine the internal field constant and the isothermal spin relaxation time for several gadolinium salts, and to determine in absolute units the absorption coefficient of $Gd_2(SO_4)_3 \cdot 8H_2O$ as a function of the intensity of the stationary field.

PARAMAGNETIC ABSORPTION has been experimentally studied in a number of salts by Gorter and his coworkers[2], Garif'ianov[3], and Sitnikov[4], over the frequency range of 10^6-10^8 cps with the high frequency field parallel to the stationary field. Garif'ianov and Sitnikov made their measurements at room temperature at frequencies of the order of 6×10^8 cps (using electronic circuitry) and with fields from 0 to 6000 oersteds. Their experiments indicated that the experimentally determined absorption as a function of the strength of the stationary field, with fixed frequency of the variable field, is in good agreement with the values obtained from Shaposhnikov's theoretical formula[1] for spin absorption if the isothermal spin relaxation time τ_s, entering into this formula, is considered to be independent of the strength of the stationary field. This made it possible for the authors of Refs. 3 and 4 to use Shaposhnikov's formula for the experimental determination of the internal field constant b/C (b is the magnetic heat capacity constant and C is the Curie constant).

The above-mentioned experiments (Refs. 2-4) were conducted at frequencies considerably lower than the reciprocal of the isothermal spin relaxation time (τ_s^{-1}). For a more complete study of spin absorption at room temperature, the author[5] performed similar experiments at frequencies for which $\tau_s \nu \geqslant 1$. This was accomplished by using centimeter wave techniques. High-frequency power from the generator was sent through a coaxial waveguide into a cylindrical resonator in which an H_{011} wave was excited. From the resonator the power went to an indicator with a germanium detector and a mirror galvanometer. It is well known that the magnetic field of an H_{011} wave is axially symmetrical, and that near the center of the resonator the lines of force are directed along the axis of the cylinder in the form of a cable. The field near the center of the resonator is therefore quite uniform. Our experimental setup differs from others known to us in that we are able to perform absorption measurements in arbitrary units for any angle between the stationary and the high-frequency fields, made possible by a rotating flange in the coaxial guide joining the resonator and the generator. A more detailed description is given in Ref. 5. The powdery paramagnetic substance was thoroughly dried and then

hermetically sealed in a polystyrene flask. The flask was fastened to the bottom of the resonator by a polystyrene rod in such a way that the paramagnetic substance was near the center of the resonator.

It was shown by Cummerow *et al.*[7] that it is possible to determine experimentally the dependence on H of a quantity d, proportional to the imaginary part of the magnetic susceptibility χ''

$$d(H) \equiv a\chi''(H) = \sqrt{\alpha_e/\alpha_m} - 1, \qquad (1)$$

where α_e and α_m are the respective galvanometer readings in the absence and in the presence of magnetic absorption in the sample, and a is a constant which depends on the construction and tuning of the apparatus.

It was established earlier by the author[5] that at frequencies for which $\tau_s\nu \gg 1$, paramagnetic absorption decreases monotonically as the strength of the stationary field is increased, and the form of the experimental curve is described well by Shaposhnikov's theoretical formula[1],

$$\chi''/\chi_0 = (1 - F)^2\tau_s\nu/[1 + (1 - F)^2\tau_s^2\nu^2], \qquad (2)$$

where $F = H^2/(H^2 + b/C)$ and χ_0 is the static magnetic susceptibility of the sample if it is assumed that τ_s is independent of H. Eq. 2 makes it possible to determine the quantities b/C, τ_s and the constant a experimentally, *i.e.*, allows us to determine the relation $\chi'' = \chi''(H)$ in absolute units. This is accomplished by taking any three values of the quantity $d(H)$ at three values of the field, and using Eq. 2 to solve the system of three equations in the unknowns b/C, τ_s and a (assuming that τ_s is independent of H). If, for example, we take the value $d_1(H_1) = d_1$ at $H_1 = 0$, $d_2(H_2) = d_1/2$ (H_2 is the half-width of the curve) and $d_3(H_3) = d_1/3$, we obtain (see Ref. 5):

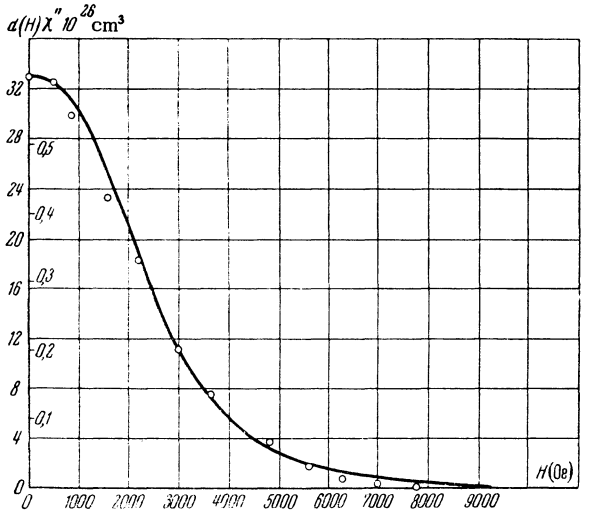
$$b/C = {}^1/_2\,(H_3^4 - 2H_2^4)/(2H_2^2 - H_3^2). \qquad (3)$$

$$\tau_s = \sqrt{H_2^4 + 2\,(b/C)\,H_2^2 - (b/C)^2}\,/(b/C)\nu, \qquad (4)$$

$$a = (1 + \tau_s^2\nu^2)\,d_1/\chi_0\tau_s, \qquad (5)$$

so that

$$\chi''(H) = \chi_0\tau_s\nu d(H)/(1 + \tau_s^2\nu^2)\,d_1. \qquad (6)$$



$Cd_2(SO_4)_3\,8H_2O$: O—experimental points for $T = 291°K$ and $\nu = 9.15 \times 10^9$ cps. Solid line—theoretical curve from Eq. 2, for $b/C = 3.4 \times 10^6$ (oer.)^2 and $\tau_s = 0.25 \times 10^9$ sec.

It must be borne in mind that for a sufficiently accurate determination of the values of b/C and τ_s we require very accurate knowledge of the values of H_2 and H_3 (differences of high powers of H occur in Eq. 3). With the usual calibration of the field to within 20-25 oersteds at field strengths in the range of 1000-2000 oersteds (as in our experiments), the values of b/C and τ_s obtained from Eqs. 3 and 4 have a comparatively large error (of the order of 30-40%).

In the present work, the absorption in parallel fields was determined experimentally in arbitrary units for hydrated halide salts of gadolinium at room temperature at the frequency $\nu = 9.377 \times 10^9$ cps. All of the absorption curves for these salts are similar in form to the curve for gadolinium sulphate shown in the figure for the frequency $\nu = 9.15 \times 10^9$ cps (this curve was obtained by us earlier[5]), the only differences being the magnitude of the initial absorption (at $H = 0$) and the width of the curves. The constants b/C and τ_s for these salts were determined by the method described above, and are given in the table. Our values of b/C and τ_s for $Gd_2(SO_4)_3 \cdot 8H_2O$ agree with those of other authors within the limits of experimental error (see Ref. 2). We found no data on b/C and τ_s for the other salts in the literature.

Using Eq. 6, we transformed our experimental curves to absolute units. The specific static susceptibility of $Gd_2(SO_4)_3 \cdot 8H_2O$ at room temperature is $\chi_0 = 73.4 \times 10^{-6}$.[6] Values of b/C and τ_s (see table) were found from the experimental curve using Eqs. 3 and 4. Substituting the values of b/C, τ_s, and χ_0 into Eq. 6, and dividing the left and

Substance	Frequency $\nu = 10^{-9}$	$b/C \times 10^{6}$ (Oer.)$^{-2}$	$\tau_s \times 10^{9}$ sec
$Gd_2(SO_4)_3 \cdot 8H_2O$	9.15	3.4	0.25
GdF_3	9.377	6.0	0.16
$GdCl_3 \cdot 6H_2O$	9.377	3.1	0.13
$GdBr_3 \cdot 6H_2O$	9.377	5.2	0.17
$GdI_3 \cdot 6H_2O$	9.377	1.0	0.9

right hand sides by the number of ions per cubic centimeter, we obtain per ion:

$$\chi''(H) = 0{,}6 \cdot 10^{-26} \frac{d(H)}{d_1} \text{ cm}^3;$$

where $H = 0$, $d(0) = d_1$ и $\chi''(0) = 0{,}6 \cdot 10^{-26}$ cm^3. (7)

Values of $\chi''(H)$ in absolute units, calculated from Eq. 7, are plotted along the right side of the ordinate in the figure. Having determined the experimental setup constant a by experiments in parallel fields using the method described above, we may then use this constant for the construction of absorption curves in absolute units for any angle between the high frequency and the stationary fields.

We also performed measurements of paramagnetic absorption at room temperature with perpendicular fields (paramagnetic resonance), using the substances indicated in the table. With stationary fields up to 8000 oersteds, all of these substances exhibited a single resonance absorption peak with a g-factor in the neighborhood of 2. A particularly strong paramagnetic resonance effect was observed in $GdI_3 \cdot 6H_2O$.

In conclusion, the author expresses thanks to I. G. Shaposhnikov for suggesting the subject and maintaining interest in the work.

[1] I. G. Shaposhnikov, J. Exptl. Theoret. Phys.(U.S.S.R.) **18**, 533 (1948).
[2] K. Gorter, "Paramagnetic Relaxation", IIL, 1949.
[3] N. S. Garif'ianov, J. Exptl. Theoret. Phys.(U.S.S.R.) **25**, 359 (1953).
[4] K. P. Sitnikov, Dissertation, Kazan University, 1954.
[5] A. I. Kurushin, Izv. Akad. Nauk SSSR, Ser. Fiz. **20**, 1232 (1956).
[6] Ia. G. Dorfman and S. E. Frish, "Collection of Physical Constants," ONTI, 1937.
[7] Cummerow, Halliday and Moor, Phys. Rev. **72**, 1233 (1947).

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A Source of Polarized Nuclei for Accelerators

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A possible method of obtaining beams of polarized nuclei by making use of the Lamb shift of the metastable level is described.

THE SPIN DEPENDENCE of nuclear forces over a broad range of energies has in the recent past been studied intensively in experiments on the scattering of nucleons by nuclei. It is well known that such experiments require double scattering of the nucleons because contemporary accelerators produce unpolarized beams.

It can be shown by a relatively easy calculation that all types of accelerators (electrostatic accelerators, linear accelerators, cyclotrons, proton synchrotrons and cosmotrons) are able to accelerate polarized particle beams without depolarizing them. An accelerator which can produce polarized particles whose spins form any given angle with the beam direction would enable us to perform many polarization experiments without double scattering.

Certain proposed sources of polarized protons for accelerators[1] make use of atomic hydrogen beams that traverse a strongly inhomogeneous magnetic field after which the polarized atoms are ionized outside of the magnetic field by collisions with electrons. The calculated intensities of such sources do not exceed 1 μa of proton current. Since in the majority of accelerators large particle losses