SOVIET PHYSICS JETP VOLUME 34(7), NUMBER 1 JULY, 1958

TEMPERATURE DEPENDENCE OF PARAMAGNETIC RESONANCE ABSORPTION AT CENTIMETER WAVELENGTHS

S. G. SALIKHOV

Physico-Technical Institute, Kazan' Branch, Academy of Sciences, U.S.S.R.

Submitted to JETP editor July 12, 1957

J. Exptl. Theoret. Phys. (U.S.S.R.) **34**, 39-44 (January, 1958)

Paramagnetic resonance absorption at centimeter wavelengths has been investigated in the temperature region 90 — 500°K in $CrCl_3$, MnF_2, MnO, CuF_2 and $Cr(OH)_3$. It was found that in $CrCl_3$ and CuF_2 the line width is temperature independent while the intensity varies in accordance with the Curie-Weiss law. In MnF_2 and MnO the temperature dependence is more complicated, indicating the existence, in these compounds, of residual antiferromagnetism at temperatures above the Curie point.

THE absorption measurements reported here were carried out in the temperature range 90 — 750°K using the standing-wave method. The details of the method are described in Ref. 1.

The measurements were carried out with a special system, a block diagram of which is shown in Fig. 1. The rf source was a klystron with a stabilized power supply. The klystron power was monitored with a thermistor bridge. The measuring cavity was a shorted rectangular waveguide excited in the TE_{011} mode; a sample of the material investigated was placed at an antinode of the magnetic field.[2] The effect of χ' on the resonance absorption curve was small. To avoid this effect the method described in Ref. 1 was employed. In the measurements of paramagnetic absorption at low temperatures, use was made of a supplementary wave guide system made from a thermally insulating material with an inner conducting surface; this was placed in a Dewar flask with liquid nitrogen or oxygen. The measurements at high temperatures were carried out with a measuring waveguide enclosed in an electric heater, with which the sample could be heated to 500°C. The temperature was measured with a platinum-rhodium thermocouple, the junction of which was attached to the end wall of the waveguide. The measurement waveguides were connected by choke joints between which there were insulators made from thin mica sheets (0.04 mm thick) at a distance of 420 mm from the end of the waveguide. The space between the measuring line and the cavity was covered by a metal jacket which was cooled by circulating water.

Curves showing the quantity χ''_{max} as a function of H_0 were plotted in the temperature range between 90° and 500°K for the following salts: $CrCl_3$, MnF_2, MnO, CuF_2, $Cr(OH)_3$. The measurements were carried out at a frequency ν = 9378 Mcs.

In Fig. 2 are shown the results of an investigation of paramagnetic absorption at different temperatures in $CrCl_3$. In the same figure is shown the absorption strength at maximum χ''_{max} in

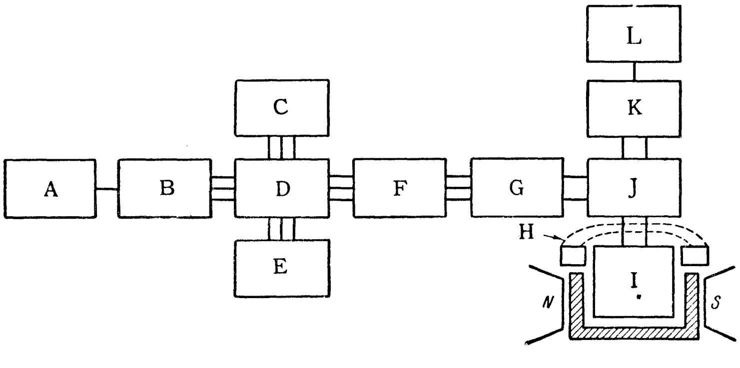

FIG. 1. Block diagram of the klystron oscillator. A) ferromagnetic resonance stabilizer; B) electronic stabilizer; C) power monitor; D) oscillator; E) resonance wave meter; F) variable attentuator; G) choke joint; H) cooling system; I) absorption cell; J) heater; K) detector; L) recorder.

$CrCl_3$ as a function of temperature. These results indicate that at all temperatures the line width of the curve remains constant ($\Delta H \sim 170$ oersted), at a value corresponding to a transverse relaxation time $\tau_2 = h/2\pi g\beta\Delta H = 3.2 \times 10^{-10}$ sec. The line width for $CrCl_3$ is in agreement with the results of earlier measurements.[3,4]

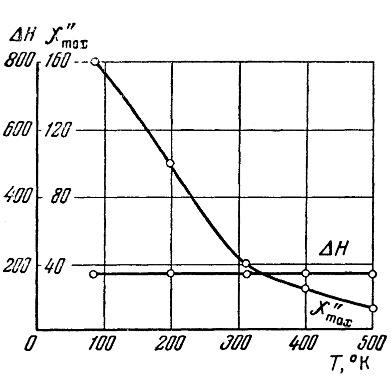

FIG. 2. ΔH and χ''_{max} as functions of temperature in $CrCl_3$; λ = 3.21 cm.

Kozyrev and the author,[5] on the basis of an investigation of paramagnetic resonance absorption in a number of salts of copper, chromium, and manganese at several frequencies, have established the fact that

$$\frac{\chi''_{max}\Delta H}{\chi_0} = \text{const}, \qquad (1)$$

where χ_0 is the static magnetic susceptibility. The experiments described here indicate that Eq. (1) also applies when the temperature is varied:

$$\frac{\chi''_{max}(T)\,\Delta H(T)}{\chi_0(T)} \approx \text{const} = W. \qquad (2)$$

In $CrCl_3$ this relation is valid over a wide temperature region, as is apparent from Table I.

It is also apparent from the table that the computed value of W remains constant over the entire temperature region which was investigated.

In Fig. 3 are shown the results of measurements of resonance absorption in MnF_2. The antiferromagnetic Curie point in this compound is $\Theta_{anti} = 72°K$. It is evident that the line width ΔH in MnF_2 is reduced by approximately a factor of 2 as the temperature is increased from 90° to 350°K. Table II lists the results of a calculation of W based on Eq. (2).

The temperature dependence of the magnetic susceptibility χ_0 is taken from Refs. 8 and 9.

It is apparent from Table II that in MnF_2 Eq. (2) applies only for temperatures between 300° and 350°K; below 300°K the quantity in question falls off monotonically with diminishing temperature. This effect is undoubtedly due to the effect that the antiferromagnetic properties of MnF_2 have on W above the Curie temperature. As a matter of fact, neutron diffraction experiments in MnF_2 indicate that even at room temperature the scattering of this material is not completely paramagnetic.[7]

A similar pattern for W is found in other antiferromagnetic materials at temperatures above the Curie point. Thus, for example, we have the case of manganese oxide MnO (Fig. 4). In this material the antiferromagnetic transition point (Curie point) $\Theta_{anti} = 116°K$. The results of a calculation of W in MnO_2 using Eq. (2) are shown in Table III. It is apparent from the table that the residual antiferromagnetism continues to have an effect on

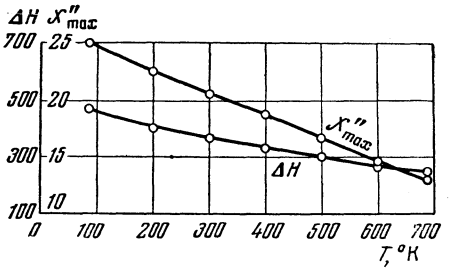

FIG. 3

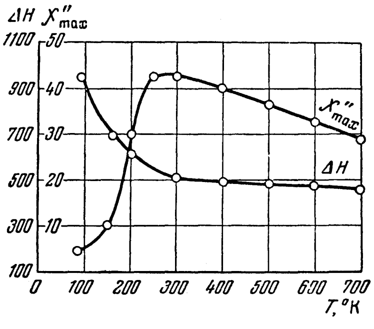

FIG. 4

FIG. 3. ΔH and χ''_{max} as functions of temperature in MnF_2.

FIG. 4. ΔH and χ''_{max} as functions of temperature in MnO.

TABLE I

T, °K	90	200	310	400	500
$\chi_0 \cdot 10^6$	1.72	100	52	34	20
χ''_{max}, arbitrary units	122	75	40	25	15
ΔH, gauss	170	170	170	170	170
W, arbitrary units	124	128	128	124	128

TABLE II

T°, K	90	200	300	350
$\chi_0 \cdot 10^6$	20.0	12.8	9.60	8.7
χ''_{max}, arbitrary units	25.0	23.0	21.0	19.5
Δ H, gauss	465	400	360	342
W, arbitrary units	58.0	72.0	78.0	77.0

TABLE III

$T°$, K	90	200	260	294	400	500	600	700
$\chi_0 \cdot 10^6$	90	81	79	78	65	58	52	45
χ''_{max}, arbitrary units	5	30	37	43	40	36	33	29
ΔH, G	950	616	560	500	495	490	480	470
W, arbitrary units	535	228	265	304	304	304	304	304

W at room temperature. Starting at room temperature, however, and up to 700°K, MnO_2 apparently exhibits paramagnetic properties. Approximately the same behavior was observed in MnS.

Thus, the present experiment on MnF_2, MnO and MnS, as well as neutron diffraction experiments in MnF_2,[9] indicate the presence of residual antiferromagnetism at temperatures above the Curie point.[10]

In order to compute the effect of the antiferromagnetic properties of MnF_2 on the spin-lattice relaxation time close to the Curie point, special experiments were performed to examine paramagnetic fields at T = 77°K. A spin-lattice absorption depending on the external magnetic field was not found in the frequency region 15 — 600 Mcs. It is possible that the spin-lattice relaxation time in MnF_2 is of the same order of magnitude as the spin-spin relaxation time τ_s.

In addition to the three indicated Mn^{++} compounds, we studied $Cr(OH)_3$ and CuF_2. In the first material the line width ΔH falls from a value of approximately 600 oersted at 90°K to approximately 400 oersted at 290°K and remains constant as the temperature is increased beyond this value. The strength of the maximum in the resonance absorption χ''_{max} increases as the temperature is increased, reaching its highest value at room temperature and then falling off slowly to one-third of its value at T = 523°K. Thus, the behavior of $Cr(OH)_3$ is similar to that of MnO. It was not possible to check the constancy of W in $Cr(OH)_3$ because of the lack of data on $\chi_0(T)$. However, the functions $\chi''_{max}(T)$ and $\Delta H(T)$ in $Cr(OH)_3$ would seem to indicate that residual antiferromagnetism in this material can still be found at room temperature.

The results of the measurements in CuF_2 are shown in Figs. 5 and 6. This material is antiferromagnetic at temperatures below 78°K. However,

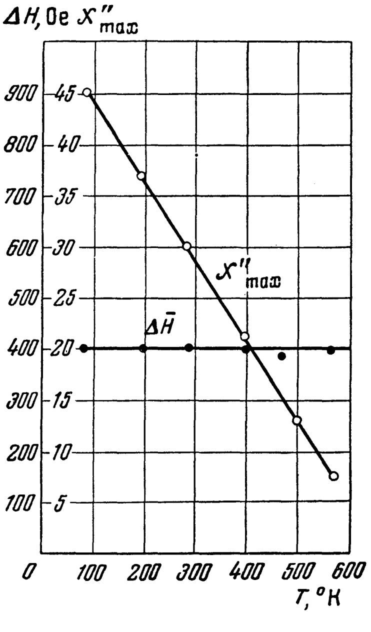

FIG. 5. ΔH and χ''_{max} as functions of temperature in CuF_2.

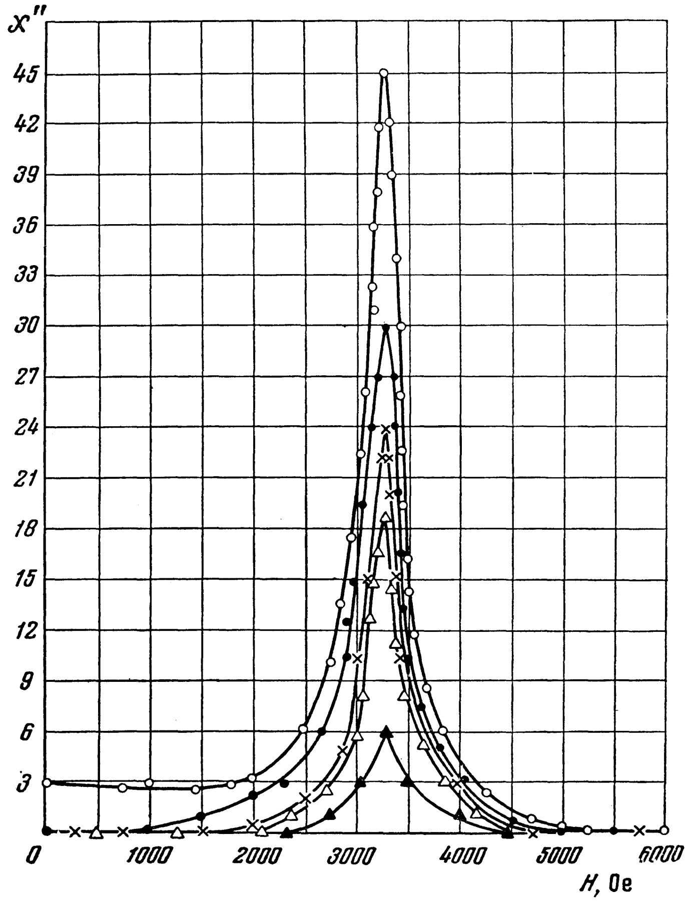

FIG. 6. Resonance absorption curves in CuF_2 at various temperatures: ○ – T = 90°K; ● – T = 290°K; × – T = 403°K; △ – T = 473°K; ▲ – T = 573°K.

no anomalous behavior above the Curie point, similar to that observed in the other antiferromagnetic materials, was found in this case. The line width for CuF_2 was constant in the temperature region investigated and equal to 400 oersted. The strength of the resonance absorption at the maximum was reduced by a factor of one and one-half as the temperature was increased. Eq. (2) is in good agreement with the results found in CuF_2 over the entire temperature region from 90° to 294°K. Thus the behavior of CuF_2 above the Curie point is that of a typical paramagetic material.

In conclusion we may note that the effective g-values for all materials investigated were close to 2 and temperature independent within the limits of the experimental accuracy. The experimental resonance absorption curves are a better fit to a Lorentzian line-shape than a Gaussian shape.[11]

This work was carried out under the guidance of B. M. Kozyrev.

---

[1] N. S. Garif'uanov, Dissertation, Kazan' State University, 1953.

[2] S. G. Salikhov, Izv. Akad. Nauk SSSR, Ser. Fiz. **18**, 456 (1954).

[3] Kozyrev, Salikhov, and Shamonin, J. Exptl. Theoret. Phys. (U.S.S.R.) **27**, 56 (1952).

[4] Al'tshuler, Zavoiskii and Kozyrev, J. Exptl. Theoret. Phys. (U.S.S.R.) **7**, 56, (1952).

[5] B. M. Kozyrev and S. G. Salikhov, J. Exptl. Theoret. Phys. (U.S.S.R.) **19**, 185 (1949).

[6] L. R. Maxwell and T. R. McGuire, Revs. Mod. Phys. **25**, 279 (1953).

[7] Antiferromagnetism, Collection edited by S. V. Vonsovskii, IIL, Moscow (1956). (Russian Translations)

[8] H. Bizette and B. Tsai, Compt. rend. **209**, 205 (1939).

[9] Corliss, Delabarre, and Elliott, J. Chem. Phys. **18**, 1256 (1950).

[10] S. V. Vonsovskii and Iu. M. Seidov, Izv. Akad. Nauk SSSR, Ser. Fiz. **18**, 319 (1954).

[11] J. H. Van Vleck, Phys. Rev. **73**, 1249 (1948).

Translated by H. Lashinsky
7

SOVIET PHYSICS JETP VOLUME 34(7), NUMBER 1 JULY, 1958

CLOUD CHAMBER INVESTIGATION OF THE NUCLEAR-ACTIVE COMPONENT OF AIR SHOWERS

I. A. IVANOVSKAIA, L. I. SARYCHEVA, and P. S. CHIKIN

Moscow State University

P. N. Lebedev Physics Institute, Academy of Sciences, U.S.S.R.

Submitted to JETP editor July 25, 1957

J. Exptl. Theoret. Phys. (U.S.S.R.) **33**, 45-52 (January, 1958)

Nuclear processes induced by particles of extensive air showers were studied by means of a cloud chamber containing seven lead plates. The lateral distribution of nuclear-active particles in extensive showers as well as the nature and the energy spectrum of the particles were found.

THE nuclear-active component of extensive air showers was studied by means of the previously described experimental arrangement[1] consisting of a cloud chamber[2] and a counter telescope. Seven lead plates, 0.5, 1.5, 2, 2, 2.5, 2, and 2.5 cm in thickness (top to bottom respectively) were placed in the cloud chamber 60 × 60 × 30 cm. The effective chamber area for detection of nuclear-active particles, accounting for their angular distribution, was equal to 0.15 m^2. A shower-detecting counter system was used to trigger the hodoscope and the cloud chamber. The hodoscope made it possible to determine the distance of the shower axis from the cloud chamber and the total number of particles in the shower.

A particle was considered nuclear-active if it produced a shower in a lead plate, satisfying at least one of the following requirements: