Filippov for their help in preparing the apparatus and carrying out the experiments, and also N. E. Yukovich, V. A. Drozdov and V. D. Sheffer for furnishing the liquid helium.

*The axis of polarization of the nuclei, in our opinion, lay in the plane of the sample because of the considerable difference between longitudinal and transverse demagnetizing factors of the thin plate.

†This mechanism was also considered in Marshall's work,[9] but his calculations did not lead to the correct sign for the resulting field.

[1] Samoĭlov, Sklyarevsky, and Stepanov, Proc. of the VIIth Int. Conf. on Low Temp. Phys., Univ. of Toronto, Canada, 1960, Univ. of Toronto Press, 1961, pp. 171-173.

[2] Hanna, Heberle, Perlow, Preston, and Vincent, Phys. Rev. Lett. **4**, 513 (1960).

[3] Dash, Taylor, Craig, Nagle, Cochron, and Keller, Phys. Rev. Lett. **5**, 152 (1960).

[4] N. E. Alekseevskii and I. F. Shchegolev, Получение ориентированных ядер и их исследование, (The Obtaining of Oriented Nuclei and Their Investigation), Report, Inst. Phys. Prob., U.S.S.R. Acad. Sci., 1954. G. R. Khutsishvili, JETP **29**, 984 (1955), Soviet Phys. JETP **2**, 744 (1956). Grace, Johnson, Kurti, Scurlock, and Taylor, Comm. Conf. de Physique des basses Températures, 263, Paris, 1955.

[5] Samoĭlov, Sklyarevskii, and Stepanov, JETP **38**, 359 (1960), Soviet Phys. JETP **11**, 261 (1960).

[6] Samoĭlov, Sklyarevskii, and Stepanov, JETP **36**, 1366 (1959), Soviet Phys. JETP **9**, 972 (1959).

[7] D. A. Goodings and V. Heine, Phys. Rev. Lett. **5**, 370 (1960).

[8] A. J. Freeman and R. E. Watson, Phys. Rev. Lett. **5**, 498 (1960).

[9] W. Marshall, Phys. Rev. **110**, 1280 (1958).

Translated by Mrs. J. D. Ullman
315

## *TEMPERATURE DEPENDENCE OF HYPERFINE SPLITTING OF* $Dy^{161}$ *LEVELS IN PARAMAGNETIC DYSPROSIUM OXIDE*

V. V. SKLYAREVSKII, B. N. SAMOĬLOV, and E. P. STEPANOV

Submitted to JETP editor April 3, 1961

J. Exptl. Theoret. Phys. (U.S.S.R.) **40**, 1874-1876 (June, 1961)

We have investigated spectra of the resonant absorption of $Dy^{161}$ gamma rays of energies 26 and 75 kev. The source used was $Gd_2^{160}O_3$ (97% $Gd^{160}$) in which $Gd^{161}$ is formed by irradiation in a reactor and then goes over ($\tau_{1/2}$ = 3.7 min) to $Tb^{161}$ ($\tau_{1/2}$ = 7.15 days). The $Dy^{161}$ gamma rays are emitted upon beta decay of the $Tb^{161}$. The compound $Dy_2^{161}O_3$ (90% $Dy^{161}$) was used as the absorber.

The dependence of the intensity of the gamma rays passing through the absorber on the rate of motion of the absorber toward the stationary source was measured. The absorber was set in motion by a mechanical system that converts (by means of a suitably shaped cam) rotary motion into reciprocating motion with constant speed. Different rates were obtained by changing the rate of rotation of the cam. The gamma rays were registered by a scintillation spectrometer using a crystal of NaI(Tl).

For the 26-kev gamma rays it turned out that the magnitude of the resonance absorption depended weakly on the temperature. This allowed the measurement of spectra at a series of temperatures: 80, 300, 400, 510, 640, and 840°K. In all cases the $Dy_2^{161}O_3$ absorber had a thickness of 15 mg/cm$^2$. Thicker absorbers gave a larger effect, but poorer resolution.

Figure 1 shows three of the spectral measurements. It can be seen that in all cases five almost equidistant peaks appear (besides the fundamental one at v = 0). Such a spectrum indicates that one of the levels of $Dy^{161}$ between which the 26-kev gamma transition occurs ($5/2^- \rightarrow 5/2^+$) is split into six magnetic sublevels, such that the magnitude of the splitting is approximately the same for emitting and absorbing nuclei, but the splitting of the other level is significantly less and apparently is responsible for the width of the peaks. These splittings are caused by the interaction of the nuclear magnetic moment of $Dy^{161}$ with the magnetic field produced at the nucleus by the electron shell.

The observed equal separation of the hfs (hyperfine splitting) levels is apparently associated

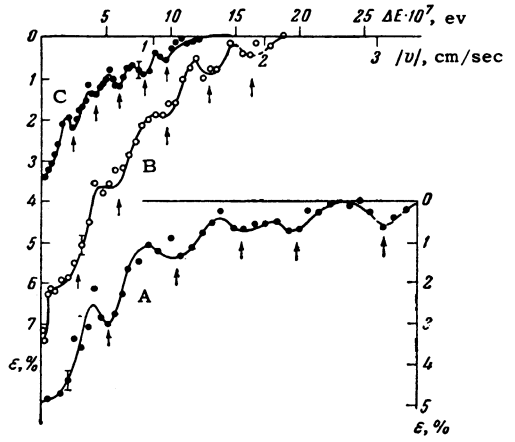



FIG. 1. Resonance absorption spectra of $Dy^{161}$ gamma rays with energy of 26 kev at different temperatures: A – 80°K, B – 300°K, C – 640°K (temperature of source and absorber the same). On the ordinate axis the quantity $\varepsilon = [N(|v|) - N(v = \infty)]/N(v = \infty)$ is plotted in percent; $N(|v|)$ is the count intensity of gamma rays passing through the absorber moving at the rate $|v|$. On the abscissa axis (the same for all three curves) $\Delta E = (|v|/c)E_\gamma$ is plotted, as well as $|v|$.

with the presence of a quadrupole interaction between the electron shells of the Dy atoms and the internal electric field, leading to a removal of the degeneracy in $J_z$. This interaction is caused by the characteristics of the $Gd_2O_3$ and $Dy_2O_3$ lattices: the atoms of Gd or Dy are located at the centers of slightly distorted cubes in all corners of which, except the two on the diagonal, lie O atoms. Besides the spectra of $\epsilon(|v|)$ at T = 300°K, a spectrum was measured with separate registration of $\epsilon(+v)$ and $\epsilon(-v)$. In this spectrum there also appeared five peaks on each side of the central one, but the center of symmetry was shifted relative to v = 0 by a small amount corresponding to $\Delta E \approx 4 \times 10^{-8}$ ev. This asymmetry is caused by the different disposition of the levels of the emitting and absorbing nuclei on account of the different crystalline lattices of the source and absorber.

From Figs. 1 and 2 it is seen that $\Delta E = \mu H_n/I$ (the hfs of $Dy^{161}$) and consequently $H_n$ (the magnetic field at the nucleus) depend significantly on the temperature.

This dependence of $H_n$ on temperature is determined by the temperature dependence of the relaxation time $\tau_{rel}$ of the spin of the electron shell that creates the field at the nucleus. It is known that in such strong paramagnetic substances as $Gd_2O_3$ and $Dy_2O_3$ the time $\tau_{rel}$ is very short and decreases with increasing T. For a sufficiently small $\tau_{rel}$, when $\tau_{rel} \ll \tau_{prec}$, where $\tau_{prec} = \hbar/\Delta E_0$ is the time of precession of the nuclear spin in the field of the electrons, the mean values

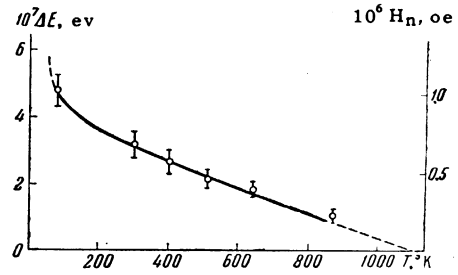



FIG. 2. The dependence of $\Delta E = \mu H_n/I$ and $H_n$ on T. The values of $\Delta E$ were found from the mean separation between the peaks of the curves in Fig. 1, and $H_n$ was determined from $\Delta E$, with the assumption that the observed $\Delta E$ belongs to the ground level of $Dy^{161}$, for which $\mu$ is known.

of $H_n$ and $\Delta E$ are equal to zero. For $\tau_{rel}$ sufficiently large $\Delta E = \Delta E_0$. In intermediate cases, which, evidently, correspond to the temperature region we have investigated, $\Delta E < \Delta E_0$ and decreases with increasing T.

Evidently, measurements of curves of $\Delta E(T)$ make it possible to obtain the dependence $\tau_{rel}(T)$. For this, our results need to be augmented by measurements in the low-temperature region. From the curve $\Delta E(T)$ obtained we estimate $\tau_{rel} \sim 10^{-10}$ sec.

In the spectrum of the resonance absorption of $Dy^{161}$ gamma rays of energy 75 kev (transition $3/2 \rightarrow 5/2$) the hfs $\Delta E^{75} \approx \mu H_n/I \approx 27 \times 10^{-7}$ ev is six times greater than $\Delta E^{25}(80°K) = 4.8 \times 10^{-7}$ ev. From this it follows that the observed $\Delta E^{75}$ is created by a splitting of the 75 kev levels. From a comparison of the values we have measured for $\Delta E^{75}(80°K)$ and $\Delta E^{25}(80°K)$ with the known quantity $\mu^0 = 0.37$ n.m.,[1] we find that the magnetic moment of the $Dy^{161}$ 75 kev levels is $\mu^{75} \approx 1.3$ n.m., which is in agreement with the shell model.[2]

The 26-kev gamma radiation of $Dy^{161}$ is one of those rare cases in which the study of resonant absorption is possible even at high temperatures of the order of 1000°K. As Yu. Kagan (private communication) has shown, one can expect such an unusually weak dependence of the resonance absorption on temperature for lattices in which the atoms differ greatly in mass. In this case, the usual Debye temperature no longer characterizes the phenomenon, and it should be replaced by a much higher "effective" Debye temperature.

The Mössbauer effect in $Dy^{161}$ has been investigated by Ofer et al.,[3] who obtained the spectrum for the 26-kev gamma rays at T = 300°K, also with $Gd_2O_3$ and $Dy_2O_3$ as source and absorber. Our spectrum at T = 300°K agrees with Ofer's results as far as the half-widths and magnitude of the effect is concerned. However, they did not notice the peaks we found, apparently on account

of using an absorber of unseparated $Dy_2O_3$.

The authors deeply thank E. K. Zavoĭskii, L. V. Groshev, D. P. Grechukhin, Yu. M. Kagan, S. T. Belyaev, and D. F. Zaretskii for numerous discussions, I. B. Filippov, K. P. Aleshin, G. P. Mel'nikov for taking part in the experiment, and V. S. Zolotarev for the gift of the separated isotopes.

[1] J. G. Park, Proc. Roy. Soc. (London) **A245**, 118 (1958).

[2] J. N. L. Gauvin, Nuclear Phys. **8**, 213 (1958).

[3] Ofer, Avivi, Bauminger, Marinov, and Cohen, Phys. Rev. **120**, 406 (1960).

Translated by L. M. Matarrese
316

## *PARAMAGNETIC RESONANCE IN METALLIC ALUMINUM*

A. A. GALKIN and V. P. NABEREZHNYKH

Physico-Technical Institute of Low Temperatures, Academy of Sciences, Ukrainian S.S.R.

Submitted to JETP editor April 12, 1961

J. Exptl. Theoret. Phys. (U.S.S.R.) **40**, 1876-1877 (June, 1961)

A number of experimental and theoretical papers[1-9] have been devoted to paramagnetic resonance in the conduction electrons of a metal. However, most of the investigations have been made on alkali metals where the electron resonance line is sufficiently narrow, due to the weak spin-orbit interaction. The difficulty of observing paramagnetic resonance in "classical" metals, in which the spin-orbit interaction is strong, is increased because impurities can lead to a sharp reduction in the spin relaxation time and thus to a broadening of the absorption curve.

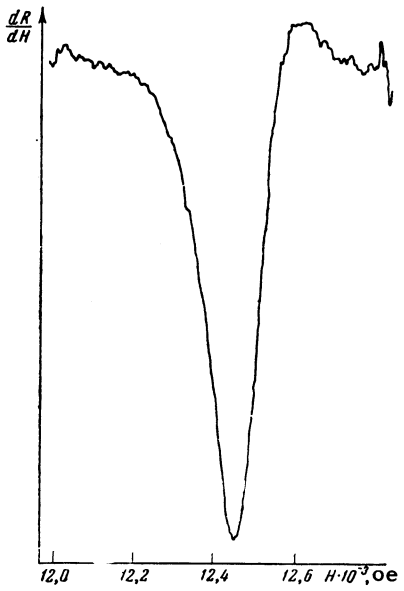
In this note we describe experiments on the observation of electron paramagnetic absorption in single crystal aluminum with a residual resistance of $6.7 \times 10^{-5}$,* corresponding to an electron mean free path $\sim 2 \times 10^{-2}$ cm.

The specimen, in the form of a 10 mm diameter disc of thickness $\sim 3$ mm, was electropolished and served as the base of a cylindrical resonance cavity in which $H_{011}$ mode oscillations were excited. The perfection of the surfaces was such that at T = 4.2° K several cyclotron resonance oscillations were fairly clearly observed.

The dependence of absorption on magnetic field was studied with a high sensitivity spectrometer, working at a frequency of $3.6 \times 10^{10}$ cps in the temperature range 300 — 4.2° K.

A broad symmetrical line was visible at temperatures of 300 and 77° K. The intensity of the line depended weakly on temperature, indicating the electronic character of the absorption. At hydrogen temperatures the absorption line has pronounced asymmetry which increases somewhat as the temperature is reduced to 4.2° K.

Figure 1 shows the dependence of the derivative of the surface impedance, dR/dH, on magnetic field H at T = 4.2° K. The results of the investigation refer to a specimen in which the fourfold axis was perpendicular to the surface of the specimen. The line width, determined at the half height of the derivative, does not change over the interval 20 — 4° K and equals 140 oe, corresponding to a spin relaxation time $\tau_{sp} \approx 5 \times 10^{-10}$ sec.




One can deduce from the fact that the line width is weakly dependent on temperature, while according to B. I. Aleksandrov's measurements an appreciable change in the dc resistance of aluminum is still observed, that the spin relaxation time is determined by impurities with strong spin-orbit coupling. This deduction is also confirmed by measurements on aluminum with a large impurity content, for which the value $\tau_{sp} \approx 5 \times 10^{-11}$ sec was found.

The absence of anisotropy in the line width and g-factor (equal to 2.06) can also be explained by