The Magnetic Moments of Cu^{63} and Cu^{65}

R. V. Pound
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts
January 12, 1948

THE magnetic moments of the two stable copper isotopes, Cu^{63} and Cu^{65}, have been determined by measurements of nuclear magnetic resonance absorption. Previously, Ritschl[1] had shown the spins of the two isotopes to be $\frac{3}{2}$ and had calculated their magnetic moments as 2.5 nuclear magnetons from measurements of the hyperfine structure of spectral lines. Schüler and Schmidt[2] confirmed these spin values and calculated 2.5 and 2.6 nuclear magnetons for the magnetic moments of Cu^{63} and Cu^{65}, respectively.

The lines were found with the recording radiofrequency spectrometer previously reported,[3] in the region of 3 Mc/sec., using a constant magnetic field of about 3000 gauss. The sample was cuprous chloride powder, compressed into a cylindrical pellet in a mold. In this way, a factor of two or three in signal strength can be gained over that obtained for the uncompressed powder. The copper lines were unusually intense for a crystalline sample and the ratio of the amplitudes of the two lines was about 2:1, as can be seen from the reproduction of a record from the spectrometer shown in Fig. 1. The lines recorded are derivatives of the absorption curves, which are similar to, but should not be confused with, dispersion curves. In agreement with Schüler and Schmidt, the larger magnetic moment is possessed by the less abundant isotope, Cu^{65}. The amplitude ratio is in good agreement with the known abundance ratio of 7:3.

The frequencies of the two lines were measured by making marks on the paper of the recording milliammeter at about 1-kc/sec. intervals as the spectrometer slowly passed through zero beat with a heterodyne-frequency meter. To minimize errors from drift of the magnetic field, measurements were made first at one line, then at the other, and finally at the first again. The frequency ratio was determined by an interpolation based on the assumption of a uniform rate of drift of the field. The total time taken for one set of three readings was about 30 minutes, and the total drift was never greater than about 1 part in 1000. Errors caused by short-period fluctuations in the field are unlikely because the magnet current is supplied from a bank of large storage cells. The procedure was repeated and the result of both measurements is

$$\nu_{Cu^{65}}/\nu_{Cu^{63}} = 1.0711 \pm 0.0002.$$

A compressed sample of sodium bromide was used to compare the frequency of the Na^{23} line with that of Cu^{63} by the same procedure. The result of these measurements is

$$\nu_{Cu^{63}}/\nu_{Na^{23}} = 1.0022 \pm 0.0002.$$

Taking the magnetic moment of Na^{23} to be 2.217 ± 0.002 nuclear magnetons and its spin as $\frac{3}{2}$,[4] and making a small correction for the diamagnetism of the electrons in the two ions,[5] the magnetic moments of the copper isotopes, in nuclear magnetons, are found to be

$$\mu_{Cu^{63}} = 2.2265 \pm 0.0025,$$

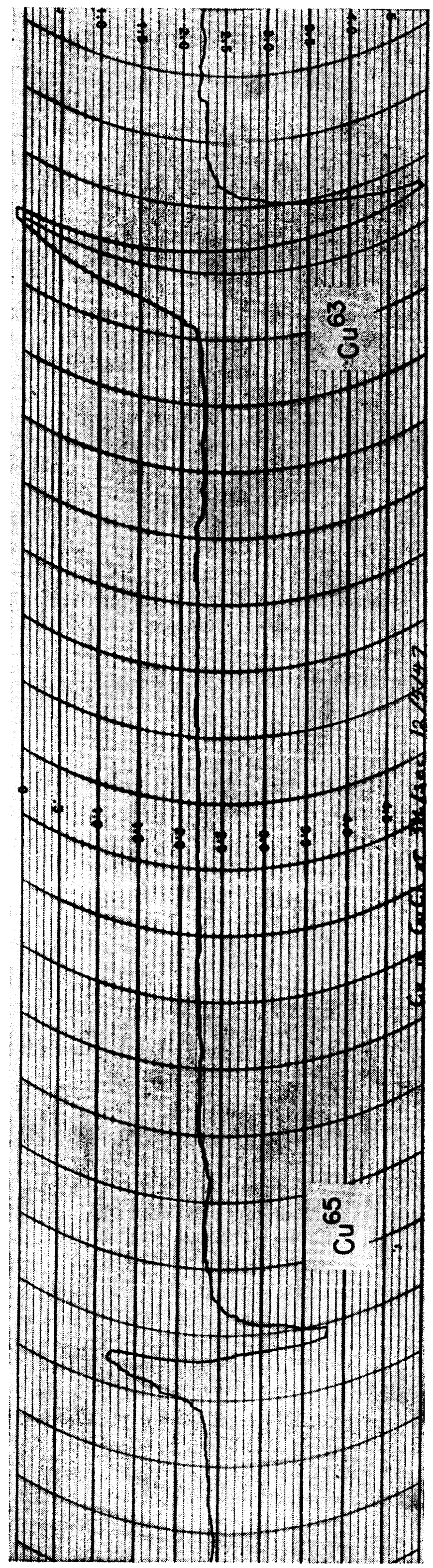

FIG. 1. Record from the r-f spectrometer. Frequency decreased toward the right at a rate of about 10 kc/sec. per division, and the paper speed was four divisions per hour.

and

$$\mu_{\mathrm{Cu}^{65}} = 2.3847 \pm 0.0030.$$

The unusual intensity of the copper lines is probably caused by a cupric impurity in the sample. Since the cupric ion is electronically paramagnetic, and since electronic paramagnetic relaxation occurs rapidly,[6] compared with the frequency of the nuclear lines in the present experiment, a fluctuating local field would result having an intensity much larger than in crystals not having a paramagnetic impurity. Therefore, the relaxation time T_1 of the nuclei of the cuprous ions would be considerably shortened. A similar effect has been observed for the protons in $CuSO_4 \cdot 5H_2O$ by Bloembergen.[7] A shortened relaxation time gives rise to relatively intense lines under the conditions of operation of the spectrometer because partial saturation is common for most crystalline samples.

The widths of the two lines as recorded, about 5 gauss or 5 kc/sec. between maxima and minima, are determined partly by inhomogeneity of the magnetic field. The magnet used for these experiments has poles only $3\frac{3}{4}$ in. in diameter and a $1\frac{5}{8}$-in. gap, while the sample was about $\frac{3}{4}$ in. long by $\frac{1}{2}$ in. in diameter. Computation of the r.m.s. line width from the spin-spin interactions in the crystal, using a formula developed elsewhere,[8] gives about 2 kc/sec., if an average is taken over all directions of the crystal axes, with respect to the field. The observed line breadth sets a lower limit on the spin-lattice relaxation time T_1 of about 10^{-4} second.

[1] R. Ritschl, Zeits. f. Physik **79**, 1 (1932).
[2] H. Schüler and T. Schmidt, Zeits. f. Physik **100**, 113 (1936).
[3] R. V. Pound, Phys. Rev. **72**, 527 (1947).
[4] J. B. M. Kellogg and S. Millman, Rev. Mod. Phys. **18**, 323 (1946).
[5] W. E. Lamb, Jr., Phys. Rev. **60**, 817 (1941).
[6] C. J. Gorter, *Paramagnetic Relaxation* (Elsevier Publishing Company, Inc., New York, 1947); R. T. Cummerow, D. Halliday, and G. E. Moore, Phys. Rev. **72**, 1233 (1947).
[7] N. Bloembergen, *Thesis*, Leiden, in press.
[8] N. Bloembergen, E. M. Purcell, and R. V. Pound, Phys. Rev., in press.

Conductivity Pulses Induced in Single Crystals of Zinc Sulfide by Alpha-Particle Bombardment

A. J. Ahearn
Bell Telephone Laboratories, Murray Hill, New Jersey
January 12, 1948

CONDUCTIVITY pulses similar to those observed in diamond[1] have been observed with specimens of single crystals of zinc sulfide when they are bombarded with alpha-particles from polonium.

The types of electrodes used were the same as in the diamond experiments. With electrodes separated by a 0.003-cm gap on the crystal surface, pulses were observed when a potential of 30 volts was applied. Pulses were also observed when a potential of 100 volts was applied between electrodes on opposite sides of specimens about 0.050-in. thick. Pulses were observed both when polished surfaces and cleaved surfaces were used. Pulses were observed with all of the limited number of specimens tested. The response both in numbers of pulses and pulse height is substantially less than that from the best diamond.

The specimens* used were natural crystals of sphalerite which is the cubic form of zinc sulfide. A qualitative spectrochemical analysis of one of the specimens showed an impurity content of the order of 0.1 percent, chiefly germanium. Similarly, the other specimens exhibited impurity contents in the neighborhood of 0.01 percent of one or more of the elements gallium, mercury, cadmium, and manganese. The appearance of pulses in zinc sulfide with this relatively high impurity content contrasts strikingly with the absence of pulses in some diamonds where the impurity content is known to be much smaller.

[1] D. E. Wooldridge, A. J. Ahearn, and J. A. Burton, Phys. Rev. **71**, 913 (1947).
* Some of the specimens were obtained through the courtesy of Dr. Keith Boyer, Massachusetts Institute of Technology, and others from Dr. M. F. Distad, Naval Research Laboratory.

A Note on Relativistic Quantum Mechanics

Hartland S. Snyder
Brookhaven National Laboratory, Upton, New York
January 14, 1948

THE usual method for obtaining a Hamiltonian for systems of interacting particles and fields is by the use of a Lorentz invariant Lagrangian or an equivalent method. An alternative method is the direct examination of the transformation properties of an assumed form for a Hamiltonian. This note reports the results of such an examination for the following example. Suppose the Hamiltonian, H, of a system may be written in the form

$$H = \int e_{\mathbf{k}} dn_{\mathbf{k}} + \int \epsilon_{\mathbf{K}} dN_{\mathbf{K}} + \int V(\mathbf{k}, \mathbf{k}', \mathbf{K}) d\alpha_{\mathbf{k}}^{+} d\alpha_{\mathbf{k}'} da_{\mathbf{K}}, + \int V^{*}(\mathbf{k}, \mathbf{k}', \mathbf{K}) d\alpha_{\mathbf{k}'}^{+} d\alpha_{\mathbf{k}} da_{\mathbf{K}}^{+}$$

and the total momentum, $\mathbf{P}$, may be written

$$\mathbf{P} = \int \mathbf{k} dn_{\mathbf{k}} + \int \mathbf{K} dN_{\mathbf{K}}.$$

In the above equations $d\alpha_{\mathbf{k}}^{+}$ are creation operators and $d\alpha_{\mathbf{k}}$ are annihilation operators for Fermi particles and satisfy the commutation relations $d\alpha_{\mathbf{k}}^{+} d\alpha_{\mathbf{k}'} + d\alpha_{\mathbf{k}'} d\alpha_{\mathbf{k}}^{+} = 0$ if $\mathbf{k} \neq \mathbf{k}'$ and $= d\mathbf{k}$ if $\mathbf{k} = \mathbf{k}'$, and $dn_{\mathbf{k}} = da_{\mathbf{k}}^{+} da_{\mathbf{k}} / d\mathbf{k}$. Also, $da_{\mathbf{K}}^{+}$ is a creation operator and $da_{\mathbf{K}}^{+}$ is an annihilation operator for Bose particles and satisfy $da_{\mathbf{K}} da_{\mathbf{K}'}^{+} - da_{\mathbf{K}'}^{+} da_{\mathbf{K}} = 0$ if $\mathbf{K} \neq \mathbf{K}'$ and $= d\mathbf{K}$ if $\mathbf{K} = \mathbf{K}'$, and $dN_{\mathbf{K}} = da_{\mathbf{K}}^{+} da_{\mathbf{K}} / d\mathbf{K}$.

The requirement that H, $\mathbf{P}$ constitute a four vector with respect to homogeneous Lorentz transformations gives the following results. First, $e_{\mathbf{k}} = \pm (M^2 + \mathbf{k}^2)^{\frac{1}{2}}$ in which the constant M may be identified with the mechanical mass of the Fermi particle. Second, $\epsilon_{\mathbf{K}} = \pm (u^2 + \mathbf{K}^2)^{\frac{1}{2}}$ in which the constant u is the mechanical mass of the Bose particle. Third,

$$V(\mathbf{k}, \mathbf{k}', \mathbf{K}) = U_0 \delta(\mathbf{k} - \mathbf{k}' - \mathbf{K}) \exp\{2g(\mathbf{k}) - 2g(\mathbf{k}') - 2f(\mathbf{K})\}$$

in which U_0 is a constant, f and g are real functions of their arguments, and $\delta(\mathbf{k} - \mathbf{k}' - \mathbf{K})$ is the Dirac δ-function. This particular Hamiltonian does not give convergent results. Other forms for Hamiltonians are being examined at the present time.

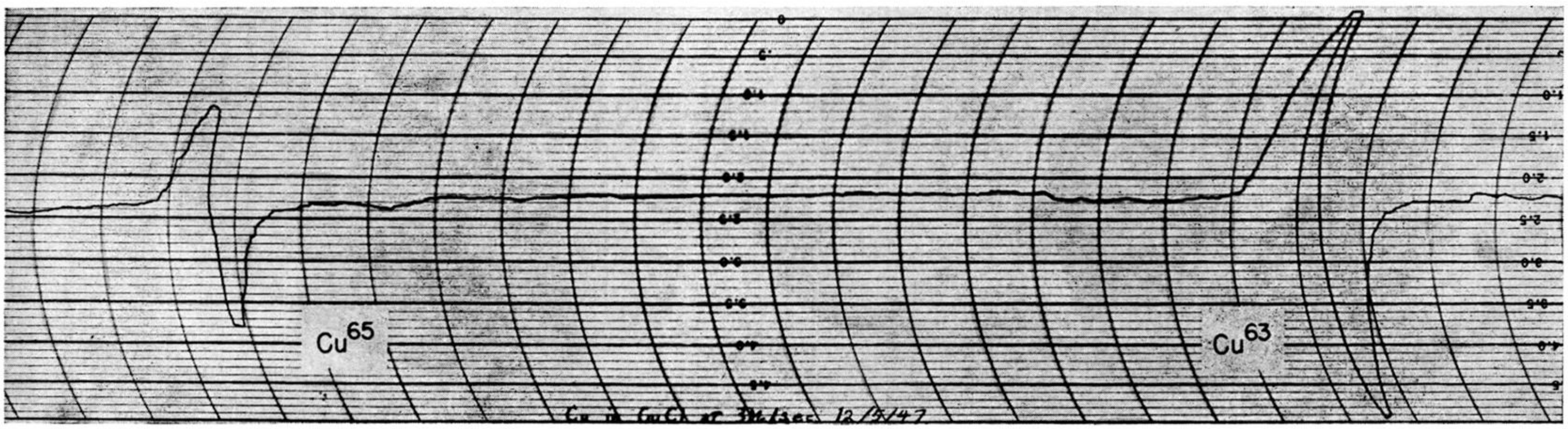

FIG. 1. Record from the r-f spectrometer. Frequency decreased toward the right at a rate of about 10 kc/sec. per division, and the paper speed was four divisions per hour.