

The measured<sup>10</sup> hyperfine splitting of the  $3s$  state leads to

$$(P_A)_{\text{expt1}} = 0.756a_0^{-3}. \quad (7)$$

The error in the quantity  $P_F/P_A$  occurring in (1) should be much less (perhaps 1-2%) than the 10% discrepancy of (6) and (7), especially since the energy at the Fermi surface is very nearly equal to the atomic  $3s$  energy.

### Metallic Wave Function in the Spherical Approximation

We write for the wave function on the Fermi surface, normalized in the equivalent sphere,

$$\psi = \sum_{l=0} a_l \varphi_l, \quad (8)$$

where  $\varphi_l$  is a similarly normalized wave function corresponding to angular momentum  $l$ . Using the same variational method as in I, and the radial wave func-

<sup>10</sup> M. Fox and I. I. Rabi, Phys. Rev. **87**, 472 (1951).

tions calculated by Von der Lage,<sup>11</sup> we find with trial functions, including up to 7 terms,

$$|a_0|^2 = 0.45, \quad |a_1|^2 = 0.45, \quad |a_2|^2 = 0.09,$$

$$\sum_{l=3}^6 |a_l|^2 = 0.01,$$

leading to the value for  $(P_F/P_A)_{\text{theoret}}$  quoted in Eq. (2). The various checks described in I were also applied to the present calculation and indicate that as a solution for the potential chosen this result has an error of less than 2%.

The calculation was repeated for a slightly different lattice constant in order to obtain the volume dependence of  $P_F$  quoted in (4).

### ACKNOWLEDGMENTS

It is a pleasure to thank Dr. R. Bowers and Professor C. P. Slichter for helpful discussions and correspondence.

<sup>11</sup> F. Von der Lage, thesis, Cornell University, 1943 (unpublished). We are indebted to Dr. J. A. Krumhansl for making these results available to us.

## Nuclear Spin-Lattice Relaxation Time in Copper and Aluminum\*

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Nuclear spin-lattice relaxation times of  $\text{Al}^{27}$  in pure Al and  $\text{Cu}^{63}$  in annealed pure Cu have been measured at 2 and 4.2°K, using the adiabatic fast-passage technique suggested by L. E. Drain. At 4.2°K,  $T_1 = 260 \pm 100$  milliseconds for copper and  $370 \pm 40$  milliseconds for aluminum. The relaxation time is apparently inversely proportional to temperature, as predicted by Korringa, from 2 to 300°K.

KORRINGA<sup>1</sup> has calculated the spin-lattice relaxation time  $T_1$  in metals and has shown that  $T_1$  should be inversely proportional to temperature and should be related to the Knight shift.<sup>2</sup> Early low temperature measurements<sup>3-5</sup> of  $T_1$  in Cu, Al, and Li were in rather poor agreement with Korringa's theory, but recently Holcomb and Norberg<sup>6</sup> have found reasonable agreement in Li, Na, and Rb near room temperature. Using two independent techniques, the writer<sup>7</sup> found that  $T_1 = 5.5 \pm 1$  milliseconds for  $\text{Al}^{27}$  in aluminum, and  $T_1 = 3.55 \pm 0.7$  milliseconds for  $\text{Cu}^{63}$  in

copper,<sup>8</sup> consistent with Korringa's theory. It seemed desirable to check the earlier low-temperature measurements on aluminum and copper to see if the discrepancy with theory is real.

The relaxation times were measured by the method of adiabatic fast passage previously used to study liquids by Drain<sup>9</sup> and by Ciaroti *et al.*<sup>10</sup> The fact that this method can also be applied to solids was discussed in a previous paper.<sup>7</sup> It is necessary that the time taken to sweep through resonance be short compared to  $T_1$  and long compared to  $T_2$  or  $(\gamma H_1)^{-1}$ , whichever is smaller. Also,  $H_1$  (the rf field) must be several times the value of rf field required to saturate the resonance under steady-state conditions.

The apparatus was similar in principle to that of

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<sup>1</sup> J. Korringa, Physica **16**, 601 (1950).

<sup>2</sup> W. D. Knight, Phys. Rev. **76**, 1259 (1949).

<sup>3</sup> J. Hatton and B. V. Rollin, Proc. Roy. Soc. (London) **A199**, 222 (1949).

<sup>4</sup> N. Bloembergen, Physica **15**, 588 (1949).

<sup>5</sup> N. J. Poulis, Physica **16**, 373 (1950).

<sup>6</sup> D. F. Holcomb and R. E. Norberg, Phys. Rev. **98**, 1074 (1955).

<sup>7</sup> A. Redfield, Phys. Rev. **98**, 1787 (1955).

<sup>8</sup> These values of  $T_1$  are quoted from Sec. IV of reference 7. The writer now feels that they are more reliable than those obtained conventionally and quoted in the abstract and Sec. II of reference 7.

<sup>9</sup> L. E. Drain, Proc. Phys. Soc. (London) **A62**, 301 (1949).

<sup>10</sup> Ciaroti, Cristiani, Giulotto, and Lanzi, Nuovo cimento **12**, 519 (1954).

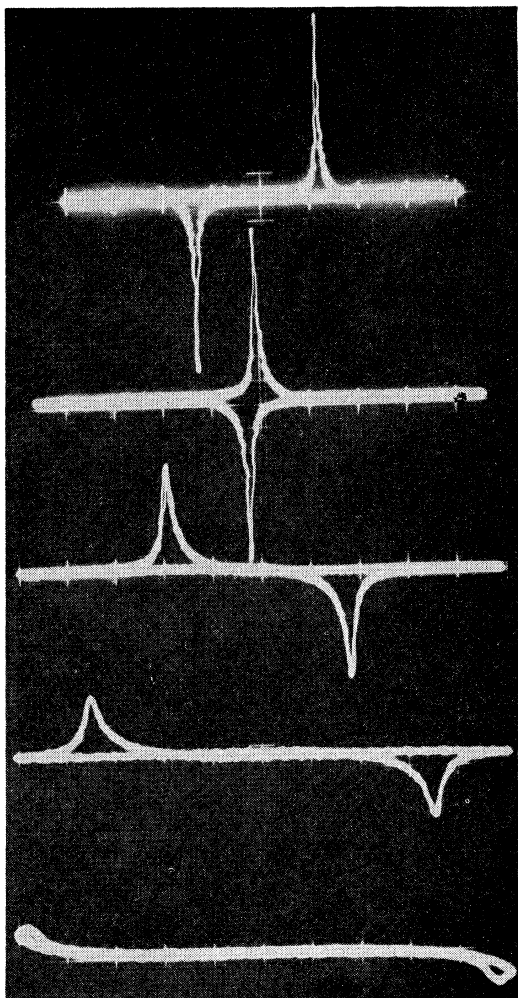


FIG. 1. Adiabatic fast-passage signals in aluminum at 2.07°K. The sweep frequencies are, from top to bottom, 0.1, 0.2, 0.5, 1.0, and 2.0 cycles per second. The shift in horizontal position of the pulses is caused by phase shifts in the sweeping circuits and is not important.

Ciaroti *et al.*<sup>10</sup> The reader is referred to their paper for a description of the method. The dispersion mode of the nuclear magnetization was observed by using a compact nuclear induction (crossed-coil) bridge immersed in the liquid helium. The rf level was about 2 gauss peak linear amplitude and the frequency was 5874 kc/sec. A triangular wave generator provided the horizontal deflection to an oscilloscope, and also reversed a polarized relay every half-cycle. The relay contacts, connected to a battery, supplied a 90-volt square wave to the sweep circuit of a Varian magnet. The resulting modulation of the magnetic field was a square wave rounded by eddy currents, with a peak-to-peak amplitude of about 200 gauss. When properly adjusted the

field swept symmetrically through the resonance in opposite directions every half-cycle. The output of the bridge was amplified and detected, and the detector voltage was applied to the vertical amplifier of the oscilloscope. The oscilloscope was direct coupled.

The metal samples were powders filed from 0.9999 pure ingots, sieved through 325 mesh, and annealed to remove strain and avoid quadrupole effects.<sup>11</sup> These particles were evidently small enough to allow the rf field to penetrate the whole volume, as evidenced<sup>12</sup> by the fact that the steady-state absorption line was almost symmetric at 4.2° when the rf bridge was balanced to observe the absorption mode. The fact that the rf field penetrates such a large (diameter  $\approx 0.004$  cm) particle is not completely understood by us. The bulk classical skin depth at 4.2° is much smaller than the diameter.

A series of signals obtained under ideal conditions is shown in Fig. 1. The time taken to sweep through resonance is roughly equal to the pulse width, which is seen from Fig. 1 to be about 50 milliseconds. This time is short compared to  $T_1$  and long compared to  $(\gamma H_1)^{-1}$  and  $T_2$ , as required for adiabatic fast passage. Previous analysis<sup>10</sup> shows that the pulse amplitude should vary as  $[1 - \exp(-1/2fT_1)][1 + \exp(-1/2fT_1)]^{-1}$ , where  $f$  is the sweep frequency. The experimental variation of the signal was in good agreement with this prediction.

We now list the experimental values of  $T_1$ . For Al<sup>27</sup>,  $T_1 = 370 \pm 40$  milliseconds at 4.2° and  $730 \pm 40$  milliseconds at 2.07°K. For Cu<sup>63</sup>,  $T_1 = 260 \pm 100$  milliseconds at 4.2° and  $640 \pm 150$  milliseconds at 1.9°K.

These measurements and the writer's previous ones<sup>7</sup> are consistent with an inverse temperature law within experimental error. The significance of the magnitude of  $T_1$  is discussed in the previous paper.<sup>7</sup> Over the whole temperature range from 2 to 300°K the experimental values of  $T_1$  are evidently in good agreement with Korringa's theory. It is not clear why the early measurements<sup>3-5</sup> in aluminum and copper were so inaccurate. Possible sources of trouble are quadrupole effects due to strain, mixing of the absorption and dispersion modes, and the use of a modulation period short compared to  $T_1$ . The adiabatic fast-passage method is thought to be much more direct and reliable than the saturation method because it involves only the simultaneous measurement of sweep frequency and pulse amplitude.

#### ACKNOWLEDGMENTS

The author wishes to thank Professor N. Bloembergen for suggesting this measurement.

<sup>11</sup> T. J. Rowland and N. Bloembergen, *Acta Metallurgica* **1**, 731 (1949).

<sup>12</sup> N. Bloembergen, *J. Appl. Phys.* **23**, 1383 (1952).

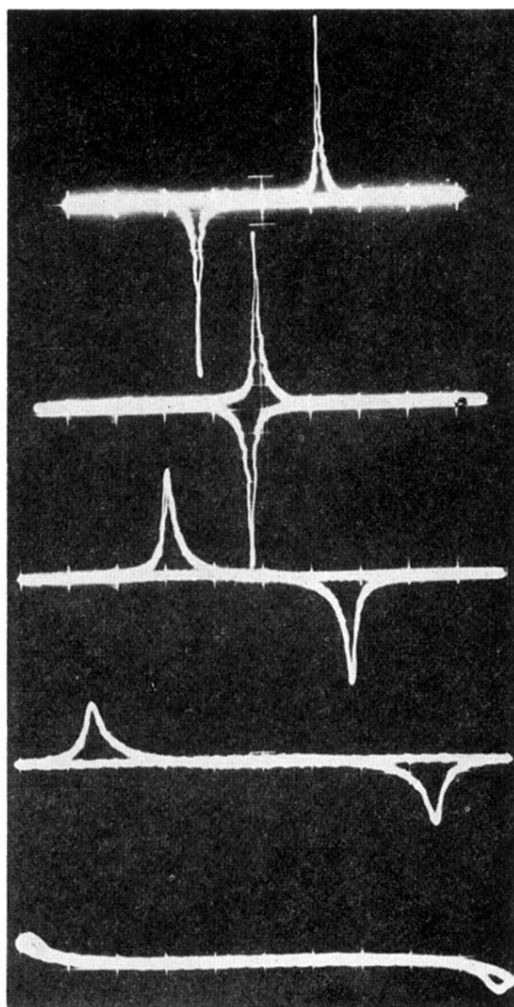


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