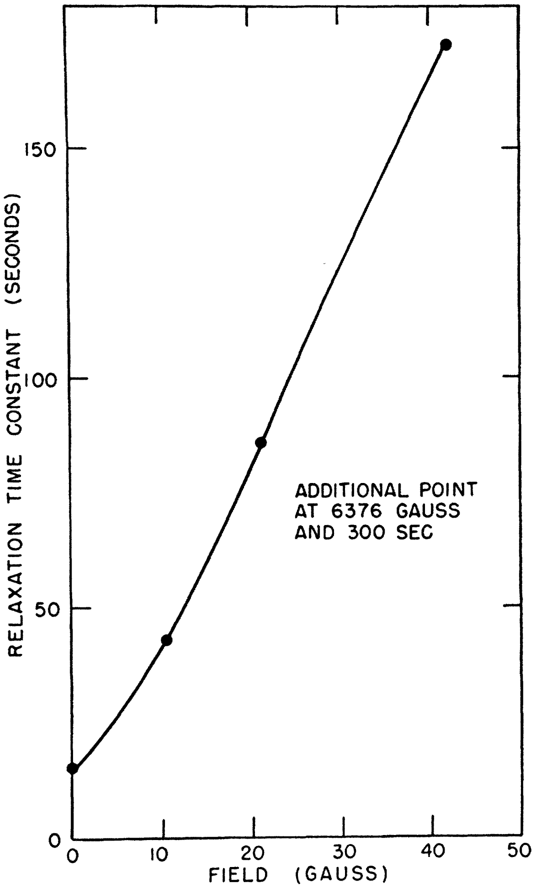

FIG. 2. Relaxation time constant as a function of magnetic field for Li^7 in LiF.

concerned and the reduction in the energy of the photons emitted and absorbed.

Therefore, when one of us (R.V.P.)[2] discovered the long relaxation time of a pure single crystal of LiF, it was suggested by the other (N.F.R.) that such long relaxation times make possible a new nuclear magnetic resonance technique which would have high sensitivity at low frequencies of the oscillating magnetic field. With the new method, the crystal is removed from a strong magnetic field for a time short compared to the relaxation time of the crystal in the absence of a strong field (15 sec for LiF) and during this short time is placed in a weak audiofrequency magnetic field. For one isotope of the crystal, the ratio of the nuclear magnetization immediately before and immediately after the removal from the strong field is measured[2] with a radiofrequency spectrometer. This ratio is then observed as a function of the frequency of the audio-oscillator. The dependence of this ratio on the audio-oscillator frequency presumably arises from resonant heating of the nuclear spin system to a temperature above the low value attained by adiabatic demagnetization when the crystal is removed from the strong magnetic field.

In this way the audiofrequency spectrum of LiF was studied between 20 and 200,000 cycles/sec with the strong field (6376 gauss) observations being of the Li^7 resonance. With audiofrequency magnetic fields of about 0.2 gauss, it was found that resonant heating did not take place below 100 cycles but did occur continuously and completely at frequencies between 1000 cycles and 200,000 cycles. However, when the amplitude of the audiofrequency field was reduced to 0.018 gauss applied for 3 sec, a nuclear audiofrequency spectrum was observed which possessed a broad maximum centered at 50 kc and with a width at half maximum of about 45 kc as shown in the lowest curve in Fig. 1. The first practical application of the 50 kc audiofrequency spectrum of LiF was its indication that the magnetic field reversal in the negative temperature experiments described in an accompanying paper[3] must be accomplished in a time short compared to 1/50 of a msec.

The effect of an external fixed magnetic field on the audiofrequency spectrum was also measured and is shown for different values of the magnetic field between 0 and 42 gauss in the upper curves of Fig. 1. It is of interest to note that the ratios of frequency to field for the two pronounced minima of the highest field curve correspond to nuclear *g*-factors 5.2 and 2.2 in surprisingly close agreement with the nuclear *g*-factors 5.26 and 2.17 for F^{19} and Li^7 respectively. The reduction of the subsequent Li^7 magnetization by an oscillatory field appropriate to F^{19} indicates that during or subsequent to the application of the oscillatory field the Li and F spin systems are in at least partial thermal equilibrium.

The effect of the external fixed magnetic field on the relaxation time in the absence of an audiofrequency field is shown in Fig. 2, where the length of time for reduction of the strong field resonance by a factor of two is plotted as a function of the strength of the weak magnetic field in which the sample is stored.

[1] Bloembergen, Purcell, and Pound, Phys. Rev. **73**, 679 (1948).
[2] R. V. Pound, Phys. Rev. **81**, 156 (1951).
[3] E. M. Purcell and R. V. Pound, Phys. Rev. **81**, 279 (1951).

A Nuclear Spin System at Negative Temperature

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November 1, 1950

A NUMBER of special experiments have been performed with a crystal of LiF which, as reported previously,[1] had long relaxation times both in a strong field and in the earth's field. These experiments were designed to discover the conditions determining the sense of remagnetization by a strong field when the initially magnetized crystal was put for a brief interval in the earth's field.

At field strengths allowing the system to be described by its net magnetic moment and angular momentum, a sufficiently rapid reversal of the direction of the magnetic field should result in a magnetization opposed to the new sense of the field. The reversal must occur in such a way that the time spent below a minimum effective field is so small compared to the period of the Larmor precession that the system cannot follow the change adiabatically. The experiments in zero field reported above[2] showed a zero field resonance at about 50 kc and therefore the following experiment was tried.

The crystal, initially at equilibrium magnetization in the strong (6376 gauss) field, was quickly removed, through the earth's field, and placed inside a small solenoid, the axis of which was

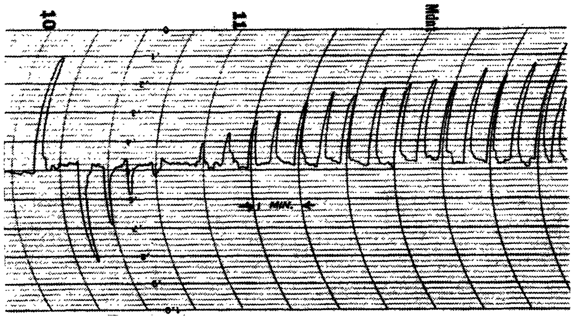

FIG. 1. A typical record of the reversed nuclear magnetization. On the left is a deflection characteristic of the normal state at equilibrium magnetization ($T \approx 300°K$), followed by the reversed deflection ($T \approx -350°K$), decaying ($T \to -\infty$) through zero deflection ($T = \infty$) to the initial equilibrium state.

parallel to a field of about 100 gauss, provided by a small permanent magnet. A 2 μfd condenser, initially charged to 8 kv, was discharged through the coil, with 500 ohms in series, in such a sense that the field in the coil reversed to about -100 gauss, with a time constant of about 0.2 μsec and decayed back to the original field with a time constant of 1 msec. The crystal was quickly returned, through the earth's field, to the strong magnet and the Li^7 resonance sampled. The operation could be done in 2 to 3 sec. A reversed deflection was found and it decayed, through zero, to the equilibrium state with the characteristic 5-min time constant. A typical record is shown in Fig. 1.

The state of spin system just after this treatment is thought to be properly described by a negative spin temperature. The system loses internal energy as it gains entropy, and the reversed deflection corresponds to induced radiation. Statistically, the most probable distribution of systems over a ***finite*** number of equally spaced energy levels, holding the total energy constant, is the Boltzmann distribution with either positive or negative temperature determined by whether the average energy per system is smaller or larger, respectively, than the mid-energy of the available levels. The sudden reversal of the magnetic field produces the latter situation.

One needs yet to be convinced that a single temperature adequately describes the nuclear spin state. Bearing on this is the fact that the crystal passes through the earth's field after the inverted population is produced, on its way back to the main magnet. The retention of the reversed magnetization requires that the spin-only-state, in the earth's field, have an inverted population and be described by a suitably small (~-1°K) negative temperature. Thus a very short time is required for the attainment of thermal equilibrium within the spin system itself (not the ordinary T_2, however).

A system in a negative temperature state is not cold, but very hot, giving up energy to any system at positive temperature put into contact with it. It decays to a normal state through infinite temperature.

This and related experiments indicate that the spin system is able to follow changes in even a small field adiabatically unless they occur in a time presumed to be less than about 20 μsec.

[1] R. V. Pound, Phys. Rev. **81**, 156 (1951).

[2] N. F. Ramsey and R. V. Pound, Phys. Rev. **81**, 278 (1951).

Erratum: Experiments on the Effect of Atomic Electrons on the Decay Constant of Be^7. II

[Phys. Rev. **76**, 897 (1949)]

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In Fig. 1 we have erroneously plotted $2\delta e^{\lambda t}$ instead of $\delta e^{\lambda t}$ as indicated on the ordinate scale on the left. The final result is in error by a factor 2 and should read:

$$\lambda(\mathrm{BeO})-\lambda(\mathrm{BeF_2})=(0.69\pm0.03)10^{-3}\lambda(\mathrm{BeO})$$
$$\lambda(\mathrm{Be})-\lambda(\mathrm{BeF_2})=(0.84\pm0.10)10^{-3}\lambda(\mathrm{Be}).$$

On the Nuclear Magnetic Moment of Na^{23}

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November 30, 1950

A discrepancy occurs between the nuclear g values of[1] Ga and[2] In as determined from measurements on the hfs spectrum of these atoms in the ground state ($^2P_{1/2}$) and as determined by the nuclear resonance method where the nuclei occur in molecules. Foley[3] has discussed the effect of the partial decoupling by the applied magnetic field of the L and S vectors in the $^2P_{1/2}$ state on the nuclear g-value obtained from observational data under the assumption that decoupling does not occur. He concludes that the diagonal magnetic interaction term $m_I g_I \mu_0 H$ which was assumed in finding g_I from the experimental data is to be modified by a small perturbation term which is, itself, proportional to the applied magnetic field. For the cases of gallium and indium the apparent g-value determined from the hfs of atoms is thus greater than the g-value obtained in the nuclear resonance experiments. Foley indicates a satisfactory agreement between the observed and calculated values of the discrepancy, especially in view of uncertainties in the theoretical calculations and a rather large experimental error.

It is of interest to determine whether or not a similar discrepancy appears for the case of a nucleus which occurs in an atom in the $^2S_{1/2}$ state, where the effect considered by Foley cannot appear. A previous measurement[4] has indicated that the apparent nuclear g-value of Cs is, indeed, the same within a rather large experimental uncertainty when measured in a molecule and when measured in an atom in the $^2S_{1/2}$ state. A precision measurement of the g-value of sodium is reported here.

Essentially use is made of the fact that certain lines $(F, m)\leftrightarrow(F, m-1)$ consist of doublets, one component of which arises in the state $F=I+\frac{1}{2}$ and the other one of which arises in the state $F=I-\frac{1}{2}$. The frequency separation of the doublet is $2g_I\mu_0 H/h$ and the mean frequency of the doublet permits determination of the quantity $x=(g_J-g_I)\mu_0 H/h\Delta\nu$, if $\Delta\nu$ is itself known, and hence of g_I/g_J. The $\Delta\nu$ of Na^{23} was found to be $1771.631\pm0.002\times10^6$ sec^{-1} by a method previously described[4] which depends on the existence of a maximum in the frequencies of certain lines in the hfs spectrum. The doublet $(F, 1)\leftrightarrow(F, 0)$ was observed at a field of about 6800 gauss where the mean frequency of the doublet is still sufficiently field dependent to permit an accurate determination of x and the doublet separation becomes large enough ($\sim16\times10^6$ sec^{-1}) to permit accurate measurement in the face of a large over-all frequency ($\sim430\times10^6$ sec^{-1}). We find then that

$$g_J(\mathrm{Na},\,^2S_{1/2})/g_I(\mathrm{Na},\,^2S_{1/2})=-2488.39\pm0.15.$$

Since[5] $g_I(H)/g_J(\mathrm{Na},\,^2S_{1/2})=-15.1927\times10^{-4}\pm0.005$ percent, we find $g_I(\mathrm{Na},\,^2S_{1/2})/g_I(H)=0.26451\pm0.008$ percent. This is to be compared with Bitter's[6] result $g_I(\mathrm{Na, mole})/g_I(H)=0.26450\pm0.01$ percent. The excellent agreement indicates that the apparent nuclear g-value measured in an atom in the $^2S_{1/2}$ state is, in fact, equal to the true nuclear g-value within the diamagnetic correction. Since no effect is here observed, it appears that the effect discussed by Foley accounts for the entire discrepancy observed for atoms in the $^2P_{1/2}$ state.

Determinations of the spin g-value of the electron reported heretofore depend on a measurement of the ratio of the electronic g_J of atoms in different electronic configurations. A combination of our present result with that of Bitter and with the result of Gardner and Purcell[7] for $2g_L/g_I(H)$ yields $g_s/g_L=2(1.00107\pm0.00012)$ under the assumption that $g_J(\mathrm{Na},\,^2S_{1/2})=g_s$ and that no differential diamagnetic correction is to be applied to the nuclear moment of sodium in an atom and in a molecular configuration. It is of interest that this result does not depend on any assumption as to the g_J-values of P-states. The result agrees with other data on the spin moment of the electron. While it could be improved, a very accurate determination is precluded by the nature of the assumptions.

* This research was supported in part by the ONR.

[1] P. Kusch, Phys. Rev. **78**, 615 (1950).

[2] Private communication from W. G. Proctor.

[3] H. M. Foley, Phys. Rev. **80**, 288 (1950).

[4] P. Kusch and H. Taub, Phys. Rev. **75**, 1477 (1949).

[5] H. Taub and P. Kusch, Phys. Rev. **75**, 1481 (1949).

[6] F. Bitter, Phys. Rev. **75**, 1326 (1949).

[7] J. H. Gardner and E. M. Purcell, Phys. Rev. **76**, 1262 (1949).

Numerical Evaluation of the Fermi Beta-Distribution Function

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November 30, 1950

Attention has recently been drawn by Feister[1] to methods of calculating the Fermi β-distribution function,

$$f(z,\,\eta)=\eta^{2+2s}e^{\pi y}\left|\Gamma(1+s+iy)\right|^2.$$

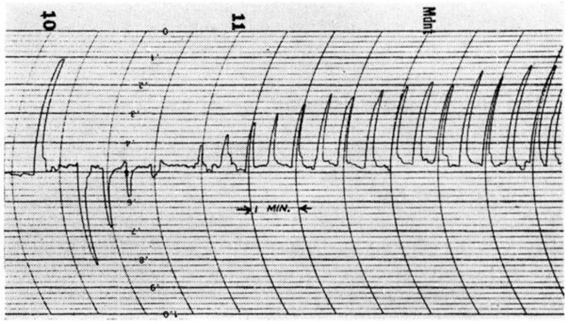

FIG. 1. A typical record of the reversed nuclear magnetization. On the left is a deflection characteristic of the normal state at equilibrium magnetization ($T \approx 300°\mathrm{K}$), followed by the reversed deflection ($T \approx -350°\mathrm{K}$), decaying ($T \to -\infty$) through zero deflection ($T = \infty$) to the initial equilibrium state.