TABLE I. The experimental and calculated eddy current torques at 30 cps for various magnetic field amplitudes. The experimental eddy current torques were obtained from the data of Fig. 2 by subtraction of the extrapolated anomalous torques at 0 cps.

H (oersteds)	T_{exp}	T_{calc}
11 300	0.280	0.278
9800	0.235	0.239
7100	0.164	0.171
4600	0.120	0.119
830	0.073	0.078

A consideration of the experimental errors and the error in calculating the eddy current contribution to the torques suggests that the anomalous loss in 0.005 in. thick 4–79 Mo-Perm is frequency-independent over the frequency range from 6–38 cps. Table I illustrates the agreement between the experimental and calculated eddy current torques.

The results quoted here plus the previous work done from 15 kc/sec to 2 Mc/sec indicate that the anomalous losses in 4–79 molybdenum Permalloy are essentially frequency-independent from 6 cps to 1 Mc/sec. The field dependence and the frequency spectrum from 0 to 6 cps are being investigated at the present time.

[1] R. Kikuchi, J. Appl. Phys. (to be published).

[2] T. L. Gilbert and J. M. Kelly, Conference on Magnetics and Magnetic Materials, Pittsburgh, Pennsylvania, June 14–16, 1955 (unpublished).

Method of Polarizing Nuclei in Paramagnetic Substances

G. FEHER
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received May 31, 1956)

OVERHAUSER[1] has shown that a saturation of the electron spin resonance leads to a large enhancement of the nuclear polarization. A necessary condition for this enhancement is that the nuclei relax via the electrons whose resonance is being saturated. A scheme which is applicable to substances which exhibit resolved hyperfine lines was proposed by Bardeen, Slichter, and Pines.[2] It requires that the predominant relaxation process for the nuclei results from a modulation of the $a(\mathbf{I}\cdot\mathbf{S})$ hyperfine interaction.

The scheme proposed in this paper, applicable to substances which show a resolved hyperfine structure, places no requirements on the detailed relaxation mechanism of either the electron or the nucleus. It requires, however, that one sweep through a certain fraction of the external magnetic field in a time short compared to either relaxation time. The method is illustrated in Fig. 1, which shows the energy levels of a system with $I=\frac{1}{2}$, $J=\frac{1}{2}$ *vs* applied magnetic field as given by the Breit-Rabi[3] formula. This system is placed

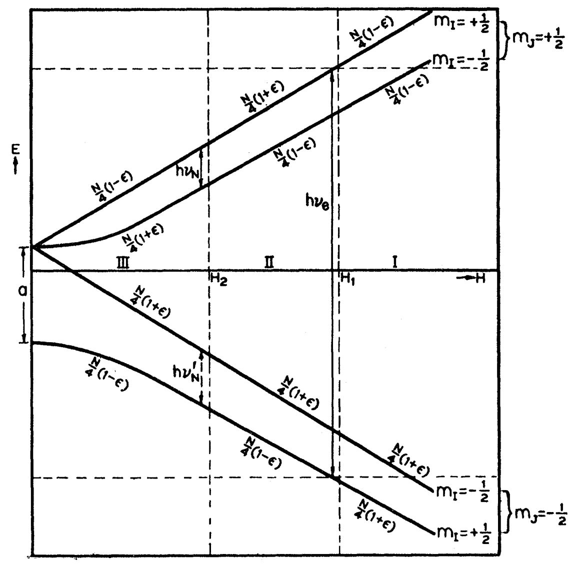

FIG. 1. Energy levels and their populations for a system with $I=\frac{1}{2}$, $J=\frac{1}{2}$.

in a microwave magnetic field of frequency ν_e and radio-frequency field ν_N, both being perpendicular to the external magnetic field H. For $H>H_1$ (see Fig. 1, region I), the population of both upper levels is given by $\frac{1}{4}N(1-\epsilon)$, where N is the total number of electrons and $2\epsilon\simeq g_e\mu_0 H/kT$ is the electronic Boltzmann factor. (We are neglecting the nuclear Boltzmann factor $g_n\mu_0 H/kT$ which is approximately 10^3 times smaller.) If we sweep through H_1, we will induce electronic transitions between the $m_I=+\frac{1}{2}$ levels. If we do this under adiabatic fast passage conditions,[4] the net magnetization of the electrons responsible for this transition will be turned through 180°. This reversal of the magnetization results in a reversal of the Boltzmann factor as indicated in region II of Fig. 1. At this stage, each set of levels corresponding to the same m_J exhibits a nuclear polarization and we could perform a nuclear resonance experiment in which the signal would be proportional to the electronic rather than the nuclear Boltzmann factor. However, the total population of both $m_I=+\frac{1}{2}$ levels equals that of the $m_I=-\frac{1}{2}$ levels, so that the sample as a whole does not exhibit a net polarization as yet. In order to obtain a net polarization we have to turn over the population of *only* one set of levels. This may be accomplished either by having a fixed radio-frequency and sweeping the magnetic field through H_2 in an adiabatic fast passage or keeping a fixed magnetic field and sweeping the radio-frequency. This is made possible by the fact that the spacing of the upper set of levels is different from the lower set ($\nu_N'>\nu_N$) as may be seen from the Breit-Rabi formula.[3] In order for only one transition to occur, the difference in level spacings has to be at least equal to the nuclear line width. The degree of nuclear polarization η obtained in region III will be given by

$$\eta=(N_{-\frac{1}{2}}-N_{+\frac{1}{2}})/(N_{-\frac{1}{2}}+N_{+\frac{1}{2}})\simeq\epsilon\simeq g_e\mu_0H/2kT,$$

or more precisely by

$$\eta=\tanh(g_e\mu_0H/2kT). \qquad (1)$$

For $T=1°K$, $H=10^4$ oersteds, and $g_e=2$, we get a polarization of $\eta\simeq0.7$. This polarization will, of course, decay with a characteristic time comparable to the nuclear relaxation time but may be re-established by successive magnetic field sweeps.

It is worth noting that from the difference in the level spacings given by[3]

$$h(\nu'-\nu)=a(1+x^2)^{\frac{1}{2}}-ax+2g_I\mu_0H, \qquad (2)$$

where

$$x=(g_I+g_J)\mu_0H/a,$$

and a is the hyperfine interaction constant, one may obtain the absolute value of the nuclear magnetic moment without having to know the electron wave function at the nucleus. Similar methods have been proposed and applied in molecular beam experiments.[5]

The transitions $\Delta m_I=\pm1$, $\Delta m_J=0$ will also affect the electron resonance line. This provides us with a sensitive method of studying nuclear resonance phenomena by observing the behavior of the electron spin resonance line.

For the sake of simplicity, the case $I=\frac{1}{2}$, $J=\frac{1}{2}$ was treated. One can easily extend the arguments for larger values of I and J, in which case a nuclear polarization of any 2 adjacent levels may be realized.

I am indebted to Professor J. Bardeen, Professor D. Pines, and Professor C. P. Slichter for sending us a preprint of their work[2] and discussing it with us. I would also like to acknowledge helpful discussions with Dr. P. W. Anderson.

1 A. Overhauser, Phys. Rev. **92**, 411 (1953).
2 Bardeen, Pines, and Slichter (private communication; to be published).
3 G. Breit and I. I. Rabi, Phys. Rev. **38**, 2072 (1931).
4 F. Bloch, Phys. Rev. **70**, 460 (1946).
5 Kusch, Millman, and Rabi, Phys. Rev. **57**, 765 (1940).

Polarization of Phosphorus Nuclei in Silicon

G. Feher and E. A. Gere
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received May 31, 1956)

In the preceding Letter a scheme for polarizing nuclei was described. This Letter deals with the experimental verification of the scheme.

The experiments were performed on a phosphorus-doped silicon crystal having a room temperature resistivity of 0.3 ohm-cm ($\simeq3\times10^{16}$ centers/cm^3). Fletcher *et al.*[1] were the first to observe a resolved hyperfine structure in a similar sample arising from the interaction of the donor electron with the magnetic moment of the phosphorus nucleus. Subsequent studies[2] showed a very long electron spin relaxation time which made this kind of sample ideal for the testing of the polarization method. The external field at which the transitions were observed was about 3000 oersteds and the temperature of the sample was 1.25°K. The electron spin resonance line was observed with a balanced-bridge superheterodyne detection scheme[3] which was sensitive to the real part of the susceptibility, χ'. The rectified output from the i.f. amplifier was fed directly into the recorder. This system avoids the necessity of modulating the magnetic field and thus eliminates unnecessary complications which may easily cause a misinterpretation of experimental results.[4] The microwave cavity was made out of Pyrex with a thin silver coating on the inside. This permitted the rf field necessary for the Δm_I transitions to penetrate. It was supplied by a coil wound around the cavity. Both the rf and microwave magnetic fields at the sample were of the order of a tenth of an oersted. This insured adiabatic fast-passage conditions for all of the transitions induced.

In order to prove that a polarization of the nuclei has taken place, we have to show that the population of the levels corresponds to the value predicted by theory. Since the amplitude of the electron spin resonance line is proportional to the population difference between two levels, it was used as a probe to investigate the occupancy of the levels.

Figure 1 shows the experimental results. The predicted populations are shown below each recorder tracing. The transitions which are induced at each stage are indicated by arrows. The time variation of the external magnetic field is shown above the tracing.

In Fig. 1(a) no rf was applied. From the theory of adiabatic fast passage,[5] we would expect the electron spin resonance line to have equal amplitude and sign when the time between two successive passages through the line is short in comparison to the relaxation time. In our case this condition was not completely fulfilled since the relaxation time of the sample was of the order of a minute whereas the time between two sweeps was approximately 20 sec. This explains, partially at least, the experimentally observed reduction in amplitude.

Figure 1(b) shows the effect of inducing nuclear transition between the $m_s=+\frac{1}{2}$ states. This was accomplished by sweeping the radio-frequency generator from 52–54 Mc/sec. A similar result was obtained by sweeping the radio-frequency generator from 64–66 Mc/sec, which induced transitions between the $m_s=-\frac{1}{2}$ states. Since this nuclear adiabatic fast passage reverses the population of the levels with the same m_s, the population of the levels with different m_s has been equalized. We should therefore not expect a signal when sweeping back through the line. Experimentally we find a small residual amplitude which again can be

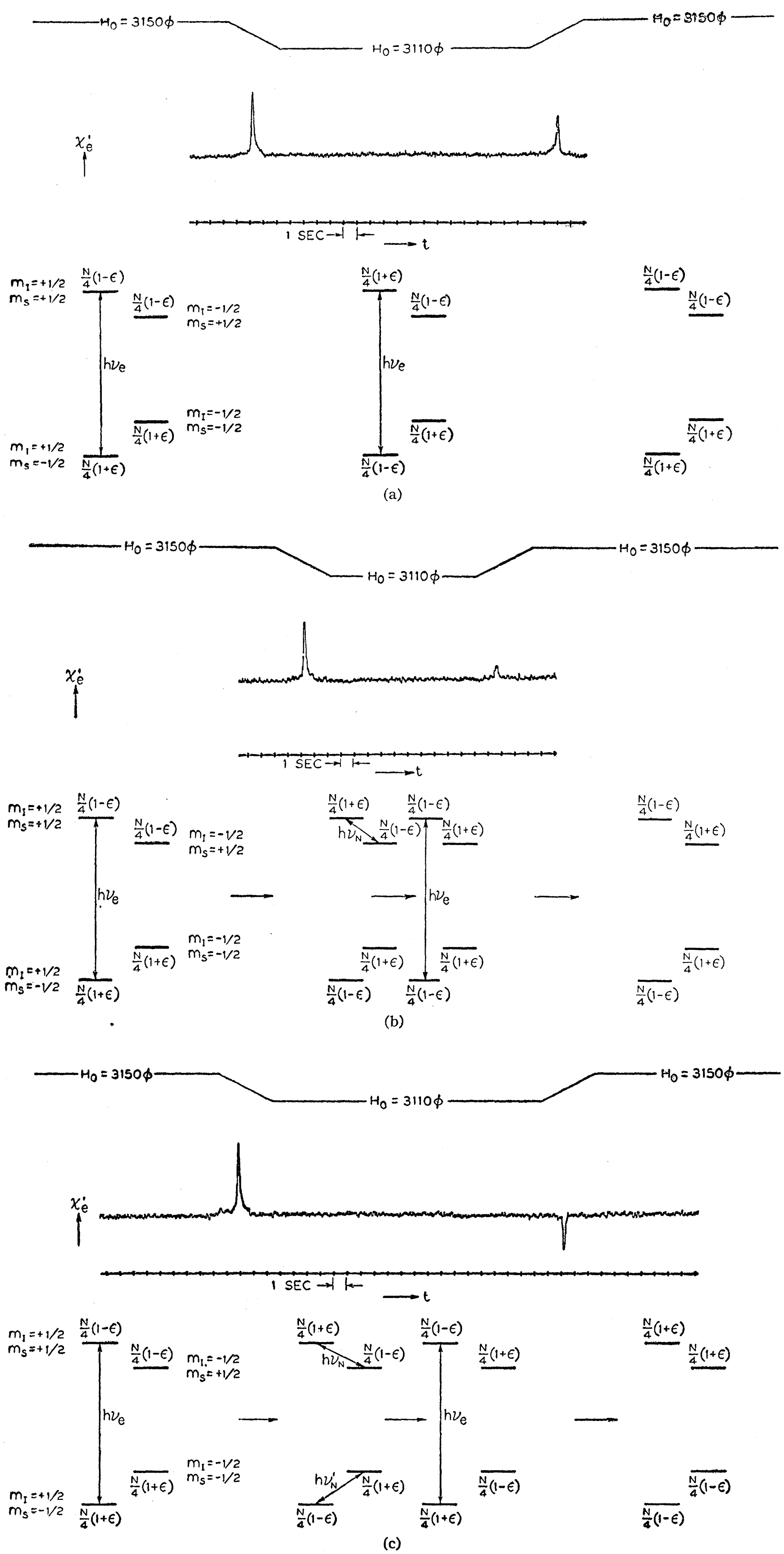

FIG. 1. Electron spin resonance lines in phosphorus-doped silicon under adiabatic fast-passage conditions. The electron line is being used as a probe to investigate the population of the levels after different transitions have been induced. (a) No radio-frequency field applied. For infinite relaxation times, the amplitude of the line after the second passage should be the same as after the first. (b) After first passage through the line, the radio-frequency field is swept from 52 to 54 Mc/sec to induce the $h\nu_N$ transition, after which nuclear polarization is established. (c) After first passage through the line, the radio-frequency field is swept from 50 to 65 Mc/sec to cover both the $h\nu_N$ and $h\nu_N'$ transitions.

explained by the finite relaxation time. It is this case that exhibits the nuclear polarization given by $\eta \simeq \epsilon \simeq g_e\mu_0 H/2kT$. This may be readily seen from the figure by merely adding the occupancy of the $m_I=+\frac{1}{2}$ levels and comparing it with that of the $m_I=-\frac{1}{2}$ levels.

Figure 1(c) shows what happens if we induce both nuclear transitions by sweeping the rf through the 52–65 Mc/sec range. We see from the level diagram that the population of the levels is just opposite to the ones in Fig. 1(a). We should observe therefore a reversal of the electron spin line, which indeed is verified experimentally.

It should be noted that it is the magnetic field in which the nuclei come to thermal equilibrium that enters into the polarization formula. This may be several times larger than the magnetic field in which the spin transitions occur, as long as the field is changed to the resonance field in a time short compared to the relaxation time.

[1] Fletcher, Yager, Pearson, Holden, Read, and Merritt, Phys. Rev. **94**, 1392 (1954).
[2] Feher, Fletcher, and Gere, Phys. Rev. **100**, 1784 (1955); G. Feher and R. C. Fletcher, Bull. Am. Phys. Soc. Ser. II, **1**, 125 (1956).
[3] G. Feher, Rev. Sci. Instr. (to be published).
[4] A. Honig, Phys. Rev. **96**, 234 (1954); A. Honig and J. Combrisson, Phys. Rev. **102**, 917 (1956).
[5] F. Bloch, Phys. Rev. **70**, 460 (1946).

Lowest Odd-Parity States in Even-Even Nuclei*

H. Morinaga
Department of Physics, University of Lund, Lund, Sweden
(Received May 25, 1956)

Although they are much less common than the even-parity states,[1,2] quite a few odd-parity states have been identified in even-even nuclei. Such states are expected to arise from configurations different from the ground-state configurations. In order to see if there is any general trend in these states, the lowest experimentally identified odd-parity states were compiled and their energies were plotted against A. The result is shown in Fig. 1. Most of the points were obtained from known beta- or gamma-ray decay schemes except for the very light nuclei. In many of the cases it is not very certain that the experimentally identified lowest odd-parity states are actually the lowest odd-parity states. In each case where the level scheme is well established there are usually several odd-parity states in a cluster, so that in the not-well-established cases the observed odd-parity states are probably close to being lowest. This situation might not occur in some light nuclei. Among 41 points plotted, the identification of the parity is quite certain for more than 30 points and the rest are more likely to be odd-parity states than even-parity states.

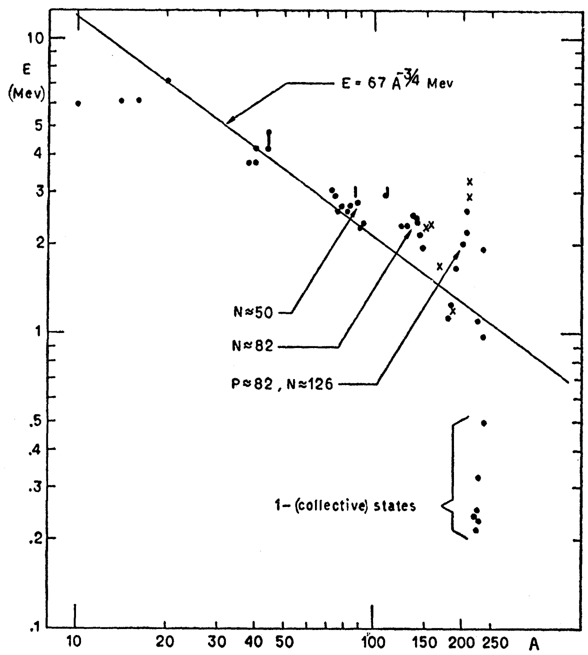

Fig. 1. Excitation energies of the lowest odd-parity states in even-even nuclei plotted against A. The dots represent the cases where parity assignments are quite certain and the crosses represent the less certain cases. The straight line represents the empirical pairing energy $E=67\,A^{-3/4}$ Mev.

The results indicate quite marked trends as follows:

(1) These states have, where the identification of the angular momentum is certain, odd angular momentum, predominantly 3, and there is no case where even angular momentum is assigned positively. This confirms the rule found by Glaubman[3] and treated theoretically by Talmi.[4]

(2) These states appear not too far from the line $E=67A^{-3/4}$ Mev (a semiempirical formula which is used to describe the separation of two mass parabolas in even-A nuclei[5]), with two kinds of exceptions: (a) anomalies at the Pb isotopes (and also around $N=82$), and (b) the low-lying 1^- states in very heavy nuclei which are considered to be collective odd-parity states.[6] This fact indicates, in other words, that in general the lowest odd-parity states lie on the odd-odd mass parabola. It is interesting to see that at $A=208$, where an anomaly takes place, the 3^- state (the lowest odd-parity state) of Pb^{208} lies closer to the odd-odd empirical mass parabola than its ground state lies to the even-even curve, indicating that the ground state is anomalously stable.

(3) The points appear in groups, around oxygen, around calcium, around strontium, etc. These are the places where the jump in the oscillator shells takes place, i.e., $1p_{3/2}$ to $1d_{5/2}$ and $2s_{1/2}$, $1d_{3/2}$ and $2s_{1/2}$ to $1f_{7/2}$, $2p_{1/2}$ to $1g_{9/2}$, etc. This might seem to be due only to the fact that in this region the states of the parent nuclei that undergo beta decay mostly have odd parity.