MASTER

Argonne National Laboratory

A TECHNIQUE FOR OBSERVATION
OF THE NUCLEAR MAGNETIC RESONANCE
OF SOME SHORT-LIVED NUCLIDES AND ITS
APPLICATION TO THE MEASUREMENT
OF THE NUCLEAR g -FACTOR OF Li^8

by

Donald Connor

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

- A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or*
- B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.*

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

*Price \$2.25 . Available from the Office of Technical Services,
Department of Commerce, Washington 25, D.C.*

ANL-6263
Physics and Mathematics
(TID-4500, 15th Ed.)
AEC Research and
Development Report

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois

A TECHNIQUE FOR OBSERVATION OF THE NUCLEAR MAGNETIC
RESONANCE OF SOME SHORT-LIVED NUCLIDES AND ITS
APPLICATION TO THE MEASUREMENT OF THE
NUCLEAR g -FACTOR OF Li^8

by

Donald Connor

Solid State Science Division

Based on a Thesis Submitted to the Faculty of
The University of Chicago
in Partial Fulfillment of the Requirements for the
Degree of Doctor of Philosophy

November 1960

Operated by The University of Chicago
under
Contract W-31-109-eng-38

TABLE OF CONTENTS

	Page
LIST OF TABLES	iv
LIST OF ILLUSTRATIONS	v
ABSTRACT	vi
 I. INTRODUCTION	 1
II. THEORY OF THE EXPERIMENT	7
A. Neutron Polarization	7
B. Nuclear Polarization	10
C. Anisotropy of Beta Emission	17
D. Effect of Radiofrequency Magnetic Fields	20
E. Relaxation Effects	33
F. Nuclear Recoil Effects	36
III. APPARATUS	40
A. Neutron Mirror	40
B. Shielding	44
C. Neutron Polarization Guide Fields	47
D. NMR Magnet	48
E. Beta Counters	49
F. Neutron String Counter	49
G. Sample Coil	50
H. R. F. Power Generator	57
I. Sample Preparation	62
IV. MEASUREMENTS	64
A. Preliminary Work	64
B. Mirror Alignment	64
C. Neutron Polarization	66
D. Completion of Shielding	68
E. Li^8 Beta-Decay Asymmetry	71
F. Li^8 Nuclear Magnetic Resonance	73

V. DISCUSSION OF RESULTS	82
A. Measured g -factor	82
B. Li^8 Capture Channel	83
C. Miscellaneous Considerations	84
D. Possible Future Applications	85
ACKNOWLEDGMENTS	87
APPENDIX	88
FOOTNOTES	92

LIST OF TABLES

Table		Page
1.	Neutron Scattering Amplitudes for Fe-Co Alloys	10
2.	Nuclear Polarization for Polarized Neutron C Capture Followed by a Single Gamma- Emission	16
3.	Nuclear Polarization for Polarized Neutron Capture Followed by the Emission of Two Successive Gamma Rays	17
4.	Asymmetry Coefficient A for Allowed Transitions	18
5.	Typical Values of Quantities Important in the Measurements	72
6.	Nuclear Polarization with Beta-Decay Asymmetry Associated with Various Spin Assignments for the Capture Channel and Ground State of Li^8	83

LIST OF ILLUSTRATIONS

Figure	Page
1. Schematic Experimental Arrangement	5
2. Diagram Illustrating Notation	12
3. Relative Probabilities $W(J_1'', M_1'')$	15
4. Larmor Precession about H_{eff}	24
5. Line Shapes According to (16)	28
6. Line Shapes According to (22')	32
7. Energy Levels of Li^8	38
8. Neutron Mirror	43
9. Plan View of Experimental Arrangement	46
10. Neutron "String" Counter	52
11. Intensity Profile of Neutron Beam	54
12. Sample Holder and R. F. Coil Assembly	56
13. Sample Holder with Electrical Shield	59
14. Oscillator Schematic Diagram	61
15. Cross Section of Neutron Beam Obtained with X-Ray Film	70
16. Radial Dependence of H_0	77
17. Li^8 Resonance Curves	81
A-1. Relative Variance Versus Acceptance Angle	91

ABSTRACT

A novel technique is described for the observation of the nuclear magnetic resonance of some short-lived nuclides; namely, those which may be produced by slow-neutron capture and which decay by beta-emission. Substantial nuclear polarization (≥ 10 per cent) is obtained by the use of polarized neutrons, permitting observation of the parity-violating anisotropy in the beta-emission as a relative measure of the polarization and hence of its change when (in addition to a strong static magnetic field) an r.f. magnetic field is applied. The resonance depolarization curves thus obtained give the Larmor frequency and hence the nuclear $\underline{g}$ -factor directly. The $\underline{g}$ -factor of Li^8 has been measured in this manner. It is found to be 0.8265 ± 0.0005 n.m./ $\hbar$, a value agreeing with one calculated by Kurath from an intermediate-coupling model but significantly greater than predicted by either extreme j-j coupling (0.65) or LS coupling (0.49). Assuming the spin of Li^8 to be 2, the observed magnitude of the beta-decay anisotropy indicates that the neutron capture occurs predominantly (≥ 80 per cent) via channel spin 2.

I. INTRODUCTION

In recent years, a considerable amount of work has been directed to the measurement of the spins and magnetic moments of short-lived nuclides. This field is reviewed in two recent articles^{1,2} and it will suffice here to point out that, among the methods normally employed for stable nuclides, only the atomic beam technique has been effective for nuclides with half-lives shorter than one month and that its present limit is reached with half-lives of about 20 minutes. Some very short-lived nuclear states ($\sim 10^{-8}$ seconds) have also been studied by an entirely different method, the measurement of the directional correlation between successive gamma rays and of the precession of the correlation in an applied magnetic field.

This thesis describes a measurement of the nuclear g-factor of Li^8 , a nuclide of half-life 0.8 seconds, by a novel technique of nuclear magnetic resonance (NMR) observation.³ The new technique should be applicable to most of the short-lived nuclides which decay by beta emission and which may be produced by neutron capture. Since conventional methods are not successful in these cases, the new technique is complementary to its elders.

For a brief outline of the new technique, it is useful

to divide it conceptually into three steps. The first of these is the polarization of the nuclear sample, accomplished by producing the sample nuclei through the capture of polarized neutrons. It is shown in the following section that substantial polarization (~ 10 per cent) usually can be achieved by this means. The second step is the detection of the nuclear polarization in a quantitative manner. A suitable means is the observation of the well known up-down asymmetry in the beta emission from polarized nuclei which offered the first experimental evidence of parity nonconservation. The third necessary step in the measurement is the perturbation of the nuclear polarization in a manner which displays resonance with the Larmor precession of the nuclei. The interaction between a radiofrequency (r.f.) magnetic field and the nuclear Larmor precession in a static field normal to the r.f. field serves admirably, producing appreciable change in the polarization only when the radiofrequency is very nearly equal to the Larmor frequency.

Of these three elements, the third is taken directly from the conventional NMR pioneered by Bloch⁴ and Purcell.⁵ The second follows directly from the fundamental experiment of Wu, Ambler, Hayward, Hoppes, and Hudson.⁶ The anisotropic beta emission from nuclei polarized by neutron capture was first observed in an early parity-testing experiment⁷ at Argonne National Laboratory which directly suggested the present work.

The geometry of the experiment is shown schematically in

Figure 1. The target, a single crystal of Li^7F , is irradiated with neutrons polarized along the static magnetic field $\underline{H}_0$. The Li^8 nuclei formed from the capture of the neutrons also will be polarized along $\underline{H}_0$ so that any "up-down" anisotropy in their beta emission will cause a difference in rate between the two counters. The coil about the sample produces an r.f. field $\underline{2H}_1$ in the plane normal to $\underline{H}_0$. If the radio-frequency is varied until it becomes equal to the nuclear Larmor frequency, $\underline{f}_0$, the equality should be signalled by the destruction of the beta-emission asymmetry as the (time-average) polarization is destroyed by the resonant interaction between the Li^8 nuclei and the r.f. field. The determination of $\underline{f}_0$ in the known field $\underline{H}_0$ yields the nuclear $\underline{g}$ factor directly.

An experiment of this type can be successful only if the nuclear polarization, averaged over the nuclear lifetime, is at least of the order of 1 per cent, because of the errors associated with drift of the counter sensitivity and the statistical fluctuations inherent in counting rate measurements with the relatively high background rates normal in the vicinity of a reactor. Since the equilibrium "Boltzmann factor" polarization is only of the order 10^{-6} at room temperature in a magnetic field of a few kilogauss, it is necessary that the relatively enormous polarization (~ 10 per cent) expected from the polarized neutron capture must persist for a time of the order of 1 second. Such slow relaxation is unusual among the many substances which have been

Figure 1. Schematic experimental arrangement. The two counters detect the beta particles emitted into one or the other hemisphere relative to the nuclear polarization axis. The coil shown around the Li^7F target provides an r.f. field $2H_1$ which, at resonance, depolarizes the Li^8 nuclei.

studied by conventional NMR techniques. However, the relaxation time of Li^7 nuclei in LiF single crystals is known to be at least 5 minutes at high fields, the chief reason for the choice of this target material.

The theory of the several effects involved in the measurement is given in the following section.

II. THEORY OF THE EXPERIMENT

A. Neutron Polarization

Three methods for the polarization of thermal neutrons are well known;⁸ namely, transmission through magnetized materials, diffraction by magnetic crystals, and reflection by a magnetized mirror. Each method suffers from certain disadvantages. In the transmission polarizer, the beam is severely attenuated by passage through several centimeters of iron and the polarization usually achieved is less than 50 per cent.⁹ The gamma background produced by captures in the iron is also objectionable. Bragg reflection from particular planes of magnetic crystals produces complete polarization¹⁰ but most of the reactor neutron spectrum is wasted because only a narrow band of wavelength is reflected. Magnetized mirrors of cobalt or some cobalt alloys provide complete polarization of a reflected beam while reflecting all the neutrons of one polarization whose wavelengths exceed a critical value set by the angle of incidence. However, for 1.5 Å neutrons, the angle of incidence must be no more than 10 minutes so that a long mirror is necessary to reflect a beam of appreciable width.

Because the reflection technique appeared most useful for this experiment, and because it was already well known

at Argonne, the use of a cobalt alloy mirror was elected. Although the theory of polarization by reflection has been given in the books by Bacon¹¹ and Hughes,¹² it is recapitulated briefly in the following paragraphs.

The interaction between the magnetic moments of the neutron and of a magnetic atom causes scattering in addition to the normal nuclear scattering. The magnetic scattering due to ordered materials, such as saturated ferromagnets, is coherent and combines with the coherent part of the nuclear scattering to produce the usual optical effects of refraction and reflection. These can be described correctly by the ordinary optical formulas if the appropriate index of refraction is ascribed to the material in question. However, since the magnetic interaction depends on the relative orientation of the atomic and neutron moments, a separate index is required for the two possible orientations of the neutron spin, parallel and antiparallel relative to the magnetization direction of the material. The index $\underline{n}$ is given by

$$n^2 = 1 - \lambda^2 (Nb/\pi) \pm \mu B/E \quad (1)$$

where $\underline{\lambda}$ is the neutron wavelength, $\underline{N}$ the atomic density, $\underline{b}$ the nuclear scattering amplitude (positive for hard sphere scattering), $\underline{\mu}$ the neutron magnetic dipole moment, $\underline{B}$ the magnetic induction in the medium, and $\underline{E}$ the neutron energy in the same units as $\underline{\mu B}$. The $\mu B/E$ term is positive when the neutron moment is parallel to the induction $\underline{B}$. In terms of the saturation magnetic scattering per atom, we can rewrite

(1) as

$$n^2 = 1 - (\lambda^2 N / \pi) (b \pm p) \quad (1')$$

where $\underline{p}$ is the magnetic amplitude for forward scattering.

A neutron wave in a medium of index unity will be reflected totally at the interface with a material of index $\underline{n}$ if the angle between the wave vector and the plane of the interface is less than the critical value $\cos \theta_c = n$. Since $1-n$ is of the order 10^{-6} ,

$$\theta_c = [\lambda^2 N b / \pi \pm \mu B / E]^{1/2} = \lambda [(N / \pi) (b \pm p)]^{1/2}. \quad (2)$$

The difference in critical angle between the two spin orientations of the neutron offers the possibility of polarization by selective reflection. For example with a collimated beam of monochromatic neutrons incident at an angle intermediate to the two critical angles, only the neutrons of polarization appropriate to the greater angle will be reflected. A simpler arrangement is possible if the mirror material is such that $p \geq b$. In this case θ_c is real for only one spin state and any reflected neutrons will be polarized. Cobalt is such a material and its use as a mirror in this manner was first suggested by Hamermesh¹³ and later demonstrated by Hughes and Burgy.¹⁴

Polycrystalline cobalt is extremely difficult to magnetize to saturation. Burgy later suggested the use of a 95Co-5Fe alloy which has a cubic structure and is relatively easy to magnetize. The pertinent scattering amplitudes are

given in Table 1 which shows that $p > b$ for the alloy as well as for pure cobalt. The design of the Co-Fe alloy mirror used in the present work is discussed in Section III.A.

TABLE 1.--Nuclear and magnetic scattering amplitudes for iron, cobalt, and 95Co-5Fe alloy. Values are based on data from Table 17, page 154 of Footnote 11.

Metal	Nuclear scattering amplitude $b, 10^{-12} \text{ cm}$	Magnetic scattering amplitude $p (\theta=0), 10^{-12} \text{ cm}$
Co	0.28	0.47
Fe	0.96	0.60
95Co-5Fe	0.31	0.48

B. Nuclear Polarization from Polarized Neutron Capture

When polarized neutrons are captured by an unpolarized target, the product nuclei generally will be polarized to some degree since the captured neutrons carried a net angular momentum in the polarization direction. In discussing the question quantitatively, we use the notation shown in Figure 2. Consider the system composed of a thermal neutron, spin $j_n = \frac{1}{2}$, and a nucleus of spin J_0 . With complete neutron polarization, m_n takes only a single value, say $+\frac{1}{2}$. For an unpolarized target, the values $M_0 = J_0, J_0-1, \dots, 1-J_0, -J_0$ are equally probable. Since thermal neutrons will be captured only if $L = 0$, the compound system spin J_1'' can take

Figure 2. Diagram illustrating the notation used in the text discussion of nuclear polarization and beta-emission anisotropy. The subscripts 0, 1, 2, refer to the target nuclide, the product nuclide, and the beta-decay daughter nuclide, respectively.

only the values $J_0 \pm \frac{1}{2}$ while the relations $M_1'' = M_0 + \frac{1}{2}$ and, of course, $|M_1''| \leq J_1''$, must also be satisfied. Calculation of the relative probability of formation of the several states (J_1'', M_1'') is a standard problem in the quantum theory of angular momentum,¹⁵ which gives the probabilities $W(J_1'', M_1'')$ as just the squares of the appropriate Clebsch-Gordan coefficients, namely

$$\begin{aligned} W(J_1'', M_1'') &= \frac{J_1'' + M_1''}{2J_1''} & \text{for } J_1'' = J_0 + \frac{1}{2} \\ W(J_1'', M_1'') &= \frac{J_1'' + 1 - M_1''}{2(J_1'' + 1)} & \text{for } J_1'' = J_0 - \frac{1}{2} \end{aligned} \quad (3)$$

We see that the probabilities depend linearly on M_1'' in each case, with positive M_1'' values favored for the state of higher spin and negative ones for that of lower spin. The relations (3) are shown graphically in Figure 3.

For the nuclear polarization, $P(J_1'') = (\sum M_1'' \cdot W(J_1'', M_1'')) / J_1'' \equiv \langle M_1'' \rangle / J_1''$, one obtains

$$\begin{aligned} P(J_1'') &= (J_1'' + 1) / 3J_1'', & \text{for } J_1'' = J_0 + \frac{1}{2} \\ P(J_1'') &= -1/3 & \text{for } J_1'' = J_0 - \frac{1}{2} \end{aligned} \quad (4)$$

The relative probability for capture into one or the other of the two compound states, $J_1'' = J_0 \pm \frac{1}{2}$, cannot be calculated without virtually complete knowledge of the level structure of the product nuclide. Since the two possible compound states have opposite polarization, some cancellation occurs

Figure 3. Relative probabilities $W(J_1'', M_1'')$ of the states (J_1'', M_1'') formed from the capture of completely polarized slow neutrons by unpolarized nuclei of spin J_0 :

whenever their formation probabilities are comparable.

The compound states will lie above the ground state (GS) of the product nuclide by the amount of the neutron binding energy, typically 6 or 7 mev (but only 2 mev for Li^8). This excitation energy will be lost in the emission of one or more capture gamma rays. As these also carry angular momentum, the GS polarization is generally less than the values given by Equations (4). If the capture decay scheme is known, the GS polarization can be calculated by angular momentum theory with results which have been reviewed by Shapiro.¹⁶ Some typical results are shown in Tables 2

TABLE 2.--Ground state nuclear polarization due to the capture of polarized neutrons followed by a single dipole gamma transition. Based on a similar table in Shapiro's article, Footnote 16, with the notation changed to that illustrated in Figure 2; target nuclide spin J_0 , compound state spin J_1 , ground state spin J_1 .

J_0	Ground State Polarization $P(J_1)$					
	$J_1'' = J_0 - \frac{1}{2}$			$J_1'' = J_0 + \frac{1}{2}$		
	$J_1 = J_0 + 1$	$J_1 = J_0$	$J_1 = J_0 - 1$	$J_1 = J_0 + 1$	$J_1 = J_0$	$J_1 = J_0 - 1$
0	—	—	—	5/9	-1/3	—
1/2	0	—	—	1/2	1/3	0
1	-5/27	1/9	—	7/15	11/27	5/9
3/2	-1/4	-1/6	0	4/9	5/12	1/2
2	-7/25	-11/45	-1/3	3/7	31/75	7/15

and 3. The outstanding feature of the results, from an experimenter's point of view, is that the GS polarization exceeds 10 per cent in all the tabulated cases except where the decay scheme includes a level of zero spin. In the latter case, the polarization vanishes identically.

TABLE 3.--Ground state nuclear polarization $P(J_1)$ due to the capture of polarized neutrons followed by two successive gamma transitions of minimum multipolarity. Based on a similar table in Shapiro's article, Footnote 16, with the notation changed to conform to that illustrated in Figure 2; target nuclide spin J_0 , compound state spin J_1'' , ground state spin J_1 .

J_0	Decay Scheme $J_1'' \rightarrow J_1' \rightarrow J_1$	$P(J_1)$
0	$\left\{ \begin{array}{l} 1/2 \rightarrow 1/2 \rightarrow 1/2 \\ 1/2 \rightarrow 1/2 \rightarrow 3/2 \\ 1/2 \rightarrow 3/2 \rightarrow 1/2 \end{array} \right.$	$\begin{array}{l} 1/9 \\ -5/27 \\ 5/9 \end{array}$
1	$\left\{ \begin{array}{l} 3/2 \rightarrow 5/2 \rightarrow 1/2 \\ 3/2 \rightarrow 3/2 \rightarrow 1/2 \\ 3/2 \rightarrow 1/2 \rightarrow 1/2 \end{array} \right.$	$\begin{array}{l} 7/15 \\ 11/27 \\ -5/27 \end{array}$
3/2	$\left\{ \begin{array}{l} 2 \rightarrow 1 \rightarrow 1 \\ 2 \rightarrow 2 \rightarrow 1 \\ 2 \rightarrow 3 \rightarrow 1 \end{array} \right.$	$\begin{array}{l} 1/4 \\ 5/12 \\ 4/9 \end{array}$

C. Anisotropy of Beta Emission from Polarized Nuclei

Present beta-decay theory¹⁷ gives the angular distri-

bution

$$W(\theta) = 1 + (v/c)P(J_1)A \cos \theta \quad (5)$$

where $W(\theta)$ is the probability of emission at an angle θ from the polarization axis. The coefficient A depends on the nature of the beta transition. Values of A for allowed transitions are given in Table 4.

TABLE 4.--Asymmetry coefficient A for allowed transitions. Based on Konopinski's article, Footnote 17, with some change of notation. J_1 is the initial and J_2 the final nuclear spin, C_A and C_V are the axial and vector coupling constants as used by Konopinski, M_F and M_{GT} are the Fermi and Gamow-Teller matrix elements.

$J_2 - J_1$	A
1	$J_1/(J_1 + 1)$
-1	-1
0	$\frac{-1}{J_1+1} \frac{ C_A M_{GT} ^2 \sqrt{J(J+1)} C_V C_A^* + C_A C_V M_F M_{GT} }{ C_V M_F ^2 + C_A M_{GT} ^2}$
0	$-1/(J_1 + 1)$ (pure G-T transition)
0	0 (pure Fermi transition)

If beta particles emitted according to the angular distribution (5) are detected by a pair of counters, each of which subtends at the source a cone of half-angle θ_m , the counting rates will be

$$N_1 = \frac{1}{2}N_0 \int_0^{\theta_m} (1 + a \cos \theta) \sin \theta d\theta$$

$$N_2 = \frac{1}{2}N_0 \int_{\pi-\theta_m}^{\pi} (1+\alpha\cos\theta)\sin\theta d\theta$$

where $\alpha = (v/c)P_n A$ and N_0 is the disintegration rate of the source. Carrying out the integrations,

$$N_1 = \frac{1}{2}N_0(1-\cos\theta_m + (\alpha/2)\sin^2\theta_m) \quad (6)$$

$$N_2 = \frac{1}{2}N_0(1-\cos\theta_m - (\alpha/2)\sin^2\theta_m)$$

or

$$\frac{N_1-N_2}{N_1+N_2} = \frac{(\alpha/2)\sin^2\theta_m}{1-\cos\theta_m} \quad (7)$$

If we think of determining α from the experimental counting rates, it is useful to solve for it:

$$\frac{1}{2}\alpha = \frac{(1-\cos\theta_m)}{\sin^2\theta_m} \cdot \frac{N_1-N_2}{N_1+N_2} \quad (8)$$

From (7), one sees that the relative difference in the counting rates has its maximum value, α , for $\theta_m = 0$. On the other hand, the rates themselves go to zero with θ_m , so that the statistical error in the relative difference becomes large. These opposite factors suggest the existence of an optimum choice of θ_m to minimize the statistical error in α . It is shown in Appendix 1 that the optimum value of θ_m is about 70° for $\alpha \lesssim 0.5$ and that the error is not much worse for $\theta_m = 90^\circ$.

With counters and source immersed in a static magnetic field, $\theta_m \approx 90^\circ$ is realized almost automatically since the beta trajectories spiral about the field lines so that nearly all intercept the counters.

D. Effect of Radiofrequency Magnetic Fields on Beta-Decay Anisotropy

The nuclei of interest are distributed more or less uniformly throughout the target crystal and are polarized along the static magnetic field $\underline{H}_0$. Magnetic interactions among the radioactive nuclei have negligible effect because of the vanishingly small concentration (average separation of the order of 10^6 lattice spacings). Since the g-factor of the unstable nuclei differs from that of the surrounding stable nuclei, if H_0 exceeds a hundred gauss or so, spin exchange among the different species will be prohibited by the difference in Zeeman energies. The only magnetic effect due to the stable nuclei will be a small magnetic field due to the superposition of the individual dipole fields of their magnetic moments. This local field $\underline{H}_{loc}$ fluctuates randomly in both space and time with a mean value zero (neglecting the Boltzmann factor polarization of the stable nuclei, of the order 10^{-6}).

In these circumstances, to a very good approximation the total magnetization of the N radioactive nuclei in the sample is just N times the expectation value of the magnetization of an isolated nucleus in a magnetic field $\underline{H} = \underline{H}_0 + \underline{H}_{loc} + \underline{H}_{rf}$. Since only expectation values are of interest,

a classical treatment is sufficient.

We first consider the effect of $\underline{H}_0$ alone.¹⁸ It is convenient to use a rotating coordinate system.¹⁹ We take $\underline{M}$ and $\hbar\underline{J}$ as the dipole moment and angular momentum of a classical spinning magnet so that $\underline{M} = \gamma\hbar\underline{J}$. In a stationary system, the equation of motion is

$$\hbar \frac{d\underline{J}}{dt} = \underline{M} \times \underline{H}_0 = \gamma\hbar\underline{J} \times \underline{H}_0 . \quad (9)$$

Denoting by $\frac{\partial}{\partial t}$ the derivative with respect to a coordinate system which rotates at angular velocity $\underline{\omega}$,

$$\frac{d\underline{J}}{dt} = \frac{\partial \underline{J}}{\partial t} + \underline{\omega} \times \underline{J} . \quad (10)$$

In (10), $\hbar\underline{J}$ remains the angular momentum which would be measured by a stationary observer. From (9) and (10),

$$\frac{\partial \underline{J}}{\partial t} = \underline{J} \times \underline{\omega} + \gamma(\underline{J} \times \underline{H}_0) = \gamma\underline{J} \times (\underline{H}_0 + \gamma^{-1}\underline{\omega}) \quad (11)$$

so that an observer in the rotating frame sees the motion of the moment as though it were in an effective field

$$\underline{H}_{\text{eff}} = \underline{H}_0 + \gamma^{-1}\underline{\omega} . \quad (12)$$

In particular, an observer rotating with angular velocity $\underline{\omega}_0 = -\gamma\underline{H}_0$ sees an unchanging angular momentum. Therefore, a fixed observer must see the moment as precessing at the Larmor frequency ω_0 .

In considering the effect of a radiofrequency magnetic field (while still neglecting $\underline{H}_{10c}$), we limit ourselves to

the special case applicable to the present experiments as well as to most conventional NMR work, taking $\underline{H}_{rf} = \underline{H}_1$, a field of constant amplitude which rotates with angular frequency ω in the plane normal to $\underline{H}_0$. This is equivalent to the experimentally more convenient case of an oscillating field of amplitude $2H_1$ since the latter may be decomposed into two rotating components of opposite sense. The "wrong"-handed rotating component can be shown to have negligible effect.²⁰

We choose a rotating coordinate system such that

$$\underline{H}_0 = H_0 \underline{k}, \quad \underline{H}_1 = H_1 \underline{i}, \quad \underline{\omega} = -\omega \underline{k}. \quad (13)$$

In this frame, (12) may be written

$$\underline{H}_{eff} = (H_0 - \gamma^{-1}\omega) \underline{k} + H_1 \underline{i} \quad (12')$$

Since (12') gives $\underline{H}_{eff}$ as a constant field, the motion in the rotating frame is merely the ordinary Larmor precession about $\underline{H}_{eff}$ with angular frequency $\omega_n = \gamma H_{eff}$, as illustrated in Figure 4. The case shown is that where initially $\underline{M}$ is parallel to $\underline{H}_0$, as in the present experiment where the nuclear polarization is created along $\underline{H}_0$.

In the fixed system, the x and y components of $\underline{M}$ oscillate at angular frequency ω with an amplitude which is modulated at angular frequency ω_n . In the cases of interest, ω is of the order of Mc/sec so that any slow observation of M_x and M_y will give a vanishing result. Defining $\theta = \sin^{-1} H_1/H_{eff}$, in either system,

Figure 4. Larmor precession of a moment about the effective field $\underline{H}_{\text{eff}}$ due to a field $\underline{H}_1$ which rotates at angular frequency ω in the plane normal to the static field $\underline{H}_0$. The motion is shown as it would appear to an observer rotating with $\underline{H}_1$.

$$M_z = M [\cos^2\theta + \sin^2\theta \cos\omega_n t] . \quad (14)$$

Calling $\gamma H_1 = \omega_1$ and $\omega - \omega_0 = \delta$, we can rewrite (14) as

$$M_z/M = [\delta^2 + \omega_1^2 \cos\omega_n t]/\omega_n^2. \quad (15)$$

At resonance, $\omega_n = \omega_1$, $\delta = 0$, and

$$[M_z/M]_{\delta=0} = \cos\omega_1 t . \quad (15')$$

Since the nuclear polarization and magnetization are parallel (or antiparallel), (15) and (15') are valid for P_z/P as well as for M_z/M . From (15'), the time-average polarization vanishes at resonance, an effect well known in conventional NMR work as "r.f. saturation" and often described in the language of quantum mechanics as the "equi-population of the Zeeman levels."

To see the effect of (15) on an observable beta-emission anisotropy, we take a time-average weighted by the beta decay probability:

$$\begin{aligned} \overline{P_z/P} &= \int_0^\infty (P_z/P) \lambda e^{-\lambda t} dt \\ &= [\delta^2 + \omega_1^2 \int_0^\infty \lambda e^{-\lambda t} \cos\omega_n t dt]/\omega_n^2 \\ &= [\delta^2 + \omega_1^2 \lambda^2/(\lambda^2 + \omega_n^2)]/\omega_n^2 \\ &= [\delta^2 + \omega_1^2/(1 + \omega_1^2 \tau^2 + \delta^2 \tau^2)]/(\omega_1^2 + \delta^2) \end{aligned} \quad (16)$$

where $\tau = \lambda^{-1}$ is the mean lifetime for the beta transition. For $\omega_1 \tau \gg 1$, (16) reduces to the Lorentz shape

$$\overline{P_z/P} = \delta^2 / (\omega_1^2 + \delta^2). \quad (16')$$

The line shapes given by (16) are shown in Figure 5 for several values of $\omega_1 \tau$. Since $\underline{H}_{loc}$ has been ignored in the derivation of (16), one would expect it to be valid only for an experiment in which $\underline{H}_1 \gg \underline{H}_{loc}$. This case is rather unlikely since, according to (16), H_1 need be only a fraction of a gauss for virtually complete depolarization with even the shortest known values of τ . (For all known nuclei, $\gamma > 70$ cycles/gauss.) H_{loc} , on the other hand, is of the order of a few gauss in most solids.²¹

In attempting to take due account of $\underline{H}_{loc}$, we may ignore its components in the x-y plane since their intensities fluctuate randomly with a correlation time of the order of 10^{-5} seconds,²² short compared to the nutation period ω_n^{-1} , and their effect, therefore, averages to zero. The fluctuations in the z-component, however, produce a similar fluctuation in the resonance frequency at any specific lattice site within the sample crystal. Consequently, if H_0 is within a few gauss of resonance with the applied radiofrequency, $H_z = H_0 + H_{loc}$ will vary randomly in and out of resonance, producing more or less depolarization.

A line shape function which takes the fluctuations in H_z into account semiquantitatively may be obtained by the

Figure 5. Depolarization resonance line shapes according to (16). The assumed value of $\omega_1\tau$ is shown with each curve.

following crude argument. We define the intrinsic fractional linewidth F as

$$F = 2\omega_1/\omega_0 = 2H_1/H_0 \quad (17)$$

so that

$$\overline{P_z}/P = 1/2 \text{ for } \delta/\omega_0 = \pm F/2$$

in the limit of large $\omega_1\tau$ for which (16') applies. Then as a rough approximation we say that H_1 will produce no depolarization except when $\delta = \omega - \omega_0$ satisfies the inequality

$$|\delta/\omega_0| \leq F/2. \quad (18)$$

When (18) is satisfied, we will take $\omega_n = \omega_1$. This is equivalent to replacing the Lorentz line shape (16') by a rectangular one. On this assumption, the absolute linewidth in gauss is $2H_1 = FH_0$. If H_0 is $\Delta H = \gamma^{-1}\delta$ gauss from resonance with ω , H_z will have the resonant value a fraction of the time

$$\epsilon = 2H_1 W(\Delta H) \quad (19)$$

where $W(H_{loc})$ is the normalized probability distribution of H_{loc} . The average value of ω_n will be

$$\langle \omega_n \rangle = 2H_1 W(\Delta H) \omega_1 = 2\gamma H_1^2 W(\Delta H) \quad (20)$$

giving an average polarization as indicated by the beta-asymmetry

$$\begin{aligned}
P_z/P &\approx \int_0^\infty \lambda e^{-\lambda t} \cos \langle \omega_n \rangle t \, dt = \lambda^2 / (\lambda^2 + \langle \omega_n \rangle^2) \\
&= [1 + (\langle \omega_n \rangle \tau)^2]^{-1}
\end{aligned}
\tag{21}$$

Comparing (15') and (20), we see that for a given depolarization at exact resonance ($\Delta H = 0$), the effect of the fluctuating local field will be to require an increased r.f. field.

$$H_1' = [H_1 / 2W(0)]^{\frac{1}{2}} \approx (\pi/2)^{\frac{1}{4}} (\sigma_H H_1)^{\frac{1}{2}}$$

where σ_H is the standard deviation of the local field, H_{loc} . Rewriting (21) to display the frequency dependence

$$\overline{P_z/P} = [1 + K^2 W^2(\gamma^{-1} \delta)]^{-1}; \quad K = 2\gamma H_1^2 \tau \tag{22}$$

from which one sees that the linewidth is of the order $2\sigma_H$. For example, if we take $W(\Delta H)$ to be gaussian,

$$W(\Delta H) = \sigma_H^{-1} (2\pi)^{-\frac{1}{2}} \exp[-\frac{1}{2}(\Delta H/\sigma_H)^2] \quad ,$$

(22) becomes

$$\overline{P_z/P} = [1 + A^2 \exp - (\Delta H/\sigma_H)^2]^{-1};$$

$$A^2 = (2/\pi)(\gamma H_1 \tau)^2 (H_1/\sigma_H)^2 \tag{22'}$$

and half values occur at $\Delta H = \pm \sigma_H (2 \cdot \ln A)^{\frac{1}{2}}$. The line shapes given by (22') are plotted in Figure 6 in comparison with experimental line shapes. The qualitative agreement found

Figure 6. Depolarization resonance line shapes according to (22'). Solid curves are computed for the value of the parameter A^2 shown with each. Dashed curves are drawn through experimental points plotted on the assumption that $\sigma_H = 10$ gauss.

seems reasonable in view of the crudeness of the model, the uncertainty as to the correct form of $W(\Delta H)$, and the error in the measurements of H_1 .

E. Relaxation Effects

It has been shown (Section 2B) that the capture of polarized neutrons may produce substantial polarization of the product nuclei, a typical value being 30 per cent. However, the nuclear polarization could be rapidly destroyed by any process which permitted the exchange of angular momentum between the minute number of polarized nuclei and either the crystal lattice or the unpolarized, far more abundant, stable target nuclei.

Such relaxation processes have been studied extensively for stable nuclei in normal concentration by the techniques of conventional NMR.²³ It is now well established that spin-spin relaxation, the exchange of angular momentum between nuclei, takes place only between like nuclei if the static magnetic field exceeds a value of the order of 100 gauss.^{24,25} This result is readily explained by the difference in Zeeman energy between unlike nuclei, spin-exchange being forbidden by energy conservation when the change in Zeeman energy exceeds the local energy fluctuations within the system of like spins.

Spin-lattice relaxation is known to occur at appreciable rates through only two processes. In one of these angular momentum is transferred by the coupling between the

electric quadrupole moment of the nucleus and the fluctuating (because of the lattice thermal vibrations) electric field gradient at its position. In the other important mechanism, the Coulomb coupling between the lattice and paramagnetic ions or centers in the crystal combines with the magnetic interaction between the nuclear moments and the paramagnetic impurity to provide an effective spin-lattice coupling.

The rate of relaxation of polarization by the electric quadrupole interaction is proportional to the magnitude of the nuclear quadrupole moment and to the electric field gradient at the nuclear position.²⁶ The dependence on temperature is as T^2 at room temperature, becoming more pronounced at very low temperatures with perhaps T^7 as the limiting case.²⁷ For any given nucleus, the relaxation rate may be reduced only by a favorable choice of crystal or by reduction of the sample temperature. Crystals in which the binding is largely ionic normally have lower field gradients than those in which the binding is covalent in character.

LiF was chosen as a sample material in the present experiment primarily because the relaxation time for Li^7 nuclei is known to exceed 5 minutes in single crystals. The binding in LiF is almost purely ionic and the quadrupole moment of Li^7 is rather small (0.02 barn), the two facts probably explaining the long relaxation time.

The Li^8 quadrupole moment might be expected to be even smaller since that of Li^6 is only 0.002 barn and the moments of nuclei differing only by two neutrons are usually quite

comparable.

The rate of relaxation via paramagnetic impurities depends on the concentrations of both the impurities and the nuclei of interest. The strong field in the vicinity of the paramagnetic center provides rapid relaxation of the polarization of nearby nuclei. If the impurity concentration is much below 10^{-3} , however, the fraction of nuclei directly affected becomes small and the mechanism of spin diffusion, the transport of polarization by spin exchange among like nuclei, becomes important.^{28,29} The rate of spin diffusion clearly depends on the nuclear concentration and becomes negligible at very low concentration because it depends on the magnetic dipole-dipole interaction between like nuclei, whose strength varies as r^{-3} with the distance between nearest like neighbors.

In the present experiment where the concentration of Li^8 nuclei is vanishingly small ($\sim 10^4/\text{cc}$), one expects that relaxation via paramagnetic impurities should be negligible if the impurity concentration does not exceed a few ppm. Since the effect is much greater for the abundant stable nuclei in the crystal, a measurement of the spin-lattice relaxation time by conventional techniques for the Li^7 target nuclei will provide an adequate check on the crystal purity. This argument could fail in one special case; namely, if there were a strong correlation between the positions of the polarized Li^8 nuclei and those of the paramagnetic centers. Such a correlation could exist if para-

magnetic centers were created by the nuclear recoil associated with the emission of capture gamma rays. This possibility is discussed in the next section.

F. Nuclear Recoil Effects

When the compound nucleus formed by neutron capture is de-excited by the emission of gamma radiation, the photon momentum must be balanced by the recoil of the nucleus. The nuclear recoil energy associated with the emission of a gamma ray of energy E_γ is

$$E_n = (533/A)E_\gamma^2 \quad (23)$$

where E_n is in ev and E_γ in mev. The binding energy of the last neutron in Li^8 is 2.04 mev so that $E_n = 275$ ev if the decay to its ground state occurs with the emission of a single gamma ray. This is probable on the basis of present knowledge of the level structure³⁰ (see Figure 7).

A recoiling "hot atom" is expected to produce about $E_n/50$ vacancy-interstitial pairs according to current estimates from radiation damage theory,³¹ so that some 5 such pairs should exist in the vicinity of each Li^8 nucleus produced from neutron capture. The binding energy of an atom in the lattice is believed to account for only about one half of the required 50 ev per vacancy pair. The other 25 ev per pair represents the energy lost in collisions which do not result in vacancy creation, particularly replacement collisions in which the striking atom replaces the struck

Figure 7. Energy levels of Li^8 . Based on a similar diagram in the review by F. Ajzenberg-Selove and T. Lauritsen (Footnote 30).

atom on a lattice site and collisions in which an atom is set in vibration without being dislodged. Very little ionization is expected when the recoil energy is so low since the recoil velocity is much smaller than the orbital velocities of the atomic electrons.

From the discussion of the last paragraph, one would expect the only effect of importance in the present work to be a broadening of the Li^8 resonance line due to the nearby lattice defects produced by the nuclear recoil. The absence of the nuclear dipoles at vacancies and the extra dipoles at interstitial positions should augment the range of fluctuation of the local field H_{loc} . However, the conclusions from radiation damage theory cited above are based largely on calculations from rather crude models and supported in the main by experiments measuring only average properties of heavily irradiated specimens. Therefore it would not be altogether astonishing if some qualitative departure from these conclusions were found in an experiment like the present one where some detailed effects of individual recoils might be observable. Having made this point, it is only fair to state that no such effects were in fact observed.

III. APPARATUS

A. Neutron Mirror

The magnetic mirror design largely followed that adopted in the Argonne polarized neutron decay experiment.³² With the reactor neutron spectrum, the maximum number of neutrons is reflected from a mirror of given length at an angle of about 8 minutes, so that a mirror length of 50 inches is required for a reflected beam width of 1/8 inch, a reasonable sample thickness for a LiF target crystal, giving only small scattering of the Li^8 beta particles ($E_0 \approx 13$ mev). As standard polishing techniques are most satisfactory for surfaces whose two dimensions are comparable, the 50 inch mirror was assembled from 10 segments, each 5 inches square, even though only about 3 inches of mirror height was to be used.

The cobalt alloy (95Co, 5Fe) was prepared (by the Metallurgy Division, Argonne National Laboratory) as 6 inch square pieces, 1/32 inch thick. After copper plating, the alloy sheets were furnace-brazed without flux, under vacuum, to 3/4 inch brass backing plates. The brass plates had also been copper plated to avoid evaporation of the zinc component during brazing. The pieces were then machined to the final 5 inch square size and four mounting holes were drilled in each piece. Before grinding and polishing, the holes were

plugged with nickel pegs in order to provide a continuous surface for the finishing operations. The final cobalt surfaces were good optical mirrors.

The mirror and its magnet are shown in cross-section in Figure 8. The ten segments were mounted with their reflecting surfaces in contact with an accurately machined 62-inch beryllium copper plate in order to align them precisely. A doubly tapered slot in the mounting plate provided an opening just sufficient to pass the incident and reflected beams. The mounting plate was clamped against the magnet pole tips by 9 leaf springs, each compressed by a screw threaded through the yoke. A clearance of about 0.005 inch is provided between the cobalt surface and the poletip in order to avoid possible warping forces on the mirror without seriously affecting the magnetic efficiency.

About 360 gauss is maintained in the cobalt with 9 amperes through the 100 turns on each pole tip. At this current, the coil dissipation is about 330 watts. The spaced layers of the coils permit some air flow and the temperature rise is tolerable (about 90°C) without forced-air cooling. According to published data on the alloy,³³ the magnetization should be 90 per cent of saturation. Experimentally, no increase in polarization was detected when the coil current was doubled.

The small reflection angle requires rather delicate alignment of the mirror relative to the incident beam. To

Figure 8. Neutron mirror and magnet, shown in end view.

facilitate adjustment of the mirror position, the center of the magnet yoke rests on a ball-cone pivot, located in the mirror plane. Each end of the yoke slides on a Teflon pad, permitting easy rotation as an appropriate adjusting screw is turned. The lower (cone) part of the pivot and the Teflon pads are mounted on a steel support plate which itself slides on ball bushings, providing easy translation in the direction normal to the mirror surface.

B. Shielding

A hole into the moderator of a reactor provides a sizeable flux of fast neutrons and gamma rays as well as the desired thermal neutron beam. These "hard" components, if they were to reach the counters directly or by scattering from the sample would produce an objectionably large background. They are not reflected appreciably by the mirror so the reflected beam is relatively free from hard radiation and the shielding problem is largely that of absorbing the radiation which is scattered by the mirror. A substantial fraction of this is in the forward direction and would strike the counters if the sample region were not shielded from the mirror so that only the minimum necessary aperture is provided for the polarized neutron beam. Collimation of the primary beam from the reactor so that only the useful solid angle contributes to the background is of obvious value.

Figure 9 shows a plan view of the arrangement which was used. In general, the apertures were just sufficient to pass

Figure 9. Plan view of experimental arrangement.

the useful beam. Reactor neutrons reach the mirror through the $4 \times 1/8$ inch slit of a 42 inch collimator imbedded in the reactor shield. The mirror is shielded by a house of heavy (magnetite and iron aggregate) concrete whose stepped exit port has a minimum aperture 1 foot square. This window was filled with shielding material, after the mirror alignment had been completed and the guide field magnets positioned.

The shielding was entirely successful so far as protecting personnel from radiation. Except in the immediate vicinity of the reflected beam, the gamma and fast neutron flux levels never were found to exceed 10 per cent of "tolerance". However, critical alignment of the mirror and of the beam defining slits was necessary in order to reduce the forward scattered gamma flux to a tolerable level for the beta asymmetry measurement.

C. Neutron Polarization Guide Fields

The neutron polarization may be attenuated if the neutrons pass through a field whose direction rotates appreciably in a distance comparable to the Larmor precession distance ($80/H$ cm for a neutron of 2200 m/sec velocity).³⁴ A satisfactory means of avoiding depolarization by such spatially varying stray fields is to provide a static "guide" field of the order of 100 gauss, thereby "swamping out" stray field variations.

A guide field which rotates in space is required by

another consideration. To minimize the scattering of the beta particles within the LiF sample the nuclear polarization axis should lie along the small dimension of the sample. The neutron polarization at the mirror is normal to the small dimension of the beam so that it is desirable to rotate the beam polarization by 90 degrees. This may be accomplished without significant depolarization if the guide field rotates through this angle in a distance long compared to the Larmor distance.

The various guide field requirements were met with the use of simple assemblies of permanent magnets with mild steel polefaces.

D. NMR Magnet

The observation of the beta asymmetry and the expected resonant destruction of it is made with the sample in the static magnetic field H_0 provided by a large electromagnet. As in an NMR experiment of conventional type, the Larmor frequency is fixed by the value of H_0 . The fractional width of the observed resonance will be at least as great as the fractional variation of H_0 over the sample volume so that a highly homogeneous field is desirable. A field strength of at least a few kilogauss is desirable for two reasons; relaxation times are somewhat greater at high fields while the relative line-width decreases with the ratio H_{100}/H_0 . In order to achieve reasonable field homogeneity with the large gap required to accommodate the beta counters, a magnet of

large pole diameter is necessary.

These requirements were met quite satisfactorily by the use of a commercial electromagnet of 12 inch poleface diameter.³⁵ The pole gap was extended to 5 1/4 inches by the removal of the normal poletips. Field strengths of 7 kilogauss could be attained within the coil current ratings at the increased gap width.

E. Beta Counters

Only one beta counter is required to carry out the measurement of the beta asymmetry but the use of two counters improves the statistics and provides a comparison check on the stability of the counters. Two counters were used throughout the experiment. Their design followed usual practice, plastic scintillators, 3 inches square by 1 inch thick, being coupled by long (19 inch) light pipes to 6810A photomultiplier tubes. The photomultipliers were shielded by the usual mu-metal shields and a wrapped shield of commercial magnetic shielding material.³⁶ In spite of the shielding, the counter sensitivity varied markedly with magnet current so data was normally taken at constant field. The associated electronic gear was entirely conventional.

F. Neutron "String" Counter

This type of counter is very useful for locating and mapping thermal neutron beams. Although its use is widespread, there seems to be no published description. The

equivalent of an extremely thin cylindrical counter is achieved by using a stretched string, thread, or wire to scatter neutrons into a conventional BF_3 counter. A typical assembly is shown in Figure 10. A string counter mounted on a milling vise was used for various location and mapping purposes in the present work. It was also used as a relative flux monitor in the asymmetry and resonance measurements. A typical beam intensity profile obtained with the string counter is shown in Figure 11.

G. Sample Coil

A radiofrequency field of the order of 1 gauss is required for complete destruction of the beta asymmetry, according to the analysis of Section 2D. The efficiency of the coil must be reasonably good if this field is to be achieved with an r.f. generator of modest power dissipation. Helmholtz coils are widely used in NMR work but their efficiency is quite low because the volume over which the r.f. field is maintained is much larger than the sample volume. For the flat samples of the present work, the simplest design which provides reasonable homogeneity with good efficiency is that shown in Figure 12, a flat coil with each dimension about twice that of the corresponding sample dimension. The coil pitch is large compared to the wire diameter in order that most of the betas may pass between turns. The resulting coil has the rather low inductance of 12 u-henries (shielded) and at low frequency greater coil current is

Figure 10. Neutron "string" counter.

Figure 11. Intensity profile of neutron beam as measured with string counter.

Figure 12. Sample holder and r.f. coil assembly.

obtained if an external series inductance is used, because of the better impedance match to the driving tube.

Shielding is necessary to avoid interference with the broadcast and communication services which have legal claim on the frequency range of interest (0.5 to 20 Mc/sec). A thin (0.005 inch) window in the aluminum shield permits the betas to reach the counters with negligible attenuation. The sample crystal is supported inside the coil in a bag of 0.002 inch Teflon foil, the bag being stretched between the two support rods to which it is attached by Scotch tape. The assembly is shown in Figure 13.

H. R.F. Power Generator

The r.f. generator provides adequate coil current over the frequency range from 350 kc to 12 mc with a single low power transmitting tube. The electrical schematic is given in Figure 14. The tuning condenser is motor driven in order to permit unattended search operation. A simple clutch permits manual tuning when desired.

An electron coupled power oscillator was used to minimize tracking problems while providing fair frequency stability and good efficiency over the wide frequency range desired. The Hartley type of oscillator circuit was used in order that the rotors of the multi-section tuning capacitors might be grounded. Cathode taps on the grid circuit coils were located empirically with the goal of maintaining

Figure 13. Sample holder with electrical shield in place.

Figure 14. Oscillator schematic diagram.

oscillation at as low a plate supply voltage as achievable so that a wide range of r.f. output could be obtained by varying the supply voltage.

The entire r.f. unit (apart from power supply) was built in an aluminum shield box, $9 \times 14 \times 10$ inches over-all. No external signal was detectable at a distance of 10 feet with a communications receiver and 15 foot antenna while the generator-coil combination was operated at full power.

I. Sample Preparation

Single crystals of LiF were chosen as the first samples to be tried because of the unusually long relaxation time (5 minutes) which had been reported for Li^7 nuclei in these crystals.³⁷ The low capture cross section of F^{19} is also a desirable feature since it minimized the interfering beta activity.

Self-shielding due to the 930 barn (n, α) cross section of Li^6 would have been intolerable if material of normal isotopic composition had been used. However, the use of isotopically pure Li^7 entailed the necessity for special preparation of the LiF and growth of the desired single crystals. In the first effort of this sort, LiF was prepared from Li_2CO_3 powder of 99.9 per cent isotopic purity obtained from Oak Ridge National Laboratory. Attempts to grow crystals by the Kyropoulos technique from this material produced only small and cloudy crystals. According to spectroscopic analysis, Mg and Ca were present at the 0.1 per cent level and it was suspected

that the difficulty in the growth of crystals might be due to these impurities.

Accordingly, the material was purified by an ion exchange technique,³⁸ producing spectroscopically pure LiCl. The fluoride was then prepared with extreme care using re-distilled HF. Crystals were grown from the pure LiF with no more than the usual difficulties. The Li^7 relaxation time was measured as about 15 minutes by conventional NMR techniques. Measurement of commercial LiF crystals with the same technique gave values of about 5 minutes.

Single crystal LiF may be cleaved quite readily along the principal (001 type) planes. The crystal ingots were cleaved into pieces 2-3 mm in thickness with 1-2 cm edges for use as samples. A mosaic of several such pieces was used in most of the preliminary measurements although the final resonance measurement was made with a single piece about $1\frac{1}{2}$ cm square by 2 mm thick.

Some hasty measurements were later made on Li_2SO_4 and Li_2CO_3 powders (of dubious purity) as a rough test of the value of the elaborate preparation described above. Apparent asymmetries were found of about 50-70 per cent of the value obtained with the LiF crystals.

IV. MEASUREMENTS

A. Preliminary Work

The first report³⁹ of an asymmetry in the beta decay of Li^8 nuclei produced by polarized neutron capture had been based on very hurried work.⁴⁰ The observed effect had been small and not satisfactorily reproducible. It seemed important therefore to establish this asymmetry unambiguously as the first step in the experiment. In October 1958 it became possible to use the polarized neutron beam of the Argonne polarized neutron decay experiment⁴¹ for a brief study of the Li^8 asymmetry. Using the large electromagnet and counters described above and the single crystal Li^7F samples, an easily observable effect was found. The rate of either counter changed by about 5 per cent between the polarized and unpolarized conditions.

B. Mirror Alignment

The first step in aligning the mirror at a glancing angle to the reactor neutron beam is the location of the beam. The simplest method for the initial location is to expose an x-ray film to the beam, thereby covering a large area in a single measurement. The usual disadvantage of the film, namely that it is much more sensitive to gammas than to slow neutrons, was of no importance in the location of the primary

beam because the gammas and the neutrons are collimated by the same aperture. Having located the beam roughly with film, the string counter could be used for a precise location and the study of the intensity profile.

After the direct beam collimator was inserted into the reactor beam tube, the direction of the direct beam was determined by exposing a film 20 feet from the pile face. Using a theodolite, the projection of the direct beam centerline was marked on the floor. The side walls of the mirror shield were then installed symmetrically relative to the centerline. The mirror and its supporting table were then moved into the space between the shield walls and, again with a theodolite, the mirror was positioned approximately parallel to the centerline of the direct beam so that the exit slit of the collimator in the reactor face could be seen through the aperture of the mirror collimator. After putting the shield front wall in place, the mirror location was rechecked.

With the reactor operating at 40 KW, rather than the normal 2000 KW, in order to reduce the background from the direct beam, the mirror position and orientation were adjusted to maximize the direct flux through the mirror aperture. The mirror was then moved into the beam until the peak intensity of the direct beam, as measured with the string counter, had been reduced to approximately one half of its earlier value so that the mirror plane more or less coincided with the vertical median plane of the beam. The

mirror was then rotated through an angle of 8' and the expected reflected beam was found by scanning with the string counter. The mirror was subsequently readjusted to maximize the peak flux in the reflected beam while still cutting off the direct beam.

C. Neutron Polarization Measurement

As soon as the mirror had been aligned, the neutron polarization was measured in a rather crude manner in order to verify roughly the expected mirror performance. In these measurements, a second mirror, magnetized parallel to the first, was used. Ideally, the completely polarized beam from the first mirror would be reflected totally by the second. If, then, the beam were depolarized in the space between the mirrors by passage through a thin (0.007 inch) unmagnetized iron foil,⁴² the twice-reflected intensity should be halved since the component of reverse polarization would not be reflected by the second mirror. With imperfect mirrors, the change in twice-reflected intensity will be less marked and the product of the polarizations which the mirrors would separately produce is given by

$$P_1 P_2 = (N_1 - N_2) / N_2 \quad (24)$$

where N_1 and N_2 are the intensities of the twice-reflected beam with and without foil interposed.

In practice, (24) cannot be applied with high accuracy

because small angle scattering in the foil changes the intensity profile of the beam. However, the change in intensity due to scattering by the foil was only 4 per cent at the peak of the beam profile (estimated from foil in/out profile comparisons made without the second reflection). Intensities at the peak of the profile were used in estimating the polarization from (24) and a correction of 4 per cent was applied.

The second mirror was only 10 inches long so that only a fraction of the beam could be reflected from it. A cadmium block was set 0.025 inches from the mirror surface in order to intercept those neutrons which missed the mirror. By moving the analyzer at right angles to the beam, the entire beam from the first mirror could be examined in successive measurements. The twice-reflected beam was scanned with the string counter at each setting of the analyzer. As expected, the intensity was considerably greater when the two mirrors were magnetized in the same direction, the ratio of intensities being 13:7. However, it was found also that reversing the common direction of magnetization changed the twice-reflected intensity about 30 per cent. This observation suggests strongly that some depolarization occurred in the flight path between the mirrors; in fact, no guide field had yet been provided. It is likely that the neutron polarization during the later beta-asymmetry measurements, when adequate guide fields existed, was markedly higher than the value found in the polarization measurements.

The values actually obtained for $P_1 P_2$ according to (24) ranged from 0.38 to 0.75, the mean being 0.53. Assuming that the mirrors are similar, one obtains $P_1 = P_2 = 0.73$. This figure is probably to be regarded as a lower limit for the actual neutron polarization.

D. Completion of Shielding

The large exit window was filled with successive layers of shielding material; brass, lead, boral, and polyethylene. The first guide field magnet and the field rotator were installed before the section of window nearest the mirror was filled with brass slabs. Subsequent guide field magnets, which included apertures just large enough to pass the beam were fitted in the following manner. A film was exposed at a point 20 feet from the shield and the center of the reflected beam determined. A theodolite centered above this point and sighted on the center of the exit slit of the mirror collimator gave an optical duplicate of the beam axis. The magnets were inserted in turn in the appropriate layers of shielding and the distance found between the beam center-line and some reference mark on each magnet. The inserts which defined the slits were then machined accordingly.

The beam location film had shown a dark line on the direct beam side of the neutron beam, as shown in Figure 15. A suspicion that the line was due to γ rays, forward scattered or not quite blocked by the mirror, was verified by cutting off the neutron beam with a boral sheet and probing with a

Figure 15. Cross section of neutron beam obtained by a one hour exposure of Eastman "No Screen" x-ray film. The comparatively sharp line is due to a contaminating beam of gamma rays.

sensitive beta-gamma survey meter. To eliminate the narrow ribbon of gammas, a slit insert with Pb edges was constructed for the last slab of polyethylene in the window. The insert could be positioned by transferring shims from one side to the other of the opening in the polyethylene. After careful shimming, most of the gamma intensity was eliminated, to the point that the measured intensity rose only slightly as a beta-gamma probe was passed through the beam. However, occasional difficulty with gamma background was experienced later, apparently resulting from small movements of the mirror or of the Pb slit.

E. Li^8 Beta Decay Asymmetry

The beta counters with their long light pipes were mounted rigidly on the magnet so that they were fairly accurately centered in the gap. The sample holder and r.f. coil assembly was mounted in the gap center on an adjustable support (a normal Varian Associates NMR probeholder) which permitted calibrated movement in both directions within the center plane of the magnet. The large magnet itself was moved to make the center plane of the gap contain the center line of the neutron beam, using the string counter on the beam peak and cadmium slits attached to the sample holder. The sample holder position was then adjusted for maximum beta counting rate with a Li^7F sample in place.

Many measurements of the beta-emission anisotropy were made in the course of the experiment; first to demonstrate

the existence of an observable effect, later, as routine checks on the performance of the apparatus. The usual procedure was to adjust the counting rates to rough equality (by changing the photomultiplier voltage) with the neutron beam depolarized by passage through the iron foil. A series of counts would then be taken with the foil alternately in and out of the beam. Some typical values for the conditions which affect the experimental intensities are given in Table 5.

TABLE 5.--Typical values of quantities important in the measurements. Except for the counting rates, values are estimated and may be a factor of three in error. The background rate was measured with the thermal neutron beam cut off by a boron plate, permitting any hard contamination of the beam to make the same contribution as in the asymmetry measurements.

Neutron flux at reactor end of beam tube	10^{13} n/cm ² /sec
Neutron flux at sample	10^7 n/cm ² /sec
Li ⁷ target area	0.6 cm ²
Li ⁷ target atoms/cm ²	1.8×10^{23}
Li ⁸ disintegration rate	2×10^4 d/sec
Beta-counting rate (one counter)	8×10^3 c/sec
Background rate (one counter)	25 c/sec

A note concerning the interpretation of the observed polarization-dependent change of counting rates may be in order. From Equation (8) of Section 2C, one sees that the relative change in counting rate depends not only on the

asymmetry coefficient α but also on the effective solid angle subtended by the counters at the LiF sample. A calculation of the counter acceptance angle which took the magnetic deflection of the beta particles into account would be very complex and has not been made. However, with the large geometric solid angle subtended by the counters (3 inches square, 1/2 inch from a sample about 3/4 inch square) augmented by the magnetic deflection of the beta particles into the counters ($H_0\rho = 3\text{-}1/2$ inches for $E_\beta = 13$ mev, the end-point energy), it seems clear that essentially all of the emitted beta particles were counted. This conclusion is supported by some measurements of apparent asymmetry as a function of $H_0\rho$ which indicated no field dependence above a few hundred gauss. This implies that θ_m in (8) should be taken as $\pi/2$, whence

$$\alpha = (N_1 - N_2)/(N_1 + N_2) = 0.1 \pm 0.01$$

where the assigned error reflects only the general reproducibility of the measurements over several weeks.

F. Li^8 Nuclear Magnetic Resonance

After verifying that the ratio of the beta counter rates changed by about the expected 10 per cent, the search for the Li^8 resonance was begun. The resonance frequency estimated from a j-j coupling model was 2.7 Mc/sec in 5400 gauss so the 1.7 to 3.8 mc oscillator range was chosen for the first trials. The effect of the local field fluctuations

was not understood at that time and it was feared that the achievable depolarization would be limited to the ratio of the intrinsic to real linewidths, about 2 per cent at the maximum available r.f. field. To avoid this imaginary difficulty the "static" field H_0 was modulated over a range of a few gauss at 10 cycles.

During the search, the oscillator frequency was varied slowly (1 octave per 25 hours) by the motor-driven tuning capacitor. The beta counters were connected to counting rate meters whose output was recorded. A very broad line was found in the vicinity of 3.6 Mc/sec. It was shown by trial that removal of the H_0 modulation had no effect on the depolarization at the center of the line but did decrease the line width. Point by point asymmetry versus frequency measurements were then made for several values of H_1 . These showed a well defined depolarization line whose width changed only slowly with r.f. amplitude. The depolarization at the line center was equal to that (change in either counting rate 10 per cent) achieved by depolarization of the neutron beam so long as the r.f. field $2H_1$ exceeded 0.2 gauss or so. The effort to understand these facts led to an appreciation of the importance of the local field fluctuations and ultimately to the analysis given in Section 2D.

Before the final measurement of the resonance frequency and line shape, the homogeneity of the static field H_0 was studied by means of an NMR gaussmeter. With the NMR probe mounted on the movable probe holder in the same

relative position as the LiF samples, the point of best homogeneity was found approximately by observing the NMR linewidth as the probe was moved in the midplane of the gap. Best homogeneity is indicated by minimum linewidth. The field was then mapped in the vicinity of this magnetic center by observing the shift in resonance frequency as the probe was moved. The results are shown in Figure 16. It can be seen that H_0 varied less than 50 ppm over a circle of 1 inch diameter.

Frequencies were measured with a BC-221 Frequency Meter, both for measurements of H_0 and in the Li^8 resonance measurements. This instrument can be read to a precision of the order of 10 ppm and its short-term stability is comparable. An internal crystal oscillator permits calibration of the instrument at each measurement. The crystal frequency was checked against WWV on several occasions and always found to be correct within the precision of the comparison, about 10 ppm.

Just prior to the final measurement of the Li^8 resonance, some poorly understood difficulties with the mirror alignment arose in the course of collateral measurements in which the mirror was turned on and off repeatedly. In consequence, the observed asymmetry declined to about 7 per cent. Since its value is unimportant for the g-factor measurement, the latter was conducted without resolving the difficulty.

With a sample crystal mounted at the magnetic center

Figure 16. Radial dependence of H_0 . Eight radial traces, spaced 45° apart, gave points which fell within the shaded area of the figure.

within the r.f. coil, a search was made for the resonance in the neighborhood of the Larmor frequency expected from earlier measurements. With $H_0 = 5418$ gauss, a clear minimum in the beta asymmetry was found at about 3410 kc/sec. The line shape was then traced out carefully for each of three values of r.f. field. An asymmetry measurement was made at each frequency, the frequencies used being spaced a few kc/sec apart across the entire resonance. As a check on the stability of the beta counters, and to provide a basis for correction if a drift were detected, the line was traversed several times and points were frequently taken at a frequency far off resonance (3600 kc). The data showed no drift in the counting rates and the standard deviation calculated from the data was about equal to that expected from statistics.

A measurement of H_0 was made at the end of the session in which the final Li^8 resonance data was taken with the probe at the sample position. During the runs, the NMR probe was mounted against one poleface so that the field could be monitored continuously. No drift greater than 0.05 per cent was observed.

At the time of the measurements, the value of the r.f. field $2H_1$ was set by adjusting the oscillator plate voltage. The r.f. voltage across the sample coil was then measured and recorded. Later, with the LiF sample removed, the relation between r.f. field and voltage was established by measuring the induced voltage in a small pickup coil introduced into the sample position. Knowing the number of turns and area of

the pickup coil, one easily deduces the r.f. field. For the sample coil used (see Figure 12), the relation is

$$2H_1 = 1.67(E/f) \text{ gauss} \quad (25)$$

where f is the frequency in mc and E is the peak-to-peak voltage. Because of the difficulty in an accurate determination of the mean coil cross section, the uncertainty in (25) may be as great as 20 per cent.

The resonance curves are shown in Figure 17, from which the Larmor frequency is 3.413 ± 0.001 Mc/sec, with the error estimate reflecting only the difficulty of locating the center of the resonance line (the error in frequency measurement is negligible, comparatively). The proton resonance frequency at the sample position was 23.07 ± 0.01 Mc/sec so that $g(\text{Li}^8) = 3.413 g(\text{H}^1)/23.07$. Since $g(\text{H}^1) = 5.5854\text{nm}/\hbar$,⁴³ one obtains $g(\text{Li}^8) = 0.8265 \pm 0.0005\text{nm}/\hbar$. No diamagnetic correction has been made (the order of magnitude of the correction would be $10^{-4}\text{nm}/\hbar$).

It should be pointed out that the sign of the g -factor has not been determined. However, the shell model interpretation is straightforward for this nuclide and it is quite incompatible with a negative g -factor.

Figure 17. Li^8 resonance curves. The r.f. field strength, $2H_1$, in gauss, is shown with each curve.

V. DISCUSSION OF RESULTS

A. Measured g-Factor

The experimental value for $g(\text{Li}^8)$, 0.8265, disagrees seriously with the values calculated from either of the two simplest models. For LS coupling, the calculated value is 0.49,⁴⁴ while for extreme j-j coupling one calculates 0.63 if the free nucleon g-factors are used, and 0.69 with the "empirical" g-factors. In the j-j model calculation, both unpaired nucleons are assumed to be in $p_{3/2}$ states. With an intermediate coupling model, Kurath was able to fit the observed value with a strength coefficient which is consistent with the only other mass 8 data.⁴⁵

The observed value of the g-factor is very nearly equal to that of Li^6 , [$g(\text{Li}^6) = 0.8292$], in agreement with the empirical rule that nuclides differing only by two neutrons have nearly the same moments. In this case, Li^6 and Li^8 probably have different spins, 1 and 2, respectively, but the nearly equal g values suggest that the odd nucleons are similarly coupled. The LS value for Li^6 is 0.85 while the extreme j-j value is of course the same as that of Li^8 .

The spin of Li^8 is probably 2,⁴⁶ in which case its magnetic moment is $\mu(\text{Li}^8) = 1.653 \pm 0.001\text{nm}$.

B. Li^8 Capture Channel

Because the ground state polarization is a function of the spins of the capture and ground states, while the beta asymmetry depends on the spin and parity change of the beta transition as well as on ground state polarization, observed asymmetry values may rule out certain spin and parity assignments. In particular, for Li^8 from the level scheme shown in Figure 5 and from the formulas given by Shapiro,⁴⁷ the ground state polarization and beta asymmetry values given in Table 6 are calculable.

TABLE 6.--Nuclear polarization and β -decay asymmetry associated with various spin assignments for the capture channel and ground state of Li^8 produced by the capture of completely polarized neutrons by Li^7 ($J = 3/2$). The sign of the nuclear polarization and β -asymmetry are given relative to the neutron polarization. Values are calculated from the formulas given by Shapiro (Footnote 16).

Ground State Spin	Capture Channel Spin	Capture γ Scheme	Ground State Polarization	β -decay Asymmetry Coefficient α
2	1	$1 \rightarrow 2$ dipole	$- 1/4$	$+ 1/12$
2	2	$2 \rightarrow 2$ dipole	$+ 5/12$	$- 5/36$
3	1	$1 \rightarrow 2 \rightarrow 3$ dipole	$- 2/9$	$+ 2/9$
3	1	$1 \rightarrow 3$ quadrupole	$- 2/9$	$+ 2/9$
3	2	$2 \rightarrow 3$ dipole	$+ 4/9$	$- 4/9$

The sign of the asymmetry was not determined in these experiments but Burgy et al.⁴⁸ have reported it to be negative (relative to the neutron polarization). The actual neutron polarization in these experiments is not well known (see Section 3C), but taking the upper limit of 1.0, the observed asymmetry $\alpha = 0.10$ requires a predominance of capture via the spin 2 channel, a result consistent with that of Burgy et al. Since the GS polarization associated with each of the two possible channels is opposite in sign, one may set an upper limit on the fraction of captures into the spin 1 channel, namely 18 per cent. These remarks are applicable only if the Li^8 GS spin is indeed 2. For spin 3, the range of possibilities is so large that no significant statement can be made.

C. Miscellaneous Considerations

No evidence was found in this work of even the existence of any effect due to nuclear recoil (see Section 2E for a discussion of possible effects). The observed line shapes are at least qualitatively in agreement with those calculated (Section 2D and Figure 6) taking into account the fluctuations of the local field and ignoring the possible production of lattice defects by the recoil process. On the other hand, neither the calculation nor the experiment is very refined in this respect so that the conclusion is very weak.

The observed anisotropy in beta-emission is sufficient

to rule out the creation of paramagnetic centers by ionization in any large fraction ($\geq \frac{1}{2}$) of the captures since such centers would quite certainly relax the Li^8 nuclear polarization and attenuate the observed anisotropy. However, the uncertainties in the data would permit an effect of magnitude 20 per cent. Since the expected ionization is quite small (see Section 2E), the conclusion is again very weak.

Finally, it is interesting to note that only about 20,000 Li^8 nuclei existed at any time during the experiment. A rough calculation indicates that there are not enough neutrons in the reactors of the world to produce sufficient Li^8 for a conventional NMR measurement ($\sim 10^{20}$ atoms/sec) apart from the possible inconvenience of handling 3×10^9 curies of a hard beta-emitter.

D. Possible Future Applications of the Technique

In this work it has been shown experimentally that relatively great nuclear polarization can be produced by the capture of polarized neutrons. It has been demonstrated also that the asymmetry of beta-emission from polarized nuclei may be employed as a useful indicator of nuclear polarization, permitting NMR experiments with extremely small numbers of short-lived nuclei. These effects have been used here to measure the g-factor of Li^8 .

An inspection of the isotope chart suggests that a similar approach should permit the measurement of g-factors

of a considerable number of those short-lived nuclei which may be produced by neutron capture. In addition, it is plausible that many of the techniques of conventional NMR will have analogues in the beta-asymmetry type of measurement. For example, it may be possible to observe the splitting due to electric quadrupole interactions, and thereby measure spins and (relative) quadrupole moments.

Some phenomena in solid state physics also may be observable with advantage by means of the novel technique. By careful study of the line shape versus crystal orientation, it may be possible to measure the fraction of radioactive atoms which are interstitial at the time of decay, thereby providing a direct measure of the relative probability of direct and exchange collisions. The observation of the asymmetry as a function of time could permit some deductions about annealing of the damage associated with the nuclear recoil. To date, no direct measurements of either effect has been possible by any other technique.

Finally since the atoms studied are present in extremely small concentration, the possibility exists of some unusual and fruitful experiments in nuclear magnetic resonance itself, that "laboratory of statistical mechanics", in Bloembergen's phrase. One possible experiment of this class would be the study of relaxation by paramagnetic impurities at concentrations so low that the normal spin diffusion process played no role.

ACKNOWLEDGMENTS

To Professor V. L. Telegdi, who suggested this experiment, I am indebted for his encouragement and advice throughout its course. The support and encouragement of Dr. W. M. Manning made it possible for me to attempt the experiment. Many aspects of the problem were discussed with Professor Fred Reif and Dr. T. B. Novey. Frequent advice from Dr. Roy Ringo on neutron physics techniques was of great value. Discussions with Dr. O. C. Simpson contributed greatly to my understanding of the solid state aspects of the work.

Dr. Martin Studier guided me in the purification of the Li^7F and Mr. Elson Hutchinson taught me how to grow the single crystals used in the experiment. Mr. Niels Hansen generously assisted with many of the measurements. The work could not have been accomplished without the skilled assistance of several divisions of Argonne National Laboratory, particularly Central Shops, Metallurgy, and Reactor Operations.

This work was performed under the auspices of the U. S. Atomic Energy Commission.

APPENDIX

Statistical Error in Asymmetry Coefficient

From (8), Section 2C, we have

$$\frac{1}{2}\alpha = \frac{(1 - \cos\theta_m)}{\sin^2\theta_m} \frac{N_1 - N_2}{N_1 + N_2} \quad (\text{A-1})$$

so that the variance of α ,

$$\frac{1}{4}\sigma^2(\alpha) = \frac{(1 - \cos\theta_m)^2}{\sin^4\theta_m} \sigma^2\left(\frac{N_1 - N_2}{N_1 + N_2}\right) \quad (\text{A-2})$$

but

$$\sigma^2\left(\frac{N_1 - N_2}{N_1 + N_2}\right) = \frac{4N_1N_2}{(N_1 + N_2)^3}$$

and

$$\frac{1}{4}\sigma^2(\alpha) = \frac{(1 - \cos\theta_m)^2}{\sin^4\theta_m} \frac{4N_1N_2}{(N_1 + N_2)^3} \quad (\text{A-3})$$

Using (6),

$$\frac{1}{4}\sigma^2(\alpha) = \frac{(1 - \cos\theta_m)^2}{\sin^4\theta_m} \frac{(1 - \cos\theta_m)^2 - (\alpha/2)^2 \sin^4\theta_m}{N_0(1 - \cos\theta_m)^3}$$

Figure A-1. Relative variance $N_0\sigma^2(\alpha)$ as a function of the counter acceptance angle, θ_m .

REFERENCES

1. W. A. Nierenberg, *Ann. Rev. Nucl. Sci.* 7, 349 (1957).
2. V. W. Cohen in *Recent Research in Molecular Beams*, I. Estermann, Editor. (Academic Press, New York, 1959), pp. 121-144.
3. D. Connor, *Phys. Rev. Letters* 3, 429 (1959).
4. F. Bloch, *Phys. Rev.* 70, 460 (1946).
5. E. M. Purcell, H. C. Torrey, and R. V. Pound, *Phys. Rev.* 69, 37 (1946).
6. C. S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, *Phys. Rev.* 105, 1413 (1957).
7. M. T. Burgy, W. C. Davidon, T. B. Novey, G. J. Perlow, and G. R. Ringo, *Bull. Am. Phys. Soc.* 2, 206 (1957).
8. For a general discussion of neutron polarization techniques, see D. J. Hughes, *Pile Neutron Physics*, (Addison-Wesley Publishing Company, Inc., Cambridge, Mass., 1953), pp. 319-326.
9. See, for example, G. Trumpy, *Nucl. Phys.* 2 664 (1956).
10. C. G. Shull, *Phys. Rev.* 81, 626 (1951), also C. G. Shull, E. O. Wollan and W. C. Koehler, *Phys. Rev.* 84, 912 (1951).
11. G. E. Bacon, *Neutron Diffraction*, (Oxford University Press, Oxford, England, 1955), pp. 245-265.
12. See Reference 8, pp. 301-306.
13. M. Hamermesh, *Phys. Rev.* 75, 1766 (1949), also Argonne National Laboratory Report No. ANL-4298, May 12, 1949 (unpublished).
14. D. J. Hughes and M. T. Burgy, *Phys. Rev.* 81, 498 (1951).

15. See, for example, J. M. Blatt and V. F. Weisskopf, Theoretical Nuclear Physics, (John Wiley & Sons, New York, 1952), pp. 789-792.
16. F. D. Shapiro, Uspekhi Fiz. Nauk 65, 133 (1958). Translation available as AEC-tr-3965.
17. E. J. Konopinski, Ann. Rev. Nucl. Sci. 9, 99 (1959).
18. The treatment given here closely follows that of G. E. Pake, Solid State Physics, edited by F. Seitz and D. Turnbull (Academic Press, Inc., New York, 1956), Vol. 2, p. 1.
19. I. I. Rabi, N. F. Ramsey, and J. Schwinger, Rev. Mod. Phys. 26, 167 (1954).
20. F. Bloch and A. Siegert, Phys. Rev. 57, 522 (1940).
21. See, for example, line shape measurements on LiF by F. J. Low and C. F. Squire, J. Phys. Chem. Solids 5, 85 (1958).
22. See Reference 18, p. 14.
23. See Reference 18, pp. 15-19.
24. R. T. Schumacher, Phys. Rev. 112, 837 (1958).
25. P. S. Pershan, Phys. Rev. 117, 109 (1960).
26. R. V. Pound, Phys. Rev. 79, 685 (1950).
27. J. van Kranendonk, Physica 20, 781 (1954).
28. N. Bloembergen, Physica 25, 386 (1949).
29. W. E. Blumberg, Phys. Rev. 119, 79 (1960).
30. F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. 11, 1 (1959).
31. G. J. Dienes and G. H. Vineyard, Radiation Effects in Solids, (Interscience Publishers, Inc., New York, 1957), pp. 18-27.
32. M. T. Burg, V. E. Krohn, T. B. Novey, G. R. Ringo and V. L. Telegdi, Phys. Rev. 120 (1960) (In Press).
33. R. M. Bozorth, Ferromagnetism (D. Van Nostrand, Princeton, New Jersey, 1951), p. 194.

34. See Reference 8.
35. V-4012A 12 inch Electromagnet, manufactured by Varian Associates, Palo Alto, California.
36. Netic and Co-Netic foil, manufactured by Magnetic Shield Division, Perfection Mica Company, Chicago, Illinois.
37. R. V. Pound, Phys. Rev. 81, 156 (1951).
38. The general procedure followed was very similar to that given by W. C. Dietrich and R. E. Barringer, Report No. Y-1254 (Union Carbide Nuclear Company, Oak Ridge, June 16, 1959).
39. See Reference 7.
40. T. B. Novey, private communication.
41. See Reference 32.
42. See Reference 8, p. 323.
43. H. Kopfermann, Nuclear Moments, (Academic Press, Inc., New York, 1958), p. 451.
44. M. E. Rose and H. A. Bethe, Phys. Rev. 51, 205 (1937).
45. D. Kurath, Phys. Rev. Letters 3, 431 (1959).
46. See Reference 30, also T. Lauritsen, C. A. Barnes, W. A. Fowler, and C. C. Lauritsen, Phys. Rev. Letters 1, 326 (1958).
47. See Reference 16.
48. See Reference 7.