Magnetic Moment of $^{17}$F
— Nuclear Magnetic Resonance by Polarization
Following $^{16}(d, n)^{17}$F Reaction —

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The nuclear magnetic resonance of $^{17}$F ($T_{1/2}=66$ sec) has been observed using the polarization of recoil nuclei produced by the reaction $^{16}(d, n)^{17}$F and the $\beta$-decay anisotropy as the indicator of the polarization. The accomplishment of the experiment was essentially due to the persistence of the polarization by specific experimental methods, i.e., the use of a strong magnetic field ($\gtrsim 5$ kG) in the direction of polarization and the use of pure CaF$_2$ crystals as the stopping material of recoil ions. The observed asymmetry of $\beta$-counting was about 2% and a spin relaxation time $T_1$ comparable to the half-life of $^{17}$F was observed. The value obtained of the magnetic moment of $^{17}$F is $\mu=4.7224\pm0.0012$ nm with the diamagnetic correction.

§ 1. Introduction

An experiment to determine the magnetic moment of the short-lived $\beta$-radioactive nucleus, whose lifetime is shorter than a minute, has been considered extremely difficult because of the shortness of the overall detection sensitivity by the available technique. A new detection technique of polarization, however, has been developed recently by using the $\beta$-decay anisotropy due to the parity violation in weak interaction. This technique was introduced by Connor in nuclear magnetic resonance (NMR) experiment by polarized neutron capture, and by Commins and Dobson in atomic beam experiment. If one can combine the nuclear polarization possibly produced by nuclear reactions with the newly developed detection technique, NMR of the short-lived radioactive nucleus hitherto inaccessible may be observed. Chase and Igo suggested such a possibility in a report of their trial to observe the nuclear polarization of recoil by the reaction $^{11}(d, p)^{12}$. In the present paper, a result of a NMR experiment using the polarization of recoil nuclei produced by the reaction $^{16}(d, n)^{17}$F and the $\beta$-decay anisotropy is described. The nucleus $^{17}$F, whose spin and parity are $5/2^+$, decays to the nucleus $^{17}$O with the half-life of 66 sec by positron emission of the maximum energy 1.75 MeV. According to the shell model, the nucleus $^{17}$F, the mirror nucleus of $^{17}$O, consists of the doubly closed shell of $^{16}$O with extra one nucleon. And the determination of the magnetic moment is interesting especially because of the mirror theorem due to Sachs.

A brief report on the present result has been published previously.

§ 2. Experimental

The present experimental method is schematically shown in Fig. 1. A beam of 2.3 MeV deuterons was incident on a thin target of SiO$_2$ to produce the nuclei $^{17}$F by the reaction $^{16}(d, n)^{17}$F. The recoil ions of $^{17}$F emerged from the target in a defined reaction angle, deposited on a recoil stopper. Some degree of polarization of recoil nuclei can be expected in the direction perpendicular to the reaction plane. If the polarization expected is preserved until $\beta$-emission, an asymmetric distribution of $\beta$-particles in the direction of polarization is observable. The asymmetry can be used as an indicator of polarization. A static magnetic field $H$ perpendicular to the reaction plane crossed by a weak radio-frequency (rf) field $H_1 \cos \omega t$ was applied. When the resonance condition is fulfilled as

$$\omega = \frac{\mu H}{I \hbar}, \quad (1)$$

where $\mu$ and $I$ are the magnetic moment and the spin of $^{17}$F, radio-frequency transitions between Zeeman levels are induced and the asymmetry of $\beta$-decay is reduced. A NMR experiment was performed in this way. The dependence of polarization on the radio frequency transition is discussed in the Appendix.
2.1. $\beta$-decay anisotropy

In the case of allowed transition, the angular distribution of $\beta$-particles from polarized nuclei is given\(^7\) by

$$W(\theta) = 1 + \frac{\langle I_z \rangle I}{l} \frac{v/c}{c} \alpha \cos \theta,$$

(2)

where $\theta$ is the angle between the direction of electron emission and the polarization axis, $\langle I_z \rangle I$ is the degree of nuclear polarization and $v/c$ is the electron velocity versus the light velocity. $\alpha$ is the anisotropy factor which depends on the relevant matrix elements and the value for the $\beta$-decay of F\(^{17}\) was estimated to be $\alpha \approx 0.99$ by using single-particle model.

Under the present experimental condition with the strong magnetic field, the effective solid angle of $\beta$-detection was nearly $2\pi$ steradian. The asymmetry $\mathbf{\mathcal{A}}$ of $\beta$-counting of the upper and the lower detectors was approximated by

$$\mathbf{\mathcal{A}} = \frac{W_U}{W_L} - 1 = \frac{\alpha}{1 - \alpha/2},$$

(3)

where $W_U$ and $W_L$ are the upper and the lower counting rates, and $\alpha = \langle I_z \rangle I (v/c) \alpha_0$.

2.2. Persistence of the nuclear polarization

In order to accomplish the present experiment, it was an indispensable condition to persist the polarization of F\(^{17}\) in the recoil stopper until $\beta$-emission. Various kinds of depolarization interactions operated successively during the lifetime of F\(^{17}\). In the following, detailed considerations to minimize these interactions are discussed.

a) Hyperfine coupling at the initial stage

The recoil ions of F\(^{17}\) are in various charge states when they are emitted from the target. Thus, the hyperfine coupling due to unpaired electrons and holes in the electronic shell is operative until a settlement in a stable state. The coupling can destroy the polarization considerably, but it may be decoupled by a strong magnetic field ($\gtrsim 5$ kG) parallel to the polarization axis.\(^8\)

b) Static quadrupole interaction

Because the spin of F\(^{17}\) is $5/2$, a coupling between the quadrupole moment of F\(^{17}\) and a possible electric field gradient can reduce the polarization. If a cubic symmetrical crystal is used as a stopping material and the recoil ion is trapped in a normal site of the crystal, any static field gradient dose not arise so that the static quadrupole interaction can be avoided. CaF\(_2\) crystals were used for the present experiment. If the recoil ion is trapped in an interstitial position of the crystal, the polarization can be destroyed by the quadrupole interaction. In this respect, it was estimated that about 50% of recoil ions were trapped in normal sites for the case of CaF\(_2\). The estimation was based on the results of angular correlation experiments on the second excited state of F\(^{19}\) by inelastic scattering of protons.\(^9\)

c) Spin relaxation due to thermal lattice vibration

For the longer period, one should consider the spin relaxation\(^10\) due to thermal lattice vibration. Both electric and magnetic interactions are active in this relaxation mechanism. As for the magnetic interaction, it has been shown by Bloembergen\(^11\) that paramagnetic impurities reduce the
spin relaxation time $T_1$ in the case of ionic crystal. To make the relaxation time long enough, the purity of the CaF$_2$ crystal is important and natural colourless crystals were used. One preferable aspect of the present type of experiment is that the polarized nucleus has a different spin and magnetic moment from those of the surrounding nuclei so that the spin diffusion process does not effective.

Consequently, the polarization was preserved long enough to accomplish the resonance experiment by the use of CaF$_2$ and a strong magnetic field. In the practice of the experiment, however, deterioration phenomena of recoil stoppers were encountered, i.e., the $\beta$-decay asymmetry decreased rather suddenly after a certain period of measurement. No definite interpretation was made for this phenomenon, but a possible cause might be the pile-up of paramagnetic disorders due to the radiation damage by the energetic recoil ions.

2.3. Equipment

The endothermic reaction O$^{16} (d, n)$ F$^{17}$ with $Q = -1.63$ MeV was induced by 2.3 MeV deuterons from the electrostatic generator at Osaka University. Kinematically, nuclei F$^{17}$ produced recoil with the energy of $300 \sim 400$ keV in the direction less than $18^\circ$ with respect to the incident deuterons. The target chamber is shown in Fig. 2. The chamber was mounted in the pole gap of a magnet whose pole diameter and gap width were 25 cm and 6 cm. A thin film of fused qualtz whose thickness was about 120 $\mu$g/cm$^2$ was used as the oxygen target. A collimator, two pairs of diaphragms between the target and the recoil stopper, defined the recoil angle but it was difficult to estimate the effective angle because the flight paths of deuterons and recoil ions were curved by the strong magnetic field. The detector assembly, i.e., the recoil collimator, the recoil stopper and a pair of solid-state detectors, was movable around the target by a sliding-membrane mechanism. The recoil stopper was inserted between the separate windings of a rf solenoid.

Fig. 2. An exploded view of the target chamber and the detector assembly by removing the upper magnet pole. The detector assembly, i.e., the recoil collimator, the recoil stopper and a pair of solid-state detectors, was movable around the target by a sliding-membrane mechanism. The recoil stopper was inserted between the separate windings of a rf solenoid.

To obtain a high purity of the stopping material, the preparation was carried out carefully using natural colourless crystals. The observed $\beta$-decay asymmetry was different for each stopper depending on the unknown condition during the preparation. The recoil stopper was necessary to be changed after a period of 1~4 hours of normal use because of the deterioration phenomena.

The $\beta$-particles were measured with a pair of Li-drifted solid-state detectors whose sensitive area and depth were 1 cm $\times$ 1 cm and 1.5 mm. The output pulses corresponded to the energy more than 500 keV were counted. It was necessary to separate the counting period from the beam bombardment because of the high intensity background. Figure 3 shows a time spectrum of $\beta$-counting after a 20 sec beam bombardment. The decay-time of the spectrum was well identified as that of F$^{17}$. There were small back-
ground contributions of a short-lived and a constant component.

In the normal procedure, the counting cycle was as follows: The deuteron beam was controlled by a mechanical beam shutter to bombard the target with a 20 sec duration and a 120 sec repetition period. The β-counting started at 10 sec after the beam bombardment to reduce the contribution of the short-lived background. The counting period was 90 sec. This procedure made possible to measure the intensity of β-particles from F^{17} with a small background contribution of less than 1%.

2.4. Preliminary experiment

In the first step of the experiment, it was necessary to observe the evidence of the polarization of F^{17}, i.e., the anisotropic distribution of β-particles. For this purpose, a special detector assembly in which a pair of detectors and the recoil stopper were separately rotative around an axis of the direction of recoil, was used. The method of observation and a result on a series of measurements are shown in Fig. 4. In this method, the instrumental effects due to the difference of detection efficiencies between the upper and the lower detectors and the asymmetrical absorption of the stopper were cancelled. The asymmetry measured was still contributed by an instrumental one besides the asymmetry of β-decay. As a null test, a Teflon foil was used for the recoil stopper. It was then, expected that the polarization was completely reduced and only the instrumental asymmetry was left. The asymmetry observed in the case of CaF_{2} was different from that of Teflon and revealed a time dependent character. It was a clear evidence of the polarization. A consistent result was obtained under the condition with the reversed reaction angle.

The next step was to search for NMR. At the initial search for resonance, the rf field whose frequency was modulated 0.5% at 60 cps was used. The ratio of counting rates of the upper and the lower detectors was observed as a function of the magnetic field strength. An

\[ (R^2) = R_1 R_2 R_3 R_4 = \gamma^4 \]

* The CaF_{2} crystals used in this stage was slightly coloured and the relaxation time observed was shorter than that in the final NMR experiment.
observation was carried out at the magnetic field of 9.4 kG and the result is shown in Fig. 5. The resonance was confirmed by the succeeded measurements at 5.5 kG and 8.3 kG. The value of the magnetic moment $\mu = 4.72 \pm 0.01 \text{ nm}$ was obtained preliminarily.

Prior to the final NMR experiment, the dependences of the asymmetry of $\beta$-counting on the incident beam energy ($E_d = 2.2 \sim 2.5 \text{ MeV}$), on the angular position of the recoil stopper and on the bias setting of the $\beta$-detector were examined. No notable dependence on the beam energy and the recoil angle was observed, so that these conditions were determined with considerations for the counting rate and the background. The dependence of the asymmetry on the bias setting of the $\beta$-detector is shown in Fig. 6 together with the pulse-height spectrum. The bias setting used was determined empirically from the result.

2.5. Final NMR experiment

Since the observed $\beta$-decay asymmetries varied with each recoil stopper and the deterioration phenomena were unavoidable, a special procedure of the data accumulation was employed in the final NMR experiment. In order to measure the $\beta$-decay asymmetry at a certain strength of the magnetic field $H$ with a fixed rf field, three couples of the counting rates of the upper and the lower detectors were measured successively with the magnetic field setting at $H$, $H_a$ and $H_b$. $H_a$ was a point on the resonance determined by the preliminary experiment and

![Graph](image)

Fig. 5. A result of the preliminary resonance experiment to search for NMR with frequency-modulated rf field. The horizontal line and the hatched zone indicate the average and its uncertainty of the counting-rate ratios except the ratio on resonance.

![Graph](image)

Fig. 6. The pulse-height dependence of the asymmetry of $\beta$-decay and the pulse-height spectrum of $\beta$-counting. Signals from detectors corresponded to the energy more than 500 keV were counted in the final NMR experiment. $H_b$ was a point far off the resonance. $H_a$ and $H_b$ were trial fixed points in a series of measurement and the relative asymmetry $\mathcal{R}(H)$ at each value of $H$ was obtained by

$$\mathcal{R}(H) = \frac{N_d(H_a)/N_d(H_b) - N_d(H_b)/N_d(H_a)}{N_d(H_a)/N_d(H_b)} - N_d(H_a)/N_d(H_b), \quad (4)$$

where the counting rates of the upper and the lower detectors at a magnetic field $H$ are denoted by $N_d(H)$ and $N_d'(H)$. The asymmetry $\mathcal{A}_N$ for each stopper was obtained from the measurement at $H_a$ and $H_b$

$$\mathcal{A}_N = \frac{N_d(H_b)/N_d(H_b) - N_d'(H_a)/N_d'(H_a)}{N_d(H_a)/N_d'(H_b)}. \quad (5)$$

$\mathcal{A}_N$ was smaller than the asymmetry $\mathcal{A}$ in general, but the difference was found to be negligible from the results of the final measurement. By this procedure, it was possible to combine the results with different magnitudes of $\beta$-decay asymmetries and to monitor the asymmetry during the measurement. As a byproduct, an information on the relaxation time $T_1$ was obtained. For this purpose, a pair
Table I. Experimental condition and result of the final NMR experiment on F\textsuperscript{17}.

<table>
<thead>
<tr>
<th></th>
<th>Run I</th>
<th>Run II</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_{ef} ) ( )</td>
<td>12.380 Mc/s</td>
<td>12.010 Mc/s</td>
</tr>
<tr>
<td>( H_{i} ) ( )</td>
<td>( \sim 30 \text{ mG} )</td>
<td>( \sim 30 \text{ mG} )</td>
</tr>
<tr>
<td>( f_{po} ) ( )</td>
<td>36.630 Mc/s</td>
<td>35.528 Mc/s</td>
</tr>
<tr>
<td></td>
<td>( \pm .005 )</td>
<td>( \pm .008 )</td>
</tr>
<tr>
<td>Correction Factor for Field Calibration</td>
<td>( \sim (8.60 \text{ kG}) )</td>
<td>( \sim (8.35 \text{ kG}) )</td>
</tr>
<tr>
<td>( \mu ): Magnetic Moment without Diamagnetic Corr.</td>
<td>1.00008</td>
<td>1.00002</td>
</tr>
<tr>
<td></td>
<td>( \pm .00005 )</td>
<td>( \pm .00005 )</td>
</tr>
<tr>
<td></td>
<td>4.7196 nm</td>
<td>4.7203 nm</td>
</tr>
<tr>
<td>Correction Factor for Diamagnetism</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \mu ): with Diamagnetic Corr.</td>
<td>1.0005 ( \pm .0001 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.7224 ( \pm .0012 \text{ nm} )</td>
<td></td>
</tr>
</tbody>
</table>

* Allowances were made to the error indicated for possible systematic contributions.

of scalers operated during initial 30 sec of the counting period was provided besides a pair of scalers of the normal counting cycle.

Two series of measurements were performed whose experimental conditions and values determined are listed in Table I, and the resonance observed is shown in Fig. 7. The value \( \bar{\alpha}_{N} \) ranged from 1.5 to 2.5% by these measurements. The relaxation time \( T_{1} \) was about 80 sec on the average. It was notable that such a long relaxation time was obtained at room temperature.

As stated in the previous section (2.2), it might be attributed to the absence of the spin diffusion process and the pureness of the \( \text{CaF}_{2} \) crystals used.

Despite of the clear evidence of the polarization and the successful utilization for the magnetic moment measurement, a reliable estimation of the initial degree of polarization was difficult because of the lack of knowledge about depolarization effects. An estimation of the initial polarization was made to be about 8% under the assumptions that about 50% of the polarized nuclei were depolarized in the initial stage as discussed in the previous section (2.2) and that the asymmetry of \( \beta \)-counting was approximated by the eq. (3). The direction of the polarization was \( (K_{d}\times K_{R})/(K_{d}\cdot K_{R}) \), where \( K_{d} \) and \( K_{R} \) are the wave number vectors of deuterio and recoil nucleus. As the recoil ions were concentrated in the forward direction, the magnitude and the direction of polarization thus obtained were averages over a wide reaction angle.

§ 3. Result

The most probable resonance curve shown in Fig. 7 was determined from the experimental points by the method described in the Appendix. The values determined are listed in Table I. The magnetic moment of \( \text{F}^{17} \) without the diamagnetic correction was determined to be

\[
\mu(\text{F}^{17}, 5/2^+) = 4.7200 \pm 0.0011 \text{ nm (uncorrected)}.
\]

The correction factor for diamagnetism was estimated from the calculated values for the atomic state by Dickinson.\textsuperscript{12} Since \( \text{F}^{17} \) was ionic in \( \text{CaF}_{2} \), the second order term of the correc-

![Fig. 7. Experimental data of NMR of F\textsuperscript{17}. The relative asymmetries \( \alpha(H) \) versus the magnetic field strength in units of proton-resonance frequency are plotted with the statistical errors. The curves drawn are the best fits of the resonance shapes calculated with appropriate parameters. The points denoted by \( a \) and \( b \) are the trial fixed points in a series of measurements as discussed in the text.](image-url)
tion could be neglected and the correction factor might be larger than the value for the atomic state of $Z=9$ but smaller than that for $Z=10$. The correction factor $\delta = 0.0005 \pm 0.0001$ was used accordingly. The final value of the magnetic moment of $^{17}$F was

$$\mu(\text{F}^{17}, 5/2^+) = 4.7224 \pm 0.0012 \text{ nm}$$ (corrected).

This value is about 1.5% smaller than the Schmidt value $\mu_s = 4.793 \text{ nm}$.

The study of the magnetic dipole moments of mirror nuclei is considered important from both viewpoints, i.e., the study of nuclear structure and the study of magnetic moment operator. Sachs pointed out that the sum of the magnetic moment of a mirror pair should be free from the contribution of meson currents in consequence of the charge symmetry of nuclear forces and the value is useful to find a wave function. The magnetic moments and the sum moments of mirror pairs available at present are tabulated in Table II. Fairly good agree-

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>$J, \pi$</th>
<th>$\mu_B$</th>
<th>Ref.</th>
<th>$\mu_S$</th>
<th>$\mu_B - \mu_S$</th>
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<tr>
<td>H$^4$</td>
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<td>2.9789</td>
<td>a</td>
<td>2.793</td>
<td>0.186</td>
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<tr>
<td>He$^4$</td>
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<td>-2.1276</td>
<td>a</td>
<td>-1.913</td>
<td>-0.215</td>
</tr>
<tr>
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<td></td>
<td>0.880</td>
<td>-0.029</td>
</tr>
<tr>
<td>B$^{11}$</td>
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<td>2.6885</td>
<td>a</td>
<td>3.793</td>
<td>-1.104</td>
</tr>
<tr>
<td>C$^{11}$</td>
<td>3/2$^-$</td>
<td>-1.027  $\pm 0.10$</td>
<td>b</td>
<td>-1.913</td>
<td>0.886</td>
</tr>
<tr>
<td>Sums</td>
<td></td>
<td>1.662</td>
<td></td>
<td>1.880</td>
<td>-0.218</td>
</tr>
<tr>
<td>C$^{13}$</td>
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<td>0.7024</td>
<td>a</td>
<td>0.638</td>
<td>0.064</td>
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<tr>
<td>N$^{13}$</td>
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<td>-0.3221 $\pm 0.0035$</td>
<td>c</td>
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<td>-0.058</td>
</tr>
<tr>
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<td>N$^{15}$</td>
<td>1/2$^-$</td>
<td>-0.2830 $\pm 0.00007$</td>
<td>d</td>
<td>-0.264</td>
<td>-0.019</td>
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<tr>
<td>O$^{15}$</td>
<td>1/2$^-$</td>
<td>0.7189  $\pm 0.008$</td>
<td>e</td>
<td>0.638</td>
<td>0.081</td>
</tr>
<tr>
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<td></td>
<td>0.374</td>
<td>0.062</td>
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<td>O$^{17}$</td>
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<td>-1.8937</td>
<td>a</td>
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<td>0.019</td>
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<tr>
<td>F$^{17}$</td>
<td>5/2$^+$</td>
<td>4.7224  $\pm 0.012$</td>
<td>f</td>
<td>4.793</td>
<td>-0.071</td>
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<tr>
<td>Sums</td>
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<td></td>
<td>2.880</td>
<td>-0.052</td>
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<tr>
<td>F$^{19}$</td>
<td>1/2$^+$</td>
<td>2.6283  $\pm 0.00005$</td>
<td>d</td>
<td>2.793</td>
<td>-0.165</td>
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<tr>
<td>Ne$^{19}$</td>
<td>1/2$^+$</td>
<td>-1.886   $\pm 0.001$</td>
<td>g</td>
<td>-1.913</td>
<td>0.027</td>
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<td>0.880</td>
<td>-0.138</td>
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<tr>
<td>Ne$^{21}$</td>
<td>3/2$^+$</td>
<td>-0.6617  $\pm 0.00005$</td>
<td>h</td>
<td>1.148</td>
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<tr>
<td>Na$^{21}$</td>
<td>3/2$^+$</td>
<td>2.3862  $\pm 0.0010$</td>
<td>i</td>
<td>0.124</td>
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<tr>
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<td></td>
<td>1.272</td>
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<tr>
<td>Cl$^{35}$</td>
<td>3/2$^+$</td>
<td>0.8216</td>
<td>a</td>
<td>0.124</td>
<td></td>
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<tr>
<td>Ar$^{35}$</td>
<td>3/2$^+$</td>
<td>0.632   $\pm 0.002$</td>
<td>j</td>
<td>1.148</td>
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<tr>
<td>Sums</td>
<td></td>
<td>1.454</td>
<td></td>
<td>1.272</td>
<td></td>
</tr>
</tbody>
</table>

a) G. H. Fuller and V. W. Cohen: *Table of Rounded-Off Values in Nuclear Moments*, Appendix 1 to *Nuclear Data Sheets* (1965), p. 3.


f) Present result.

g) See ref. 2.


j) F. P. Calaprice, E. D. Commins and D. A. Dobson: Phys. Rev. 137 (1965) B1453,
ments of the sum moments as well as the individual moments to the Schmidt values can be seen in the cases of $A=15$ and $17$. The residual small deviations of sum moments may be responsible for the unfitness of the single particle wave function,\(^{10}\) and for the effect of the spin-orbit interaction on the magnetic moment. Several analyses on the mesonic effect\(^{14}\) have been made but it seems too early to make any conclusion quantitatively.

Acknowledgement

The authors wish to thank Professor T. Waketsumi and Professor S. Yamabe for their encouragement throughout this work and also to Professor J. Kanamori for his discussions about the depolarization mechanism. They thank to Mr. Y. Takahashi for his technical assistance and to Miss Y. Nakanishi for her assistance. One of authors (K.N.) is indebted to the Sakkokai Foundation for support.

Appendix  Resonance Line Shape and the Method of Data Fitting

1. Radio frequency transition

A polarization $P_z=\langle I_z \rangle$ of nuclei with magnetic moment $\mu$ induces a magnetization $M_z$ parallel to the polarization axis as

$$M_z = \mu n P_z, \quad (A.1)$$

where $n$ is the number of nuclei per unit volume. When unstable nuclei with polarization $P_z=P_0$ are produced $q$ nuclei per unit volume per unit time and a static field $H$ together with a weak rf field $H_1 \cos \omega t$ is applied, the magnetization $M_z$ shows a behaviour given by the following equation\(^{10}\)

$$\dot{M}_z = \mu q P_0 - M_z \left[ \lambda + A + \pi \gamma H_1^2 f(\omega) \right], \quad (A.2)$$

where $\lambda, A=1/T_1$ and $\gamma$ are the decay constant, the reciprocal of the spin relaxation time $T_1$ and the gyromagnetic ratio.* $f(\omega)$ is the line shape function and can be approximated by either Lorentzian or Gaussian function for solid. In the present case, the nuclei $F^{17}$ ($\gamma=1440$ cps/G) are surrounded by $F^{19}$ ($\gamma=4007$ cps/G), so that the Lorentzian type is suitable;

$$f(\omega) = \frac{1}{\pi} \frac{\delta}{\omega^2 + (\omega - \omega_0)^2}, \quad (A.3)$$

where $\delta$ is a width parameter.

* Equation (A-2) is applicable under the condition that $P_0$ is a polarization after a settlement of initial depolarization interactions and the relaxation time can be approximated by a unique value $T_1$.

The density of nuclei $n$ is given by

$$n = q - \lambda n. \quad (A.4)$$

To obtain a polarization for the present experiment, equations (A.2) and (A.4) were integrated over the time intervals of production ($t_1$), cooling ($t_2$) and counting ($t_3$). The time dependences of the magnetization $M_z$ and the density $n$ are shown in Fig. 8, and the values at each time are as follows:

$$M_z(t) = \frac{\mu q P_0}{[L]} \left[ 1 - \exp \left( -\frac{[L]}{T_1} \right) \right],$$

$$n(t) = \frac{q}{\lambda} \left[ 1 - \exp \left( -\frac{\lambda t_3}{T_1} \right) \right] \left[ 1 - \exp \left( -\frac{\lambda t_2}{T_1} \right) \right]. \quad (A.5)$$

The dependence of polarization on rf transition is represented by

$$P = \frac{\int_{t_0}^{t_3} \left( M_z(t) \langle m(t) \rangle \right) \exp \left( -\lambda t \right) dt}{\int_{t_0}^{t_3} \exp \left( -\lambda t \right) dt}$$

$$= \frac{P_0 2^8 \left[ 1 - \exp \left( -\frac{[L]}{T_1} \right) \right] \exp \left( -\frac{[L]}{T_2} \right) \left[ 1 - \exp \left( -\frac{\lambda t_1}{T_1} \right) \right] \exp \left( -\frac{\lambda t_2}{T_1} \right)}{[L]^5 \left[ 1 - \exp \left( -\frac{[L]}{T_1} \right) \right] \exp \left( -\lambda t_2 \right)} \times \left[ \frac{1 - \exp \left( -\frac{[L]}{T_1} \right)}{1 - \exp \left( -\frac{\lambda t_2}{T_1} \right)} \right]. \quad (A.6)$$

2. Method of data fitting

For the purpose of data fitting, a theoretical expression for the relative asymmetry $B_r(H)$

\[ BEAM \quad ON \]
\[ COUNTING \]
\[ t_1 \quad t_2 \quad t_3 \]
\[ M_z \quad M_{z2} \quad M_{z3} \]
\[ n_1 \quad n_2 \quad n_3 \]
\[ M_z(t) \]
\[ 0 \quad \rightarrow \quad t \]

Fig. 8. The time dependences of the magnetization $M_z$ and the density $n$. 

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\[ n_1 \quad n_2 \quad n_3 \]
\[ M_z(t) \]
\[ 0 \quad \rightarrow \quad t \]

Fig. 8. The time dependences of the magnetization $M_z$ and the density $n$. 

For the purpose of data fitting, a theoretical expression for the relative asymmetry $B_r(H)$
was calculated from the eq. (A·6). The two parameters, the width and the center of resonance, should be adjusted. The parameter adjustment was carried out to minimize the value

\[ Q = \sum \left( \frac{\Delta \mathcal{R}_\theta(H_k) - \mathcal{R}_\tau(H_k)}{\Delta \mathcal{R}_\theta(H_k)} \right)^2 \]  

(A·7)

where \( \mathcal{R}_\theta(H_k) \) and \( \Delta \mathcal{R}_\theta(H_k) \) are the relative aspects and its uncertainty observed, and \( \mathcal{R}_\tau(H_k) \) is the theoretical value with trial parameters. A typical example of parameter adjustment is shown in Fig. 9.

**References**
