Measurement of the magnetic dipole moment of β-emitting ^{25}Al by use of a polarized proton beam and nuclear magnetic resonance detection*

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(Received 5 April 1976)

Polarized β-emitting ^{25}Al nuclei ($I^{\pi} = 5/2^+$, $T_{1/2} = 7.2$ sec) were produced in the reaction ^{28}Si($\vec{p}$,α)^{25}Al in a thick single crystal of Si which served as host for the implanted ^{25}Al nuclei. The net polarization transferred to the ^{25}Al nuclei was detected by measuring the asymmetry in the β-decay. The magnetic dipole moment of ^{25}Al was measured by nuclear magnetic resonance destruction of the polarization. Including the diamagnetic correction, we obtain $\mu = [3.6455(12)]\mu_N$.

[RADIOACTIVITY Polarized ^{25}Al from ^{28}Si($\vec{p}$, α); measured β asymmetry, polarization transfer, relaxation time T_1, NMR; ^{25}Al deduced magnetic moment μ. Natural thick target, magnetic fields, plastic scintillators.]

In previous experiments[1,2] it has been demonstrated that the net polarization transfer to the product nuclei in ($\vec{d}$,p), ($\vec{d}$,n), and ($\vec{p}$,n) reactions can be as large as 10% with a production rate of $10^3 \rightarrow 10^4$/sec for a thick target and incident beam intensity of 10 nA. In the present experiment the ($\vec{p}$, α) reaction was employed to produce polarized ^{25}Al nuclei and, as in the earlier work, an NMR measurement of the destruction of the polarization was used to determine the magnetic dipole moment of ^{25}Al.

The experimental arrangement was essentially the same as before.[1,2] The β-emitting ^{25}Al nuclei ($I^{\pi} = \frac{5}{2}^+$, $T_{1/2} = 7.2$ sec) were polarized in the reaction ^{28}Si($\vec{p}$, α)^{25}Al initiated with polarized protons from the Stanford tandem Van de Graaff accelerator. The polarization of the beam ($P_z = 0.65$) was perpendicular to the beam direction. In the thick Si target (single crystal: $t \approx 150$ mg/cm and $\rho \approx 100$ Ω cm) the reaction yield was integrated over all proton energies up to the incident beam energy and over all recoil angles of the implanted nuclei.

A significant fraction of the recoil nuclei were expected to find substitutional sites[3] in the Si lattice, which has a cubic structure. A magnetic field $H_0 = 4.6$ kG applied along the polarization axis, was sufficient to maintain the ^{25}Al polarization, which was detected by measuring the asymmetry in the β decay with two particle telescopes placed at 0° (up) and 180° (down) to H_0. By means of a mechanical chopper, the beam was pulsed to produce a 4 sec beam irradiation, followed by an 8 sec counting period. The proton polarization was reversed every cycle.

An rf magnetic field was applied during the beam period and continued for a subsequent period of 300 msec. Counting was initiated immediately after the rf field was turned off. The β-decay asymmetry, $2(r-1)/(r+1)$, was observed, where r is the up-down counting ratio for proton polarization down divided by the ratio with proton polarization up. The β counts were multiscaled as a function of time, thus allowing both the β-decay lifetime and the time dependence of the asymmetry to be measured.

Since natural silicon is composed of ^{28}Si (92.2%), ^{29}Si (4.7%), and ^{30}Si (3.1%), the proton beam (E_p = 12 MeV) initiated the reactions ^{28}Si($\vec{p}$, α)^{25}Al ($T_{1/2}$ = 7.2 sec), ^{29}Si($\vec{p}$, n)^{29}P ($T_{1/2}$ = 4.2 sec), ^{30}Si($\vec{p}$, n) ^{30}P ($T_{1/2}$ = 150 sec), and ^{29}Si($\vec{p}$, α)^{26}Al ($T_{1/2}$ = 6 sec), all of which produce implanted β emitters in the thick Si target. The relative yield of β particles from each of the products was determined from the lifetime data to be 20% (^{25}Al), 41% (^{29}P), 39% (^{30}P), and $\ll$1% (^{26}Al). In addition to being negligible, the β decay from ^{26}Al ($I = 0$) is isotropic, so it makes no contribution to the β asymmetry. The asymmetry contributed by the β decay of ^{30}P was also expected to be negligibly small because the ^{30}P half-life is much longer than the beam repetition period. Only 3% of the β particles detected in any counting period were emitted by "fresh" ^{30}P (produced in the immediately preceding beam period) and thus, 36% of the β particles detected in any counting period were emitted by "stale" ^{30}P which had lost polarization by relaxation mechanisms. Analysis of the multiscaling data is consistent with the expection that only ^{25}Al and ^{29}P contribute to the β-decay asymmetry.

In the NMR measurement a modulated rf field H_1 of strength $0.5 \rightarrow 1$ G was applied in the presence of the static magnetic field $H_0 = 4.6$ kG. Two NMR lines were observed corresponding to g factors of 1.45(1) and 2.472(6), as shown in Figs. 1(a) and 1 (b). Off resonance the asymmetry was 2.1%; the first resonance destroyed 0.6% of the asymmetry and the second resonance 1.5%. Therefore, we conclude that the total asymmetry is due to two ensembles of polarized nuclei. Sugimoto, Mizobuchi, and Minamisono[4] have reported a value of $g = 2.4698(6)$ for $^{29}P(I=\frac{1}{2})$; thus, the "1.5% resonance" can be identified with ^{29}P. The "0.6% resonance" with $g \approx 1.5$ can then be attributed uniquely to ^{25}Al, especially since this value of g is close to that estimated by assuming that the spin expectation value $\langle \sigma_z \rangle$ is close to $\langle \tau_3 \sigma_z \rangle$, as derived from the $^{25}\mathrm{Al} \rightarrow {}^{25}\mathrm{Mg}$ β-decay ft value.[8] As an additional check, the moment (or g factor) of $^{30}\mathrm{P}(I=1)$, estimated on the basis that it is the sum of the moments of $^{29}\mathrm{P}(I=\frac{1}{2})$ and $^{29}\mathrm{Si}(I=\frac{1}{2})$, is $0.68\mu_N$ which is less than half the value observed for the 0.6% resonance.

In the final NMR measurement we used an improved asymmetry detection technique[5] which is insensitive to possible fluctuations in the effective beam position on the target. Each counting period (8 sec) was separated into two intervals (3 and 5 sec) and a second rf field ($\approx$0.5 G) with a large frequency modulation was applied for 300 msec *between* the two counting intervals to completely destroy the residual ^{25}Al polarization. The up-down β-asymmetry ratio for the first counting interval was then normalized to the up-down ratio of the second period, so that the asymmetry in each counting interval was "self-normalized." An NMR line was then traced out by varying the first rf signal while keeping the second constant. Two "clean" NMR lines observed in this manner are shown in Figs. 2(a) and 2(b). In each case the residual asymmetry ($\approx$0.5%) is due to the decay of ^{29}P since the two rf signals do not disturb its polarization, which was shown to have a long relaxation time, $T_1 = 22(2)$ sec. The frequency modulation of the first rf signal was $\pm$5 kHz in Fig. 2(a) and $\pm$25 kHz in Fig. 2(b).

Analysis of the narrow resonance in Fig. 2(a) indicates the NMR linewidth (HWHM) is less than 2 kHz, which confirms the expectation that those ^{25}Al nuclei which maintain polarization over the counting period do reside in sites of cubic sym-

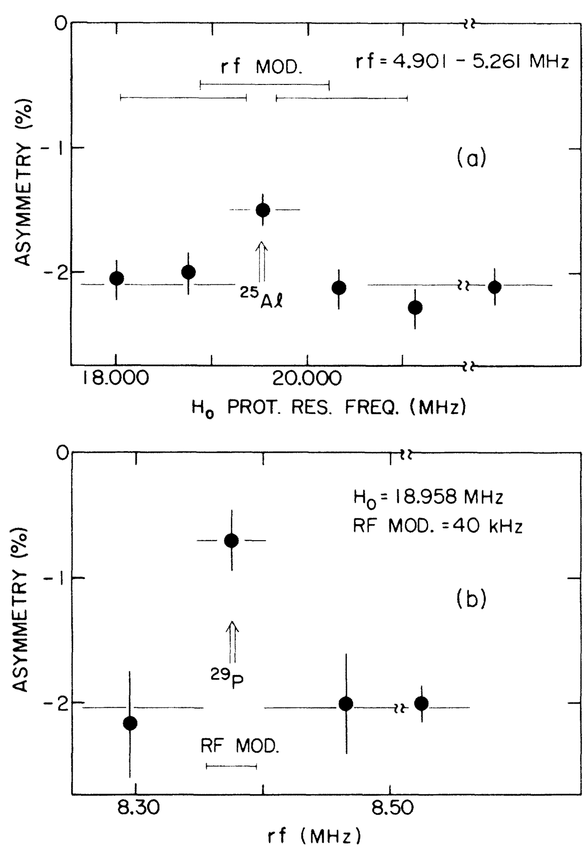

FIG. 1. The two NMR lines observed when polarized nuclei are produced in a thick single crystal of Si bombarded with polarized protons. According to arguments given in the text, the resonance in Fig. 1(a) is identified with ^{25}Al and the one in Fig. 1(b) with ^{29}P.

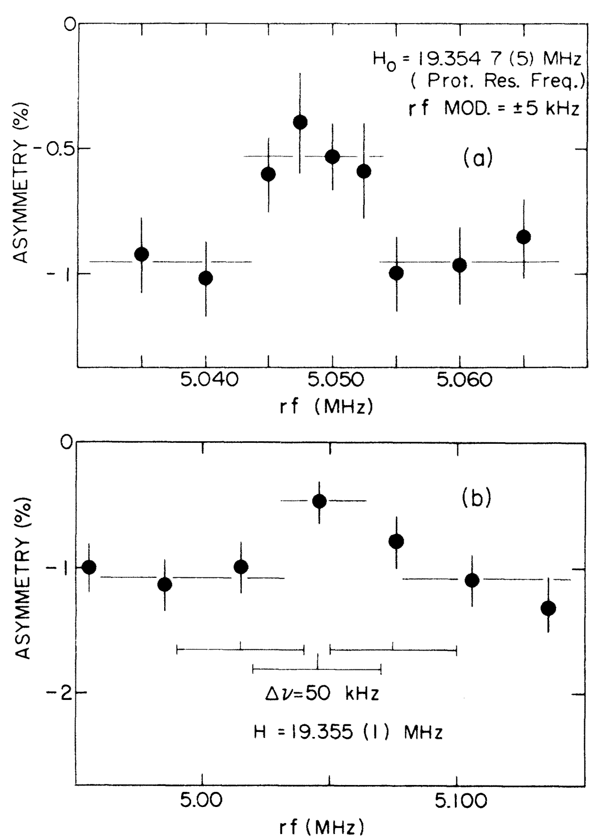

FIG. 2. The NMR lines of ^{25}Al observed for two different modulations of the frequency. The final value of the moment was obtained from the high resolution data of Fig. 2(a).

TABLE I. NMR measurements on polarized ^{25}Al implanted in Si crystals.

	Fig. 1(a)	Fig. 2(b)	Fig. 2(a)
H_0 (MHz [a])	19.533(10) [b]	19.355(1)	19.3547(5)
rf modulation (MHz)	4.901→ 5.261	$\Delta\nu = \pm 25$ kHz	$\Delta\nu = \pm 5$ kHz
NMR frequency (MHz)	5.081(1)	5.045(5) [b]	5.0488(13) [b]
Measured μ (μ_N)	3.63(3)	3.640(4)	3.6425(10)
Diamagnetic factor σ			$8.3(5)\times 10^{-4}$
Corrected μ (μ_N)			3.6455(12) [c]

[a] Proton resonance frequency.
[b] Obtained by NMR-line fit.
[c] Possible chemical shift of $\lesssim 1.5\times 10^{-4}$ is included in the error.

metry. However, the relaxation time was found to be $T_1 = 4(1)$ sec, considerably shorter than for ^{29}P, indicating appreciable quadrupole interaction with the lattice which could arise from radiation damage. Also, in the course of the experiment, it was found that with a 10 nA beam intensity, the useful lifetime of the Si targets for maintaining polarization was about 10 hours.

The magnetic moment values for ^{25}Al, measured in three independent runs and shown in Table I, are in good agreement with each other. We take the value from the final measurement in Fig. 2(a) as the uncorrected result for ^{25}Al$(I=\frac{5}{2})$, $\mu = [3.6425(10)]\mu_N$. The primary correction to the measured moment is the diamagnetic shielding factor,[6] $\sigma = 8.3(5)\times 10^{-4}$. The Knight shift in Si is negligibly small because of the low free-electron density in the semiconducting Si crystal at room temperature. After applying the multiplicative shielding factor, we obtain a corrected magnetic dipole moment for ^{25}Al$(I=\frac{5}{2})$ of $\mu = [3.6455(12)]\mu_N$. We include in the error a possible chemical shift[4,7] in Si of order $\lesssim 1.5\times 10^{-4}$.

The sum magnetic moment for the mirror doublet ^{25}Mg-^{25}Al is $-0.85545 + 3.6455 = 2.790\mu_N$, which is close to the sum of the Schmidt values, $2.880\mu_N$. The angular momentum distributions of this pair also agree with the general trends of mirror moments as analyzed by Sugimoto.[8]

The present experiment demonstrates that the $(\vec{p},\alpha)$ reaction is promising for the production of polarized nuclei and for studies of polarization transfer in nuclear reactions. It shows that the polarization transferred to the products ^{25}Al and ^{29}P are parallel to the incident proton polarization direction, a result that is common to several other cases we have measured.[9] The experiment also shows that with the present method multiple NMR lines can be observed and assigned uniquely to different product nuclei.

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*This work supported in part by the National Science Foundation.

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