Measurement of the Quadrupole Moment of ^{8}Li by Use of a Polarized Deuteron Beam and NMR Detection*

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Polarized ^{8}Li nuclei ($T_{1/2}=0.84$ sec), produced in ^{7}Li$(d,p)^8$Li with polarized deuterons, were implanted in a thick $LiIO_3$ crystal used as the target. The asymmetry in the β decay of ^{8}Li was used to detect NMR in a strong magnetic field. About $\frac{1}{3}$ of the ^{8}Li nuclei found Li substitutional sites where the polarization persisted for $T_1 \approx 11$ sec. The quadrupole moment of ^{8}Li was determined from a knowledge of the electric field gradient in $LiIO_3$.

Producing an oriented nuclear state is the first step in standard methods for determining multipole moments of unstable nuclear states. The second step is to observe how the orientation becomes modified when the nuclear moments are allowed to interact with suitably well-defined electric and magnetic fields.

Of particular interest are the nuclear moments of β-unstable members of isospin multiplets. Often these nuclei must be produced and polarized by a reaction process. The polarization can then be monitored by measuring the asymmetry produced in the β decay. However, if unpolarized particles are used to initiate the reaction and if all recoil angles for the product nuclei are allowed, the process has a single axis of symmetry and the magnetic substates are at most aligned.[1] In this case an asymmetry is not produced in the β decay.

To obtain an asymmetry, one procedure is to select the recoil angle of the product nuclei so that there is no longer a single axis of symmetry in the reaction process. Nuclear moments have been determined[2] with this type of geometry by using the resulting β-decay asymmetry to detect a nuclear magnetic resonance (NMR). A thin target must be used if the recoil angle is to be defined. Reasonable counting rates then require beam currents typically greater than 10 μA. These currents are not always available at the energies required for producing many of the β-emitting nuclei of interest.

In this Letter we describe the successful application of an alternative procedure in which the reaction process is initiated with a polarized beam of fast deuterons, so that selection of the recoil angle is not required.[3] This method is attractive since adequately intense polarized beams are now widely available at energies convenient for producing many of the β-emitters of interest. The technique, together with NMR detection,[4] was applied to the determination of the quadrupole moment of the ground state of ^{8}Li ($I^\pi = 2^+$, $T_{1/2}=0.84$ sec).

The ^{8}Li nuclei were produced and polarized by initiating the reaction ^{7}Li$(d,p)^8$Li with vector-polarized deuterons from the Stanford FN tandem Van de Graaff accelerator. Since recoil-angle selection was not required, a thick target could be used which produced a β-particle counting rate as high as 10^3/sec for an incident beam current of only 10 nA. A $LiIO_3$ crystal 1.5 mm thick was chosen for the target so that the recoil ^{8}Li nuclei could be implanted in a Li substitutional site where the electric and magnetic fields are suitably prescribed.

The deuteron beam was vector polarized in a direction transverse to the beam direction. The magnitude of the vector polarization P_z was 0.62. A 1.63-kG magnetic field H_0 was applied along the polarization direction. The β particles from the ^{8}Li decay were detected by two charged-particle telescopes placed along the magnetic field axis such that one was above and the other below the target. Energy discrimination ensured that only β particles from ^{8}Li were counted.

The $LiIO_3$ target was exposed to the beam for periods of 1 sec every 4 sec, by means of a remotely controlled beam chopper. The β particles were counted in the intervening period of 3 sec in the absence of the beam. The polarization of the deuteron beam was set equal to zero on alternate cycles, so that the absolute β-particle asymmetry could be determined independent of instrumental asymmetries associated with the two separate detector channels. The polarization of the ^{8}Li nuclei was monitored by determining the ratio $r = W_p(0°)W_u(180°)/W_p(180°)W_u(0°)$, where $W_p(0°)$

and $W_p(180°)$ were the counts from the upper and the lower detectors when the deuterons were polarized while $W_u(0°)$ and $W_u(180°)$ were the corresponding counts when the deuterons were unpolarized.

The β-decay asymmetry, defined as the quantity $2(r-1)/(r+1)$, was measured as a function of time by performing simultaneous multiscaling for both detector signals. Thus the spin-lattice relaxation time T_1 was determined for each run. The asymmetry was not very sensitive to deuteron energy. Typical results for $E_d = 9$ MeV are shown in Fig. 1. The initial asymmetry was determined to be 0.035 ± 0.002 with a relaxation time of $T_1 \approx 11$ sec which is much longer than the half-life of ^{8}Li. The large value of T_1 demonstrated the usefulness of the $LiIO_3$ crystal for recoil implantation. The magnitude of the asymmetry and the relaxation time remained constant during the experiment. Also these were found to be independent of the beam bombardment time when this was changed from 1.0 sec to 0.5 sec or to 2.0 sec. Radiation damage was evidently unimportant, which also has been the experience at Stanford University in other experiments with proton and deuteron beams.

For the hexagonal $LiIO_3$ crystal structure[5] the electric field gradient q at a Li site is symmetric and parallel to the crystal c axis.[6] For an $I = 2$ state, such as the ground state of ^{8}Li, the transition frequency ν_m for an $m \leftrightarrow (m-1)$ transition is given in first-order perturbation theory by[7]

$$\nu_m = \nu_L + \tfrac{1}{2}\nu_Q(m - \tfrac{1}{2})(3\cos^2\theta - 1), \quad (1)$$

where θ is the angle between the field-gradient axis and the magnetic field axis, ν_L is the Larmor frequency for the field H_0, and $\nu_Q = eqQ/4h$. For an axially symmetric field gradient and $\theta = 0$, all higher-order perturbation terms vanish.

The four NMR resonances were clearly observed at room temperature (see Fig. 2) by ap-

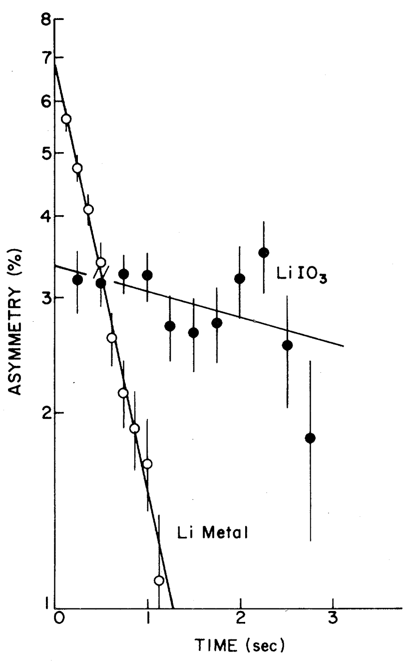

FIG. 1. Observed β-decay asymmetries as a function of time for polarized ^{8}Li nuclei implanted in a $LiIO_3$ crystal and in Li metal. The ^{8}Li nuclei were produced from the reaction ^{7}Li$(d,p)^8$Li initiated with a deuteron beam with a vector polarization of 0.62.

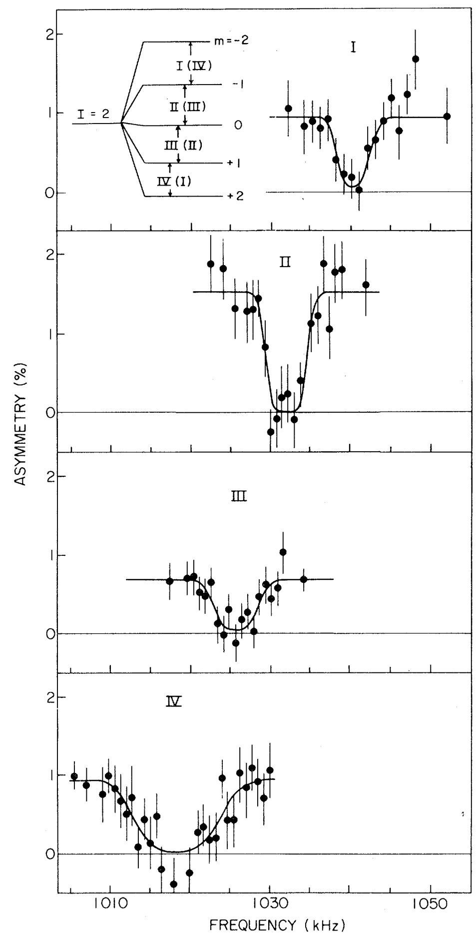

FIG. 2. The four NMR lines observed for polarized ^{8}Li implanted in a $LiIO_3$ crystal. Resonances I, II, and III were obtained with an rf field $H_1 \approx 0.1$ G while IV was obtained with $H_1 \approx 0.16$ G which accounts for its greater linewidth. The present experiment does not determine the sign of the quadrupole moment and hence the ordering of the NMR transitions in the level diagram is not known.

TABLE I. The NMR results on ^{8}Li implanted in $LiIO_3$. The c axis was parallel to H_0 for the resonances I, II, III, IV and perpendicular to H_0 for resonance V.

	Magnetic substate transition	Center frequency (kHz)	Line-width (kHz)
I	$\pm2 \leftrightarrow \pm1$	1040.1 ± 0.4	1.8 ± 0.4
II	$\pm1 \leftrightarrow 0$	1032.5 ± 0.4	1.6 ± 0.2
III	$0 \leftrightarrow \mp1$	1025.5 ± 0.4	1.7 ± 0.4
IV	$\mp1 \leftrightarrow \mp2$	1018.3 ± 0.5	3.0 ± 0.7
V	$\pm2 \leftrightarrow \pm1$	1022.9 ± 0.7	1.5 ± 0.7

plying frequency-modulated rf magnetic fields ($H_1 \approx 0.2$ G) perpendicular to H_0 to saturate three of the transitions, and an unmodulated rf magnetic field ($H_1 \approx 0.1$ G) perpendicular to H_0 to map the remaining transition as a function of rf frequency. The rf fields were applied during the beam bombardment period and for a time $\Delta t = 250$ msec after the beam was stopped. Counting began immediately after the rf fields were switched off. The c axis was parallel to the faces of the $LiIO_3$ crystal and was set parallel to H_0 to measure the resonances I, II, III, and IV in Table I and perpendicular to H_0 to measure resonance V.

The center frequency of each resonance was determined by fitting a theoretical line shape to the data shown in Fig. 2. Dipolar broadening,[7] the time duration Δt, and the finite value of H_1 for the unmodulated rf magnetic field were included in the line-shape analysis. The resonant frequencies given in Table I are consistent with the description provided by Eq. (1). As shown in Fig. 2, the β asymmetry dropped to zero at the center frequency of each resonance. This result implies that ^{8}Li nuclei which retained their polarization had found sites all having the same electric field gradient, and that the gradient was axially symmetric and parallel to the c axis. We concluded that the sites were Li substitutional sites in $LiIO_3$. The value obtained for the dipolar broadening was 1.7 kHz. This value is in agreement with the one expected for a substitutional site, 1.4 kHz, when the c axis is parallel to H_0.

The values $\nu_Q = 7.3 \pm 0.2$ kHz and $\nu_L = 1029.1 \pm 0.2$ kHz were obtained by fitting the results in Table I by Eq. (1). The small ratio ν_Q/ν_L implies that higher-order corrections are negligible. The value of ν_L is consistent with the previously determined[8] value for the g factor of ^{8}Li. The value obtained for the ^{8}Li coupling constant is $|eqQ/h| = 29.2 \pm 0.8$ kHz. Comparing this with the known[6] quadrupole coupling constant of ^{7}Li in $LiIO_3$ (44 ± 3 kHz) yields

$$|Q(^8\mathrm{Li})/Q(^7\mathrm{Li})| = 0.66 \pm 0.05.$$

From the value[9] $Q(^7\mathrm{Li}) = -3.66 \pm 0.03$ fm^2 we obtain

$$|Q(^8\mathrm{Li}_{\mathrm{g.s.}})| = 2.4 \pm 0.2 \text{ fm}^2.$$

Our result for the ratio of quadrupole moments is in fair agreement with the value of 0.79 ± 0.06 measured by Ackerman *et al.*[10] using polarized ^{8}Li nuclei produced by the capture of polarized slow neutrons.

When the $LiIO_3$ crystal was replaced with a thick Li metal target the initial β-decay asymmetry was 0.097 ± 0.004 with $T_1 = 0.66 \pm 0.04$ sec, as determined from the data in Fig. 1. If we compare this asymmetry with the values observed for $LiIO_3$, we conclude that approximately $\frac{1}{3}$ of the ^{8}Li nuclei found sites in $LiIO_3$ which preserved the polarization for $T_1 \approx 11$ sec.

An invaluable experimental aid was the ability to make measurements with the deuteron polarization switched on and off which eliminated systematic errors arising from instrumental asymmetries. In particular, we could show that the β-particle asymmetry became zero at the center of each NMR resonance, as discussed above.

The success of the method illustrates the advantages of deep, in-beam implantation which results in very dilute implantations far from surface impurities and irregularities.

The method should be widely applicable since we have also measured substantial β-particle asymmetries for ^{12}B, ^{29}P, and ^{28}Al produced by (d,n) or (d,p) reactions initiated with vector-polarized deuterons.

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Optical-Model Analysis of N + C and C + C Elastic Scattering*

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Two direct search methods have been applied to extract the optimum optical-model parameters for the elastic scattering of ^{14}N by ^{12,13,14}C, ^{12}C by ^{13,14}C, and ^{13}C by ^{14}C for center-of-mass energies in the range 7.8 to 12.6 MeV. The success of the analysis suggests that it is possible to interpret these data in terms of an optical-model potential alone, indicating that such experiments do not provide unambiguous evidence for interference between the elastic-scattering and elastic-transfer modes.

Experiments[1-4] which have measured the cross section for elastic scattering of a heavy-ion projectile A by a target nucleus a throughout most of the observable angular range have revealed the characteristic feature that, at energies above the Coulomb barrier, the ratio of this cross section to the Rutherford cross section, for systems where a and A differ by the order of a few nucleons, decreases relatively slowly with increasing center-of-mass angle and displays regular oscillations which increase in amplitude on passing into the backward hemisphere, with an increase at the extreme backward angles in some cases. In a quantal description it is not possible to distinguish experimentally elastic scattering, $a(A,A)a$, observed at a center-of-mass angle θ from the "elastic"- (or $Q=0$) transfer reaction $a(A,a)A$ observed at the center-of-mass angle $\pi-\theta$. Therefore, it has been suggested[1,5] that since the differential cross section for elastic scattering usually decreases rapidly with increasing θ, and reaction cross sections are usually peaked at forward angles, a plausible model for such cases would be one which summed coherently an elastic-scattering amplitude calculated at θ and an amplitude for the reaction calculated at $\pi-\theta$ (the analogy is Mott scattering of identical particles where the amplitude at both θ and $\pi-\theta$ is the one for elastic scattering). Such a model makes the implicit assumption that there is a large probability of the two nuclei reentering the elastic channel after the transfer reaction. Since experimentally the two processes are not distinguishable, the testing of this model has rested on comparisons of similar systems, e.g., observed angular distributions of elastic scattering of ^{14}N by ^{12}C and by ^{13}C,[1,2] or ^{12}C by ^{13}C and ^{13}C by ^{14}C,[3-5] at similar center-of-mass energies. On the basis of such comparisons the experimental results have been interpreted as unambiguous evidence for the interference between elastic-scattering and elastic-transfer processes. It was furthermore suggested that only by inclusion of the elastic-transfer mode is it possible to obtain reasonable agreement with experiment, whence the hypothesis that the observed oscillatory structures in the angular distributions are due to the exchange of the mass difference of the two colliding nuclei.[2] The present study shows that these data can be consistently interpreted in terms of the optical model alone and consequently such data do not provide unambiguous evidence for the need to include the elastic-transfer mode explicitly.

The two search codes utilized in the present analysis differ in the method which they use to optimize the quality-of-fit parameter Δ.[6] The