QUADRUPOLE MOMENT OF ^{11}Li

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ABSTRACT

The quadrupole coupling constants of ^{11}Li and ^9Li in LiNbO_3 have been measured by β -NMR spectroscopy on implanted lithium nuclei. These were polarized by optical pumping on a fast beam of neutral atoms. The deduced ratio of quadrupole moments, $|Q(^{11}\text{Li})/Q(^9\text{Li})| = 1.14(16)$ is in accordance with the current models describing the ^{11}Li nucleus as being clustered into a ^9Li core and a halo of two loosely bound neutrons.

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Abstract

The quadrupole coupling constants of ^{11}Li and ^9Li in LiNbO_3 have been measured by β -NMR spectroscopy on implanted lithium nuclei. These were polarized by optical pumping on a fast beam of neutral atoms. The deduced ratio of quadrupole moments, $|Q(^{11}\text{Li})/Q(^9\text{Li})| = 1.14(16)$ is in accordance with the current models describing the ^{11}Li nucleus as being clustered into a ^9Li core and a halo of two loosely bound neutrons.

Recent investigations of light nuclei near the neutron drip line have revealed a new structure for systems in which the last neutrons are much more loosely bound than in ordinary nuclei. An outstanding example is ^{11}Li consisting of 3 protons and 8 neutrons which should fill the 1p shell. The two-neutron separation energy is only about 250 keV, and ^{10}Li is unbound against neutron emission. This leads to the conclusion that ^{11}Li essentially consists of a ^9Li core and two neutrons whose spatial distribution extends far

beyond the core radius [1]. The two-body model of a dineutron coupled to a structureless ${}^9\text{Li}$ core relates the size of this halo (about 8fm compared to 2.5fm for the core) to the separation energy and predicts a soft dipole mode at low excitation energy [1]. Both a large root mean square matter radius [2] and large cross-sections for electromagnetic dissociation [3, 4] have been found in projectile fragmentation experiments. So far all observations, including the narrow momentum distribution of the neutrons [4, 5] are consistent with a model describing ${}^{11}\text{Li}$ as being clustered into a ${}^9\text{Li}$ core and a halo formed by the two extra neutrons [6]. Different aspects of the structure of halo nuclei are tested by the electromagnetic ground-state properties. A preceding experiment yielded the nuclear spin $I = \frac{3}{2}$ and the magnetic moment $\mu = 3.6673(25) \mu_N$ [7] which identify the ${}^{11}\text{Li}$ ground state with a spherical $\pi 1p_{\frac{3}{2}}$ configuration like in the lighter isotopes ${}^7\text{Li}$ and ${}^9\text{Li}$. The spectroscopic quadrupole moment is directly related to an anisotropy of the nuclear charge distribution. Therefore, we have measured the quadrupole splittings of the β -NMR signal of ${}^{11}\text{Li}$ and ${}^9\text{Li}$ nuclei implanted in a non-cubic LiNbO_3 crystal.

The experimental method is a combination of in-beam polarization by optical Zeeman pumping and β -NMR on implanted spin polarized lithium nuclei. This basic principle and the experimental setup are described in previous papers [7, 8]. The lithium isotopes are produced by fragmentation in a Ta-foil target irradiated with 600 MeV protons, ionized and mass separated at 60 keV beam energy. The ion beam is neutralized by charge exchange in a sodium vapour cell. The fast lithium atoms are then polarized by optical pumping with a circularly polarized collinear laser beam tuned to one of the hyperfine structure components of the transition $2s \ ^2S_{\frac{1}{2}} \rightarrow 2p \ ^2P_{\frac{1}{2}}$ at 670.7 nm in the presence of a small longitudinal magnetic field. Owing to the hyperfine interaction this atomic polarization also involves the nuclear spins. Downstream of the optical pumping zone the spins are rotated adiabatically into the direction of a strong transversal magnetic field of $H_0 \approx 1\text{kGauss}$. The atoms are implanted into a LiNbO_3 single crystal at room temperature, mounted with its symmetry axis parallel to H_0 . During the implantation process the static magnetic field H_0 decouples the nuclear spin and the spin of the valence electron. The nuclear polarization is detected by the angular asymmetry in the β -decay with pairs of plastic scintillators covering a solid angle of 11% of 4π around the directions parallel and antiparallel to H_0 .

The asymmetry in the angular distribution of the electrons is given by

$$W(\Theta) = 1 + A(v/c)P\cos\Theta \quad ,$$

where Θ is the angle between the electron momentum and the nuclear spin I , $P = \langle I_z \rangle / I$ the nuclear polarization and A the asymmetry factor of the transitions involved. For ${}^9\text{Li}$,

$A = -0.098$. The parameter A of ^{11}Li is not known a priori, since there is no detailed information about the various decay modes of ^{11}Li existing.

A pair of coils generates a magnetic rf field perpendicular to H_0 at the position of the crystal. At resonance the transitions induced between the m_I -sublevels cause a reduction of the nuclear polarization and thus of the measured asymmetry a defined by the normalized count rate difference between the scintillators, $a = (N \uparrow - N \downarrow) / (N \uparrow + N \downarrow)$.

The interaction of the quadrupole moment Q with the axially symmetric field gradient eq shifts the energy of the $2I + 1$ magnetic sublevels by

$$E_Q = \frac{1}{4} h \nu_Q (3 \cos^2 \Phi - 1) (m_I^2 - \frac{1}{3} I(I+1))$$

with

$$\nu_Q = \frac{3e^2 q Q}{2hI(2I-1)} \quad ,$$

where Φ is the angle between the symmetry axis of the crystal and the direction of the static field H_0 . For isotopes with the spin $I = \frac{3}{2}$ the NMR spectrum consists of an unshifted central component at the Larmor frequency $\nu_L = \gamma H_0$ and two symmetrically situated satellites. Since the frequency difference (Δ_Q) between the central component and the satellites is proportional to the quadrupole moment Q , a measurement of Δ_Q for both isotopes ^{11}Li and ^9Li yields the ratio of their quadrupole moments. An NMR spectrum for ^9Li (Fig.1) shows the three equidistant components clearly resolved. With a beam intensity of about 10^7 ions/s this spectrum was measured within 75 min. For ^{11}Li the low production rate of 10^3 ions/s excludes such a measurement. To enhance the signal intensity of the satellites we have applied simultaneously three rf fields of equal strength. The central one was locked to the known Larmor frequency ν_L [7], whereas the two others were scanned symmetrically up and down starting from ν_L , i.e. $\nu_L \pm \Delta\nu$. At resonance ($\Delta\nu = \Delta_Q$) all m_I -sublevels are coupled by the rf fields and the nuclear polarization is destroyed. This yields one strong triple-resonance signal. The gain is evident from a comparison of the ^9Li signal in Fig.2a with the spectrum of Fig.1, both of which were taken within comparable measuring times. Off resonance the asymmetry is somewhat reduced due to the permanent exposure of the nuclei to the central frequency ν_L , but the triple resonance signal is stronger and better resolved than the satellites in the single-frequency scan. Fig.2b shows the corresponding signal of ^{11}Li observed in two four hours' measurements.

The asymmetry curves were fitted by the χ^2 -minimizing routine MINUIT using the function

$$a(\nu, T) = B + AP(\nu, T)$$

where B is the instrumental asymmetry, A the asymmetry parameter of the decay and $P(\nu, T)$ the polarization of the lithium nuclei exposed to the rf fields during an interaction time T . $P(\nu, T)$ is evaluated by the numerical solution of a rate equation system for the population differences of the four magnetic substates, representing the interaction of the polarized sample with the rf fields. The induced transition rates between the sublevels N_i and N_{i+1} are given by

$$\Gamma_{i,i+1} = f_{i,i+1} g(\nu_0, \delta\nu, \Delta_Q)$$

The amplitudes $f_{i,i+1}$ of the three $\Delta m = \pm 1$ transitions have the ratio 3:4:3, because the interaction is proportional to $|\langle m | I_x | m \pm 1 \rangle|^2$. We have used a Gaussian spectral shape function $g(\nu_0, \delta\nu, \Delta_Q)$ with equal width $\delta\nu$ for all three components. This is justified by conventional NMR measurements performed on ${}^7\text{Li}$ in LiNbO_3 [9]. In addition to the three parameters of this shape function, six parameters describing the transition amplitude, the three population differences, the asymmetry A and asymmetry offset B enter the numerical fit. Some of these parameters could be fixed from the results of the fully resolved ${}^9\text{Li}$ resonances (Fig.1). The population differences between the magnetic substates were assumed to be equal in the spectra of ${}^9\text{Li}$ and ${}^{11}\text{Li}$ because of the similar hyperfine structures [7]. The asymmetry factor A for ${}^{11}\text{Li}$ was fixed to be 3.5 times larger than for ${}^9\text{Li}$ according to the independently observed asymmetries $a({}^9\text{Li}) \approx 1\%$ and $a({}^{11}\text{Li}) \approx 3.5\%$. Thus the spectra were consistently fitted with five free parameters, the most critical of which was the quadrupole splitting Δ_Q (Fig.3). The results $\Delta_Q({}^9\text{Li}) = 19.3(9) \text{ kHz}$ and $\Delta_Q({}^{11}\text{Li}) = 22(3) \text{ kHz}$ correspond to a ratio of the quadrupole moments $|Q({}^{11}\text{Li})/Q({}^9\text{Li})| = 1.14(16)$. The error is exclusively determined by the statistical error, because systematic errors cancel in the ratio of the quadrupole splittings. Using a recent standard value for the ${}^7\text{Li}$ quadrupole moment [10, 11] and the results of our earlier measurements on ${}^9\text{Li}$ [8], one obtains the quadrupole moment $|Q({}^{11}\text{Li})| = 31.2(4.5) \text{ mb}$. A recalibration of the earlier results [8] with the new value of $Q({}^7\text{Li})$ yields the quadrupole moments of all radioactive isotopes as listed in Table1.

The quadrupole moment of ${}^{11}\text{Li}$ is only slightly larger than the one of ${}^9\text{Li}$. This is consistent with the spherical structure suggested by recent models introduced to reproduce the large matter radius and the small two-neutron separation energy. The shell model should be able to provide rather accurate quadrupole moments of light nuclei. On the other hand, it is unable to explain the formation of a neutron halo [13], since the low nuclear density in the halo is incompatible with a mean field approach. Alternatives are based on a three-body model in which two neutrons form a spatially extended halo around an inert ${}^9\text{Li}$ core. The motion of these neutrons relative to the core is then predicted to have total angular momentum $L = 0$ with less than 1% admixture of $L = 2$ [14]. A more

detailed treatment of pairing using a density dependent contact interaction yields strong correlations between the valence neutrons at large distances from the core [15]. This again supports the dineutron model assuming a neutron pair of fixed internal structure.

Within such a simple two-body model the wave function of ^{11}Li is given by

$$\Psi(^{11}\text{Li}) = \Psi_C(^9\text{Li}) \otimes \Psi_{2n}(r) \quad ,$$

where $\Psi_C(^9\text{Li})$ is the internal wave function of the ^9Li core and $\Psi_{2n}(r)$ is the wave function of the relative motion of the core-dineutron system. One may speculate whether the extended $\Psi_{2n}(r)$ by a small $L = 2$ admixture contributes significantly to the quadrupole moment via the recoil of the core. An estimate in analogy to the deuteron problem [16] leads to the conclusion that even an admixture of a few percent affects the quadrupole moment by less than our experimental error. Thus a difference between the quadrupole moments of ^{11}Li and ^9Li would imply a change in the core density distribution rather than a core recoil effect.

Cluster-orbital shell model calculations [17] take into account the internal structure of the core and predict an essentially unchanged quadrupole moment for the system of two neutrons added to a ^9Li core. However, they fail to reproduce the low binding energy. This problem has been overcome in a hybrid model [18] combining the shell model and the three-body aspects. The valence neutrons stay in shell model orbits close to the core and form a dineutron far from it. This model should be able to predict a small change in the quadrupole moment between ^9Li and ^{11}Li .

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Figure captions

Figure 1: β -NMR signal of ${}^9\text{Li}$ in LiNbO_3 using the conventional single-frequency scanning technique. Quadrupole splitting $\Delta_Q = 18.6(1.4) \text{ kHz}$.

Figure 2: Triple resonance signals of ${}^9\text{Li}$ and ${}^{11}\text{Li}$ in LiNbO_3 .

a) ${}^9\text{Li}$ with central frequency locked to $\nu_L = 1.6295 \text{ MHz}$

b) ${}^{11}\text{Li}$ with central frequency locked to $\nu_L = 1.7390 \text{ MHz}$;

The solid curves represent the best fits to the signals and the dashed curves correspond to the one standard deviation in the determination of the quadrupole splitting. The dashed horizontal lines give the β -asymmetry without rf.

Figure 3: Statistical significance of the determination of the quadrupole splitting of ${}^{11}\text{Li}$ from Fig. 2b): χ^2 per degree of freedom for four-parameter fits as a function of the quadrupole splitting Δ_Q .

Table 1: Electromagnetic moments of lithium isotopes. The quadrupole moments are recalibrated for the recent standard value of $Q(^7\text{Li})$.

Isotope	I	μ_I [n.m.]	Q [mb]
^7Li	$\frac{3}{2}$	$3.2564268(17)^a$	$-40.0(3)^b$
^8Li	2	$1.653560(18)^a$	$+31.1(5)^c$
^9Li	$\frac{3}{2}$	$3.4391(6)^a$	$-27.4(1.0)^c$
^{11}Li	$\frac{3}{2}$	$3.6678(25)^d$	$-31.2(4.5)^e$

a : [12] b : [11] c : [8] d : [7], [12] e : this work

The negative sign for the quadrupole moment of all $I = \frac{3}{2}$ isotopes was assumed.

Figure 1

a)

b)

Figure 2

QUADRUPOLE SPLITTING [kHz]

Figure 3