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Precision Measurement of ^{11}Li moments: influence of halo neutrons on the ^{9}Li core

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Abstract

The electric quadrupole moment and the magnetic moment of the ^{11}Li halo nucleus have been measured with more than an order of magnitude higher precision than before, $|Q| = 33.3(5)$ mb and $\mu = 3.6712(3)\,\mu_N$, revealing a 8.8(1.5)% increase of the quadrupole moment relative to that of ^{9}Li. This result is compared to various models that aim at describing the halo properties. In the shell model an increased quadrupole moment points to a significant occupation of the $1d$ orbits, whereas in a simple halo picture this can be explained by relating the quadrupole moments of the proton distribution to the charge radii. Advanced models so far fail to reproduce simultaneously the trends observed in the radii and quadrupole moments of the lithium isotopes.

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Since nuclear physicists could produce and investigate bound systems of nucleons in many possible combinations, a wealth of isotopes with unexpected properties have been discovered. For example, some neutron-rich isotopes of light elements, such as ^{11}Li, were found to have exceptionally large radii [1]. Upon discovery in 1985, this phenomenon was attributed to either large deformation or to a long tail in the matter distribution [2]. Deformation was soon excluded by the spin and magnetic moment of ^{11}Li belonging to a spherical $\pi p_{3/2}$ state [3]. Considering the weak binding of the last two neutrons [4], one could conclude that such a nuclear system consists of a core with two loosely bound neutrons around it [5]. This is the concept of 'halo' nuclei which has been related to similar phenomena in atomic and molecular physics [6], showing the universality of the concept. To fully unravel the mechanisms leading to the existence of halo nuclei, many types of experiments have been devoted to the investigation of their properties. An observable that gives information on the nuclear charge deformation is the spectroscopic quadrupole moment. By comparing the quadrupole moment of ^{11}Li to that of ^{9}Li, one can investigate how the two halo neutrons modify the deformation of the core which contains the three protons. Already fifteen years ago, a first attempt to do so giving $Q(^{11}\text{Li})/Q(^{9}\text{Li}) = 1.14(16)$, suggested just a slight increase in agreement with the halo concept [7]. Unbiasedly, for a nucleus with a neutron magic number of $N = 8$ one would expect a minimum value of the quadrupole such as for ^{13}B [8]. If ^{11}Li has a larger quadrupole moment than ^{9}Li, it can not be considered as semi-magic, and the two halo neutrons have to be responsible for an expansion or polarization of the proton distribution in the core. The latter, in terms of the shell model, must be understood by an excitation of halo neutrons to the $1d$ orbits, and a precise value of the ^{11}Li quadrupole moment may provide evidence for this. The effect of a more extended charge distribution can be estimated on the basis of a recent laser spectroscopy measurement of the charge radius [9]. The increase of the charge radius for ^{11}Li, as well as other properties of Li isotopes are well described by cluster models [10, 11] which also explain the large quadrupole moment of ^{7}Li [12]. For ^{11}Li they predict a quadrupole moment over 30% larger than that of ^{9}Li. Again, this calls for a more precise measurement.

In this Letter, we report the measurement of the quadrupole moment of ^{11}Li relative to that of ^{9}Li, intended to resolve a difference at the percent level. Improvements over the first study were made to gain an order of magnitude in precision. These concern the experimental method which is based on the nuclear magnetic resonance (NMR) technique. Spin-polarized beams of β-decaying isotopes are implanted into a crystal with a non-cubic lattice structure placed between the poles of an electromagnet. Due to the electric field gradient V_{zz} in such a crystal, in combination with the static magnetic field B, the Zeeman levels of the nuclear spin are shifted by the m_I-dependent quadrupole interaction which is proportional to the interaction constant $\nu_Q = eQV_{zz}/h$ (as illustrated e.g. in [13] for ^{9}Li) and thus to the nuclear quadrupole moment Q. The frequency ν_{rf} of an additionally applied radio-frequency (rf) magnetic field is scanned over the resonances between adjacent m_I quantum states. Whenever ν_{rf} matches one of the transition frequencies, a reduction of the spin polarization shows up as a drop in the β-decay asymmetry [14]. The resonances are equidistant and symmetric with respect to the Larmor frequency ν_L, with the spacing given by $\Delta_r = 6\nu_Q/[4I(2I-1)]$.

The resonance amplitude is enhanced by more than an order of magnitude by applying all resonance frequencies simultaneously, thus mixing all m_I states [7]. For nuclei with spin $I = 3/2$, such as ^{9}Li and ^{11}Li, this involves the three correlated frequencies ν_L, $\nu_L + \Delta$ and $\nu_L - \Delta$. A spectrum is then measured as a function of the parameter Δ, with the resonance value Δ_r determining the quadrupole interaction frequency ν_Q. The signal enhancement and the width, thus also the error on ν_Q, depend on the sufficiently precise knowledge of the Larmor frequency, measured in a crystal with cubic lattice structure.

In the previous study of Arnold et al. [7] the resonance width, mainly determined by variations of the electric field gradient over the implantation sites in the $LiNbO_3$ crystal, was of the same order as the splitting Δ_r itself. Now, we have reduced this width by an order of magnitude to less than 2 kHz [13], by using a metallic Zn crystal. This also means that less rf power is needed to saturate the resonances. The known magnetic moment $\mu(^{11}\mathrm{Li}) = 3.6673(25)\,\mu_N$ [3] corresponds to an uncertainty of 3.5 kHz on the Larmor frequency of about 5 MHz, but an accuracy much better than the expected line width is needed for a multiple-rf resonance measurement. This is achieved by implanting into a Si crystal [13] where the NMR line width is an order of magnitude smaller than in Au [15] or LiF [3].

The experiments have been performed at ISOLDE/ CERN. Beams of ^{9}Li and ^{11}Li were produced by a 1.4 GeV proton beam (3×10^{13} protons per pulse every 2.4 s) on a thin-foil Ta [16] or a conventional UC_2 target. With the short release times of both targets typical production rates of a few 1000 ions/pulse were realized for the short-lived ^{11}Li ($T_{1/2} = 8.5(2)$ ms). The experimental setup and the method of optically polarizing Li beams have been described in detail in Borremans et al. [13], where we report results from our studies on the resonance properties in different crystals for the less exotic isotopes ^{8}Li and ^{9}Li.

The results include the magnetic moment $\mu(^9\mathrm{Li}) = 3.43678(6)\,\mu_N$ which was measured relative to that of ^{8}Li. Now we present a similarly accurate measurement for ^{11}Li relative to ^{9}Li. Typical NMR resonances of both isotopes implanted in a Si crystal at room temperature are shown in Fig. 1. Seven spectra on ^{9}Li and three spectra on ^{11}Li were recorded in total, while the magnetic field of about 0.29 T was kept constant. During the measurements, the magnetic field drifted by 0.005% at most, which is consistent with the scatter of the ^{9}Li resonance frequencies and gives an upper limit for a systematic difference between the fields applied for both isotopes. The weighted means of the Larmor frequencies yield $g(^9\mathrm{Li})/g(^{11}\mathrm{Li}) = 0.93615(6)$ and with the g factor of ^{9}Li [13] we have $g(^{11}\mathrm{Li}) = 2.44746(17)$. With the spin $I = 3/2$ this gives the magnetic moment $\mu(^{11}\mathrm{Li}) = 3.6712(3)\,\mu_N$, improved by an order of magnitude and meeting the requirement for a precise measurement of the quadrupole moment.

The quadrupole moments of ^{8}Li and ^{9}Li have been reported from measurements in several different crystals (see [13]). Although some of the values seem to be in poor agreement with

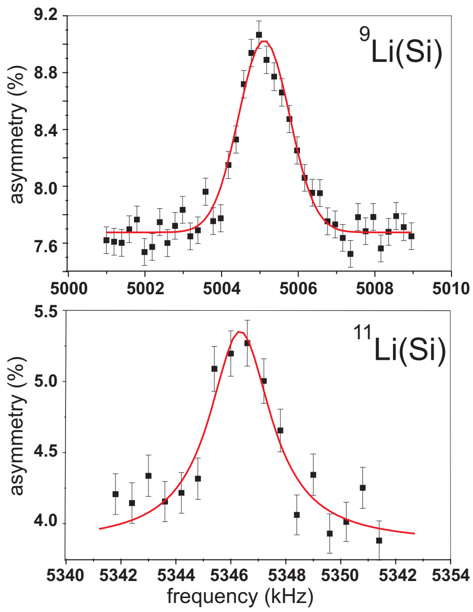

FIG. 1: NMR resonances for ^{9}Li and ^{11}Li in a Si crystal.

one another, we found that for ^{8}Li they become consistent [13], if they are evaluated with respect to the same reference value $Q(^7\text{Li}) = -40.0(3)$ mb. From this we adopted a weighted mean value of $Q(^8\text{Li}) = 31.4(2)$ mb. For ^{9}Li, in order to remove a discrepancy between two earlier measurements, we remeasured the quadrupole moment relative to that of ^{8}Li. Two implantation hosts, a metallic Zn crystal (hcp structure) and a $LiTaO_3$ crystal (orthorhombic structure) gave consistent results, leading to $Q(^9\text{Li}) = -30.6(2)$ mb [13].

With this precise value, and by measuring the quadrupole frequency of ^{11}Li relative to that of ^{9}Li, we can now determine the ^{11}Li quadrupole moment to a similar precision. Three independent experimental runs were performed, during which the quadrupole splitting Δ_r was measured successively for ^{9}Li and ^{11}Li implanted in the Zn crystal. Typical multiple-rf resonances are shown in Fig. 2. Each run started by measuring the Larmor frequency of ^{9}Li in Zn, which was then used to calculate the Larmor frequency of ^{11}Li from the g-factor ratio given above. These two values define the center frequencies of the multiple-rf scans. The resonance values Δ_r for ^{9}Li and ^{11}Li directly give the ratio of the quadrupole moments. Results from the three runs are presented in Fig. 3, with the weighted mean of $|Q(^{11}\text{Li})/Q(^9\text{Li})| = 1.088(15)$. Thus the quadrupole moment of the halo nucleus, $|Q(^{11}\text{Li})| = 33.3(5)$ mb, with a negative sign from theoretical considerations, is nearly 10% larger than that of bare ^{9}Li.

In Table I we summarize the experimental quadrupole and magnetic moments of the Li isotopes, which are now all known to about 1% or better, thus allowing tests of various nuclear models (Fig. 4). In the shell model it is known that some magic numbers which are valid near stability, disappear in nuclei with extreme isospin due to the changing strength of the spin-isospin dependent term in the residual nucleon-nucleon (NN) interaction [17]. In

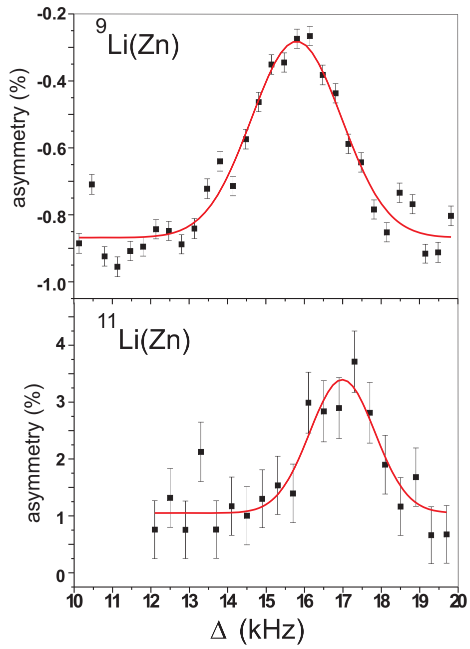

FIG. 2: Multiple-rf resonances for ^{9}Li and ^{11}Li in a Zn crystal.

light neutron-rich nuclei this leads to the disappearance of the $N = 8$ magic number when protons are taken out of the $\pi p_{3/2}$ orbital. A first experimental proof for this was found in the positive parity of the ^{11}Be ground state, shown to be dominated by $\nu 2s_{1/2}$ [18, 19] and not $\nu 1p_{1/2}$ as expected for 7 neutrons. In ^{11}Li this is manifest in the halo structure which has about 45% of $(2s_{1/2})^2$ occupancy [20]. It is also reflected in the quadrupole moments, but the increase from ^{9}Li to ^{11}Li can not be understood by an excitation of neutrons to the spherical $2s$ orbit only. Comparing our result to large-scale shell model calculations may provide a clue for some $1d$ occupancy of the halo neutrons. Suzuki et al. modified an effective shell-model interaction in order to describe both stable and exotic nuclei in this p-sd region assuming ^{4}He as an inert core [21]. The calculated quadrupole moment of ^{11}Li relative to that of ^{9}Li approaches the experimental value if the model space is extended from the p shell

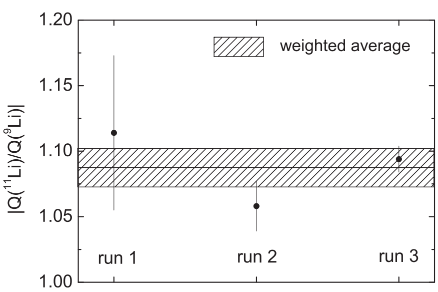

FIG. 3: The ratio of the ^{11}Li to ^{9}Li quadrupole moment has been measured in three independent runs. The weighted average with the error is presented as the dashed bar.

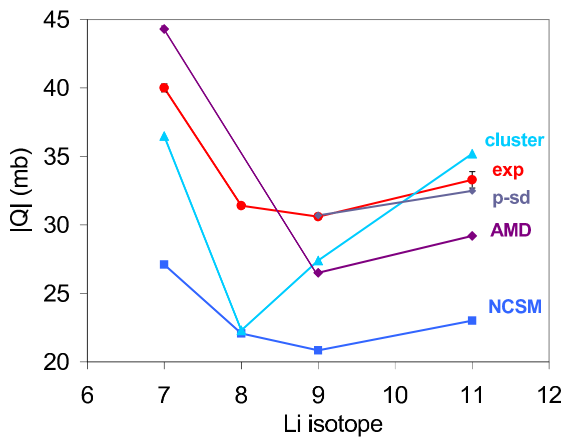

FIG. 4: Quadrupole moments of the Li isotopes compared to values from different theoretical models.

only ($Q_p = 28.2$ mb) to include excitations into the *sd* shell ($Q_{psd} = 32.5$ mb), and effective charges $e_p = 1.2e$ and $e_n = 0.3e$ are used [22]. The halo wave function then has 50% of $(2s_{1/2})^2$, 25% of $(1p_{1/2})^2$ and 25% of $(1d_{5/2})^2$ occupation probability. Advanced Quantum Monte Carlo calculations, including additionally a three-nucleon potential [23], have been successful in describing the moments of ^{7,8,9}Li [24], but so far no results are available for ^{11}Li.

More sophisticated models abandon the assumption of an inert core: all nucleons are active in the no-core shell model (NCSM). Navratil et al. have performed such calculations, using an effective interaction derived microscopically from a NN potential fitted to NN scattering data [25], and they find good agreement with the ground state properties of $A = 7$-11 nuclei. The model does not explain the charge radii, but it perfectly reproduces the trend of experimental quadrupole moments of the Li isotopes. Only an overall scaling factor is missing, which is explained by a limited model space and might be compensated by using effective charges.

An alternative approach is to consider the Li nuclei made of α and triton clusters plus

TABLE I: Experimental dipole and quadrupole moments of Li isotopes from [13]. Results on ^{11}Li are from this work, with the sign of $Q(^{11}\text{Li})$ assumed from theory.

isotope	I^π	$\mu(\mu_N)$	Q(mb)
^{6}Li	1^+	0.8220473(6)	-0.806(6)
^{7}Li	$3/2^-$	3.256427(2)	-40.0(3)
^{8}Li	2^+	1.653560(18)	+31.4(2)
^{9}Li	$3/2^-$	3.43678(6)	-30.6(2)
^{11}Li	$3/2^-$	3.6712(3)	(-)33.3(5)

additional neutrons. In the microscopic cluster model by Varga et al. [12], various cluster arrangements are combined to include all possible correlations between the clusters. In this approach, the quadrupole moments are underestimated, except the one of ^{11}Li which is about 30% larger than that of ^{9}Li [10]. This is surprising, because the model happened to reproduce best the development of the charge radii [9].

The microscopic antisymmetrized molecular dynamics (AMD) approach [26] has been rather successful in describing many features of light nuclei including their electromagnetic moments. For the quadrupole moments it predicts an 8% increase from ^{9}Li to ^{11}Li, very close to the experimental value. However, this agreement should not be overrated as long as halo properties, in particular the large matter radius of ^{11}Li, are not reproduced.

Finally, it is not clear to what extent the different theoretical approaches have included the center-of-mass motion of the proton distribution introduced by the two halo neutrons. Therefore we try to describe the observations assuming the very simple picture of a ^{9}Li core surrounded by two halo neutrons known to be in spherical orbits. From experiment [9] we know that the rms charge radius $\langle r^2\rangle^{1/2}$ increases by 11(2)%, from 2.185(33) fm for ^{9}Li to 2.423(34) fm for ^{11}Li according to the most recent evaluation [27] , while we find that the quadrupole moment increases by 8.8(1.5)%.

If the deformation of the charge distribution would be the same for ^{9}Li and ^{11}Li, one should expect an increase of the quadrupole moment proportional to the mean square radius $\langle r^2\rangle$. However, if we ascribe the increase of the radius to a recoil effect caused by the spherical halo, the center-of-mass movement produces a spherical expansion of the (non-spherical) charge distribution for which the quadrupole moment increases only with the square root $\langle r^2\rangle^{1/2}$. This can explain the striking analogy between the quadrupole moments and the rms charge radii without any additional change of the ^{9}Li-core structure caused by the presence of the halo neutrons. In particular, the ^{11}Li quadrupole moment seems to be unaffected by quadrupole core polarization involving a substantial $1d$ component in the halo wave function. We note that this intuitive relationship between the ^{11}Li quadrupole moment and charge radius is independent of correlations in the movement of the halo neutrons, although these affect strongly the behavior of both quantities.

In conclusion, we have measured the quadrupole moment of the ^{11}Li halo nucleus relative to that of its ^{9}Li core, with a precision improved by an order of magnitude, thus providing a test of modern nuclear theories. While these theories have difficulties to reproduce simultaneously the charge radii and quadrupole moments of both isotopes, we found a relationship between both quantities in a simple halo picture that is surprisingly well fulfilled.

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