The development of pure β-NQR techniques for measurements of nuclear ground state quadrupole moments in lithium isotopes

A Voss[1,2], MR Pearson[1], J Billowes[2], F Buchinger[3], KH Chow[4], JE Crawford[3], MD Hossein[5], RF Kiefl[1,5], CDP Levy[1], WA MacFarlane[1,5], E Mané[1,2], GD Morris[1], TJ Parolin[5], H Saadaoui[5,6], Z Salman[6], M Smadella[5], Q Song[5] and D Wang[5]

[1] TRIUMF, Vancouver, V6T 2A3, Canada
[2] The University of Manchester, Manchester, M13 9PL, United Kingdom
[3] McGill University, Montreal, H3A 2T8, Canada
[4] University of Alberta, Edmonton, T6G 2G7, Canada
[5] University of British Columbia, Vancouver, V6T 1Z1, Canada
[6] Paul Scherrer Institut, 5232 Villigen PSI, Switzerland

E-mail: annika@triumf.ca

Abstract. A β-NQR spectrometer becomes a powerful tool to study changes in nuclear ground state properties along isotopic chains when coupled to a laser excitation beamline to polarise the nuclei of interest. Recently, the β-NQR technique in a zero magnetic field has been applied for the first-time to measure ratios of static nuclear quadrupole moments of ^{8,9,11}Li. Preliminary results of the experiment determining the ratios Q_9/Q_8 and Q_{11}/Q_9 show agreement with present literature values with improved precision.

1. Introduction

Apart from being an effective tool for condensed matter physics to investigate the internal fields of materials, β detected Nuclear Magnetic Resonance (β-NMR) is a well known spectroscopic method to study fundamental properties of the nuclear ground state [1]. In this case, however, the interaction arising from the electric quadrupole moment has to be treated as a perturbation on the NMR spectrum. Thus, it would be of a significant advantage to observe the pure quadrupole interaction directly. As such, β detected Nuclear Quadrupole Resonance (β-NQR) spectroscopy in a zero magnetic field becomes a highly sensitive technique for probing quadrupole moments in the nuclear ground state where not prohibited by the lifetime of the species of interest.

Of particular interest are the properties of nuclei with extraordinary structure. Tanihata and co-workers discovered the exceptional structure of the ^{11}Li nucleus in the mid 1980s [2]. The phenomenon of neutrons or protons orbiting outside a core became later known as the halo structure of nuclei. ^{11}Li is now considered to be a di-neutron halo orbiting a core of ^{9}Li [3].

Charge radius measurements of ^{6,7,8,9,11}Li at TRIUMF-ISAC showed that the Root Mean Square (RMS) charge radius of ^{11}Li is significantly larger than that of ^{9}Li (figure 1) [4]. This could be due to a larger static electric quadrupole deformation as suggested by the ratio of the
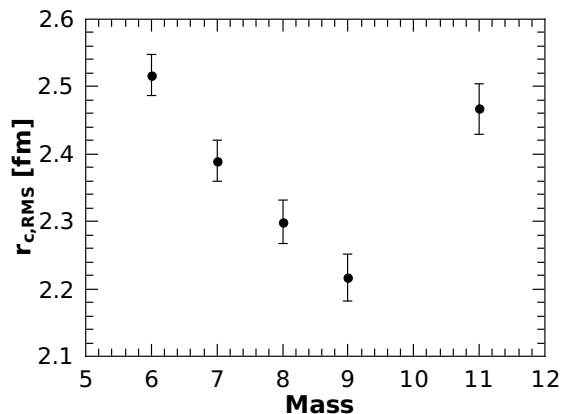
Figure 1: RMS charge radii $r_{c,\mathrm{RMS}}$ of Li. Data taken from [4].

quadrupole moments of ^{11}Li and ^{9}Li, $Q_{11}/Q_9 = 1.088(15)$ [5]. It is thus interesting to make a further measurement of this ratio in order to confirm the value, and to improve the precision.

2. Theory

Following [6], the interaction of a polarised ion beam implanted within a crystal can be described as

$$\mathcal{H} = -m_I \frac{\mu}{I} H_0 + \frac{e^2 qQ}{4I(2I-1)} \left[3I_z^2 - I^2 + \eta \left(I_x^2 - I_y^2 \right) \right] , \tag{1}$$

where μ is the magnetic dipole moment and Q the electric quadrupole moment in the nuclear ground state. This Hamiltonian consists of two parts. The first term describes the interaction of μ with the local magnetic field H_0 while the second term describes the interaction of Q with the local Electric Field Gradient (EFG). In a large magnetic field, the quadrupole interaction can be treated as a perturbation of the magnetic interaction (as in [5, 7]). As a result, multiple fit parameters will have to be extracted which can potentially lead to greater uncertainties.

However, in a zero magnetic field the first term in (1) is absent. Therefore, only the pure quadrupole interaction is relevant. Furthermore, an insulator crystal with cubic structure and an axially symmetric EFG at the implantation site results in a crystalline asymmetry parameter $\eta = 0$. With these conditions, (1) reduces to the pure quadrupole Hamiltonian

$$\mathcal{H} = \frac{e^2 qQ}{4I(2I-1)} \left[3m_I^2 - I(I+1) \right] . \tag{2}$$

The relevant transition for ^{8}Li with $I = 2$ takes place between the $|m_I = \pm 2\rangle$ and $|\pm 1\rangle$ substates, whereas the only transition for ^{9,11}Li with $I = \frac{3}{2}$ is the transition between the $|\pm \frac{3}{2}\rangle$ and $|\pm \frac{1}{2}\rangle$ substates. From this, the transition frequencies can be calculated. It can be shown from (2) that the ratio of the transition frequencies is directly proportional to the ratio of quadrupole moments

$$\frac{\nu_{9,11}}{\nu_8} = \frac{4}{3} \frac{Q_{9,11}}{Q_8} . \tag{3}$$

3. Experimental method

Low energy (28 keV) ion beams from the radioactive beam facility TRIUMF-ISAC were delivered to the polariser beamline (shown in figure 2a) coupled to the β-NQR spectrometer. In the polariser, the isotopes of interest were nuclear spin polarised via collinear optical pumping. This is a three step process comprising of
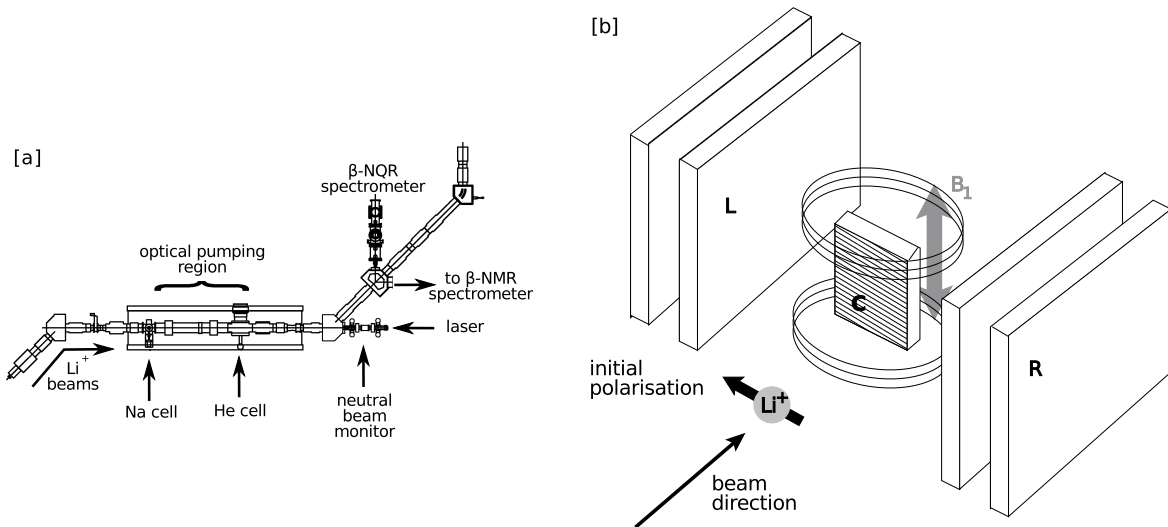
Figure 2: [a] Schematic drawing of the polariser beamline. [b] Inside view of the β-NQR spectrometer. Shown are the left (L) and right (R) detectors, the implantation crystal (C) and the oscillating magnetic field (B_1). See text for more detail.

(i) neutralisation of the ions in a Na vapour cell,

(ii) optical pumping on the D_1 transition using a dye-laser at 761 nm and

(iii) re-ionisation in a He cell.

The ions were then sent to the β-NQR spectrometer [8] where they were implanted into a strontium titanate (SrTiO$_3$) crystal C in a zero magnetic field. A non-resonant "transmission line" Helmholtz coil assembly [9] provides a Continuous Wave (CW) oscillating magnetic field. Scanning a suitable range of Radio Frequency (RF) frequencies, the β-decay asymmetry is observed in the left (L) and right (R) scintillator detectors shown in figure 2b. The application of a resonant magnetic field B_1 destroys the initial polarisation. This destruction of polarisation is observed in a loss of the β-decay asymmetry in the left and right detector.

A more complete and detailed description of the experimental technique and setup may be found elsewhere [10].

4. Preliminary results
4.1. Zero field β-NQR of ^{8,9}Li
The experiment was supplied with 6.0×10^6 ^{8}Li$^+$s^{-1} and 4.7×10^6 ^{9}Li$^+$s^{-1}. Figure 3 shows the β-NQR spectra of ^{8,9}Li implanted into SrTiO$_3$ at a temperature of $T = 295$ K in a zero magnetic field. The two lines correspond to opposite helicities of the polarising laser light. Both helicities were fitted simultaneously using the same Gaussian peak shape but independent centroids. The allowance for different centroids was made due to the residual magnetic field of the order of a few mG perturbing the pure NQR resonance. The pure NQR resonance is the geometric mean of the two centroids.

The weighted average of all runs calculates to a resonance frequency of $\nu_8 = 229.145(5)$ kHz for ^{8}Li and $\nu_9 = 295.369(26)$ kHz for ^{9}Li. From these two frequencies the ratio of quadrupole moments in the nuclear ground state can be calculated to be
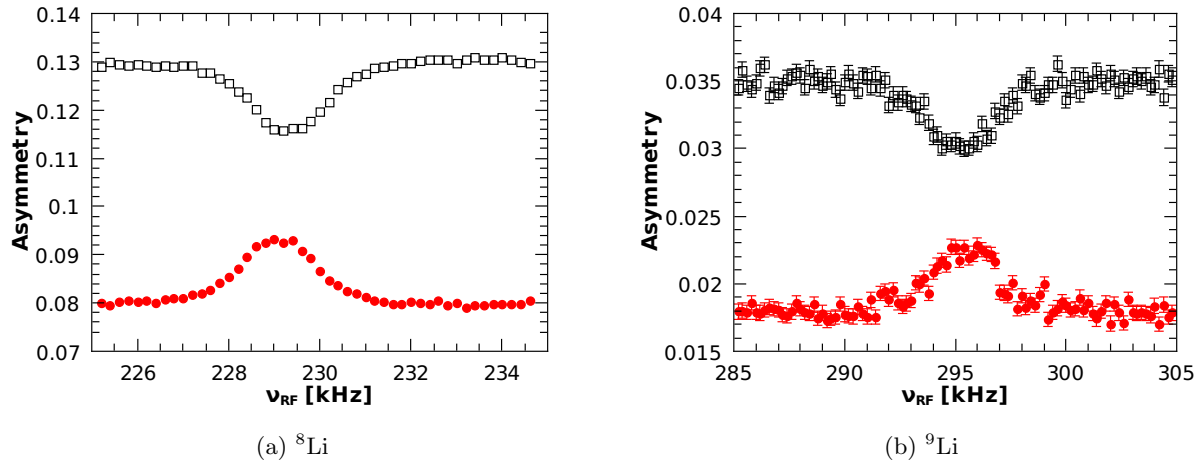
$$\frac{Q_9}{Q_8} = 0.96675(9) \tag{4}$$

(a) ^{8}Li

(b) ^{9}Li

Figure 3: (a) and (b) β-NQR spectra for ^{8,9}Li. The two data sets in each panel correspond to opposite helicities of the polarising laser light. For ^{8}Li the error bars are within the data points. The red filled circles are for negative and the black open squares for positive helicity.

according to equation (3) with a preliminary statistical error. This ratio is in good agreement with the current literature value, $Q_9/Q_8 = 0.975(9)$ [7], but with a significantly improved uncertainty. Studies of systematic uncertainties are currently under way.

4.2. Zero field β-NQR of ^{11}Li

For ^{11}Li with considerably fewer ions at the experiment $(200 - 400$ s$^{-1})$, all runs from approximately two days had to be summed up and baseline averaged to correct for shifts due to e.g. the movement of the ion beam on the crystal with time. The averaging was by calculating the β-decay asymmetry on a frequency by frequency basis for each RF scan. The asymmetries are then averaged on a scan by scan basis. This average is subtracted from all asymmetries in the scan leading to a common baseline around zero for both helicities.

The ^{11}Li β-NQR spectrum after baseline correction and re-binning by a factor of two is shown in figure 4. The width of the scan is comparable to two standard deviations of the current literature value [5]. A Gaussian fit resulted in $\nu_{11} = 318.022(440)$ kHz as a resonance
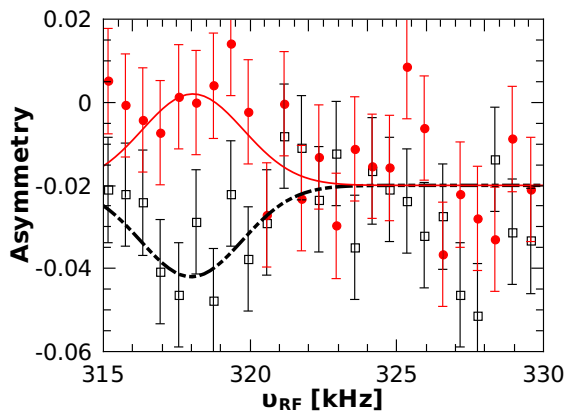

Figure 4: Total β-NQR spectrum for 2×10^7 ^{11}Li ions. The two data sets were re-binned by a factor of two and correspond to opposite helicities of the polarising laser light. The red filled circles are for negative and the black open squares for positive helicity. The Gaussian fit is denoted by a thin full line in red for the negative and by a thick dashed line in black for the positive helicity.

frequency. This leads to a preliminary ratio of the static quadrupole deformation of ^{11}Li and ^{9}Li of

$$\frac{Q_{11}}{Q_9} = \frac{\nu_{11}}{\nu_9} = 1.077(1) \tag{5}$$

with a purely statistical error. This ratio is in agreement with the one presented by Neugart *et al.*, $Q_{11}/Q_9 = 1.088(15)$ [5] but with a significantly improved uncertainty. Further analysis and studies will be carried out in order to assign systematic errors to this value.

5. Conclusion

This work presents the measurement of the ratios Q_9/Q_8 and Q_{11}/Q_9 for lithium. Both ratios show agreement with their respective current literature values and follow the trend of the RMS charge radius in figure 1 for two bound lithium nuclei adjacent in mass numbers.

The ratio Q_9/Q_8 has been determined with a significantly improved uncertainty. Given this result, it has been demonstrated that the measurement of ratios of electric quadrupole moments in a zero magnetic field by observing the pure quadrupole interaction is an advantageous method leading to small uncertainties.

The determination of Q_{11}/Q_9 and the improvement of its statistical uncertainty shows that the β-NQR technique conveys good results for cases where only low yields are available. For both ratios, further analysis and studies are under way.

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