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QUADRUPOLE INTERACTION OF ^{8}Li AND ^{9}Li IN LiNbO$_3$ AND THE QUADRUPOLE MOMENT OF ^{9}Li

E. Arnold*, J. Bonn, W. Neu, R. Neugart, E.W. Otten
Institut für Physik, Universität Mainz, Mainz,
Fed. Rep. of Germany
and
The ISOLDE Collaboration
CERN, Geneva, Switzerland

Abstract: The quadrupole interaction of nuclear spin polarized ^{8}Li (I=2) and 9Li (I=3/2) in LiNbO$_3$ has been studied at room temperature. The polarization was achieved by optical pumping of a fast atomic beam with circularly polarized laser light. The atoms were implanted into a hexagonal LiNbO$_3$ single crystal and the quadrupole splitting of β-NMR spectra was measured. A ratio of $|Q(^9\mathrm{Li})/Q(^8\mathrm{Li})| = 0.88(4)$ for the nuclear quadrupole moments was deduced, yielding a new value of $|Q(^9\mathrm{Li})| = 25.3(9)$ mb for the quadrupole moment of ^{9}Li.

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* Present address: CERN, CH-1211 Geneva 23, Switzerland

1. Introduction

Recently the quadrupole coupling constant (QCC) of ^{9}Li ($T_{1/2}$ = 178 ms) in $LiNbO_3$ and the quadrupole moment of ^{9}Li were reported from a β-NMR measurement on recoil-implanted nuclei [1]. The required nuclear spin polarisation was achieved in the reaction $^{7}Li(\vec{t},p)^{9}Li$, induced by a spin polarized tritium beam. Stimulated by this result, theoretical shell-model calculations in a truncated model space attempted to describe the experimental quadrupole moments of ^{7}Li and ^{9}Li with the same effective charge for the nucleons [2]. A more extended range of nuclei was investigated by Glaudemans and coworkers [3,4]. They studied the electromagnetic properties of light nuclei A = 4 - 16 within the shell model including several types of two-body interactions and excitations from the major-shell configuration up to $2\hbar\omega$. These calculations were performed without the assumption of an inert nuclear core so that core polarization effects are implicitly included. With some exceptions reasonable agreement with the experimentally known spectra, spins, rms charge radii, magnetic dipole and electric quadrupole moments was obtained [5,6].

Considering the fact that a precise knowledge of the quadrupole moments is important for a uniform description of the sp-shell nuclei, and that the previously mentioned experiment suffers from poor statistics and strong radiation damage due to the tritium beam passing the $LiNbO_3$ stopper crystal, we have remeasured the QCC of ^{8}Li ($T_{1/2}$ = 842 ms) and ^{9}Li ($T_{1/2}$ = 178 ms) in $LiNbO_3$ to determine the quadrupole moment of ^{9}Li.

2. The Experiment

The experiment was performed at the ISOLDE facility at CERN using the β-Radop variant of collinear laser spectroscopy which has been described in a previous paper [7]. Lithium isotopes were produced by fragmentation reactions in a Ta-foil target with a 600 MeV proton beam of 2 μA from the CERN synchro-cyclotron. The isotopes were ionized on a hot tungsten surface, accelerated to 60 keV, mass separated and deflected into the apparatus for collinear laser spectroscopy. In passing through a sodium vapour cell heated to 300 °C the ion beam was neutralized by charge exchange. Polarization of the fast atomic beam was achieved by absorption of circularly polarized light in the transition $2s^2S_{1/2} \longrightarrow 2p^2P_{1/2}$ at = 670 nm from a superimposed laser beam. The optical excitation scheme of ^{9}Li is shown in Fig. 1.

Since the spins of the valence electron and the nucleus are coupled due to the hyperfine interaction, a nuclear polarization is generated in the optical pumping process. The spins are initially polarized along the beam direction and then rotated adiabatically by 90° into a static transversal magnetic field H_0 of about 1 kG. Here the atoms are stopped in a $LiNbO_3$ single crystal, mounted with the c axis parallel to H_0. Two plastic scintillators are used to count the β particles emitted within a solid angle of 11% of 4π around the 0° and 180° directions with respect to the static magnetic field. The angular distribution of the β emission is given by

$$W(\theta) = 1 + v/c \; P \; A \cos(\theta) \tag{1}$$

where P is the degree of nuclear polarization before the decay and A is the asymmetry factor [8]. For the pure Gamow-Teller transitions of the lithium isotopes with known branching ratios [9], A is easily calculated to be -33% for ^{8}Li and -9% for ^{9}Li.

The measured asymmetry

(2) $a=(N(0^\circ)-N(180^\circ))/(N(0^\circ)+N(180^\circ))$

evaluated from the count rates N is used to detect the optical resonances. The beam intensities were of the order 10^6 atoms/s for ^{9}Li and 10^7 atoms/s for ^{8}Li. The extremely low concentration of radioactive nuclei in the crystal thus excludes perturbation due to radiation damages of previous implantations. The asymmetry observed for ^{8}Li and ^{9}Li was -3% and -1%, respectively, corresponding to an effective nuclear polarization of 10% inside the crystal.

A resonant rf field H_1, perpendicular to H_0, is generated by small coils around the stopper crystal. The stopper crystal of $LiNbO_3$ has a hexagonal lattice with a three-fold symmetry at the lithium sites; thus the asymmetry parameter of the electric-field-gradient tensor vanishes. For those lithium atoms coming to rest at substitutional lattice sites the energy of the (2I+1) magnetic substates with respect to H_o (parallel to the axially-symmetric electrical field gradient eq) is given in first order perturbation theory by [10]

(3) $E_m = -g_I \mu_K H_o m + h^2 \nu_Q \ (3m^2-I(I+1))/(4I(2I-1))$.

Here the QCC is defined as $\nu_Q = e^2qQ/h$ and all other symbols have their usual meanings. The approximation of first order perturbation theory is sufficient, because the Lamor frequency for both isotopes ^{8}Li and ^{9}Li is more than two orders of magnitude higher than the expected quadrupole splitting. For a nucleus with I = 2 four equidistant single quantum transitions occur with a frequency difference of $\nu_Q/4$, and for the I = 3/2 case one expects three equidistant resonances spaced by $\nu_Q/2$. The Larmor frequency and the QCC can be independently deduced from the line center and the splitting.

3. Experimental Results

Fig. 2 shows the β-NMR spectrum of ^{8}Li implanted into $LiNbO_3$ at room temperature. The four $\Delta m = 1$ transitions are clearly resolved. The strength of the rf field was kept small enough (H_1 = 0.3 G), not to increase the line width due to power broadening, and to avoid two-quantum transitions $\Delta m=2$.

The relative intensities of the lines correspond to the population differences produced by the optical pumping process. Since the optical excitation affects only one hyperfine component of the ground state, hyperfine pumping occurs into the second component. The resulting differences of population numbers between the m_I sublevels ensure the visibility of all 2I rf resonances, since the nuclear polarization is incomplete. The spectrum was fitted by four equidistant Gaussian curves with equal width. While the Gaussian curve is only an approximation of the real line shape caused by dipolar broadening and second-order quadrupole effects, the assumption of equal width is justified from conventional NMR measurements performed on ^{7}Li in $LiNbO_3$, where equal linewidths were measured for the inner and outer lines at room temperature. The observed magnetic splitting ν_L = 639.2(4) kHz, together with the well known magnetic moment of ^{8}Li [11] corresponds to an external magnetic field of H_0 = 1014.3(6) G. The splitting of the lines yields a QCC of ν_Q = 42.5(6) kHz for ^{8}Li. This value is in perfect agreement with an earlier measurement of 43(3) kHz [12].

Under the same conditions the QCC was measured for ^{9}Li in $LiNbO_3$. Fig. 3 shows the result of the β-NMR measurement. The data evaluation was analogous to the previous case. The magnetic splitting of ν_L = 1.7698(8) MHz gives a magnetic moment for ^{9}Li of μ_I = 3.4335(52) μ_N in agreement with ref. [1]. A QCC of ν_Q = 37.4(1.1) kHz was evaluated from the splitting. This is substantially smaller than the recently reported value [1] of 48.4(3.0) kHz, whereas the QCC of ^{8}Li agrees well with earlier results. A possible explanation for this discrepancy may be sought in radiation damage effects, occurring in experiments where strong primary beams pass through the target crystal. As mentioned in ref. [1], a similar difference is found by comparing the quadrupole moments of ^{8}Li evaluated from measurements using polarized neutron capture in $LiNbO_3$ [12] and $LiTaO_3$ [13] with a measurement using recoil implantation into $LiIO_3$ following the reaction $^7\mathrm{Li}(\vec{d},p)^8\mathrm{Li}$ induced by polarized deuterons [14].

Taking into account that in our experiment the QCC of ^{8}Li and ^{9}Li were measured under the same experimental conditions, we deduce a ratio for the quadrupole moments free from systematic errors

$$(4) \qquad |Q(^{9}Li)/Q(^{8}Li)| = \nu_Q(^{9}Li)/\nu_Q(^{8}Li) = 0.88(3)$$

Using the known QCC for ^{7}Li in $LiNbO_3$ of $\nu_Q(^{7}Li) = 54.7(3)$ kHz [15,16] and the quadrupole moment $Q(^{7}Li) = -37.0(8)$ mb [17], and assuming that the implanted lithium isotopes substitute the ^{7}Li in the host crystal, we obtain the quadrupole moments of ^{8}Li and ^{9}Li according to the relation

$$(5) \qquad |Q(^{A}Li)| = |Q(^{7}Li)| \; \nu_Q(^{A}Li)/\nu_Q(^{7}Li)$$

The results are $|Q(^{8}Li)| = 28.7(7)$ mb and $|Q(^{9}Li)| = 25.3(9)$ mb, where the uncertainties quoted include the experimental errors of our measurement and the calibration values.

4. Discussion

Since the quadrupole moments are very sensitive to core polarization and higher-order configuration mixing, they are interesting test quantities for theoretical nuclear models. The quantitative adequacy of these models is limited by the necessity to work in a truncated model space. Influences of configuration mixing not included in the chosen basis are normally taken into account by the introduction of effective charges $e_p = (e+\delta e)$ for protons and $e_n = \delta e$ for neutrons. A vanishing δe reproducing the properties of a nucleus would indicate that the model space was chosen large enough to include all existing excitations. Models using small configuration spaces [18,19] underestimate the absolute value of the quadrupole moments of light nuclei systematically. Assuming a positive sign for the quadrupole moment of ^{8}Li and a negative one for ^{9}Li Table 1 shows a comparison of measured and calculated quadrupole moments [5] for the lithium isotopes. The shell model calculation by Glaudemans and coworkers, including excitations up to $2\hbar\omega$ and a vanishing δe predicts $Q(^{9}\mathrm{Li}) = -28$ mb in good agreement with the experiment. The calculation was performed with a Reid soft-core potential and Talmi integrals to derive the effective two-body matrix elements. Even in a $2\hbar\omega$ model space the values for the quadrupole moment of ^{7}Li and ^{8}Li are somehow too small, indicating the importance of higher configuration mixings.

Since Q is proportional to the square of the harmonic-oscillator size parameter b, special care has to be taken as to a proper choice of this value. Normally b is adjusted to the rms charge radii which are assumed to be constant in these calculations for all lithium isotopes up to ^{9}Li. In this context it would be very interesting to measure the quadrupole moment of ^{11}Li ($I = 3/2$; $T_{1/2} = 8.7$ ms) to find out if the recently measured large increase in the matter radius [20] between ^{9}Li and ^{11}Li is also reflected in an increasing value for the quadrupole moment due to a larger charge radius, or if ^{11}Li near the neutron drip line behaves more like a ^{9}Li core plus two loosely-bound neutrons. Strong collective deformation with a correspondingly large quadrupole moment seems to be excluded already by the recent measurements of the spin $I = 3/2$ and a magnetic moment close to the single-particle value of the spherical $\pi(p_{3/2})$ state [7].

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FIGURE CAPTIONS

Fig. 1 Optical excitation scheme of ^{9}Li with the laser frequency fixed at the transition $2s\,^2S_{1/2}(F=2) \longrightarrow 2p\,^2P_{1/2}(F=2)$.

Fig. 2 β-asymmetry versus rf frequency of ^{8}Li (I=2) implanted into $LiNbO_3$.

Fig. 3 β-NMR spectrum of ^{9}Li (I=3/2) implanted into $LiNbO_3$.

Table 1

Measured and calculated quadrupole moments for the lithium isotopes. The theoretical values are taken vom ref. [5]. [a] [17]. [b] This work.

Nucleus	I^{π}	Q (mb)		
		theory		exp.
		$\delta e=0$	$\delta e=0.08e$	
^{7}Li	$3/2^-$	-25.	-31.	-37.0(8)[a]
^{8}Li	2^+	+22.	+26.	+28.7(7)[b]
^{9}Li	$3/2^-$	-28.	-39.	-25.3(9)[b]

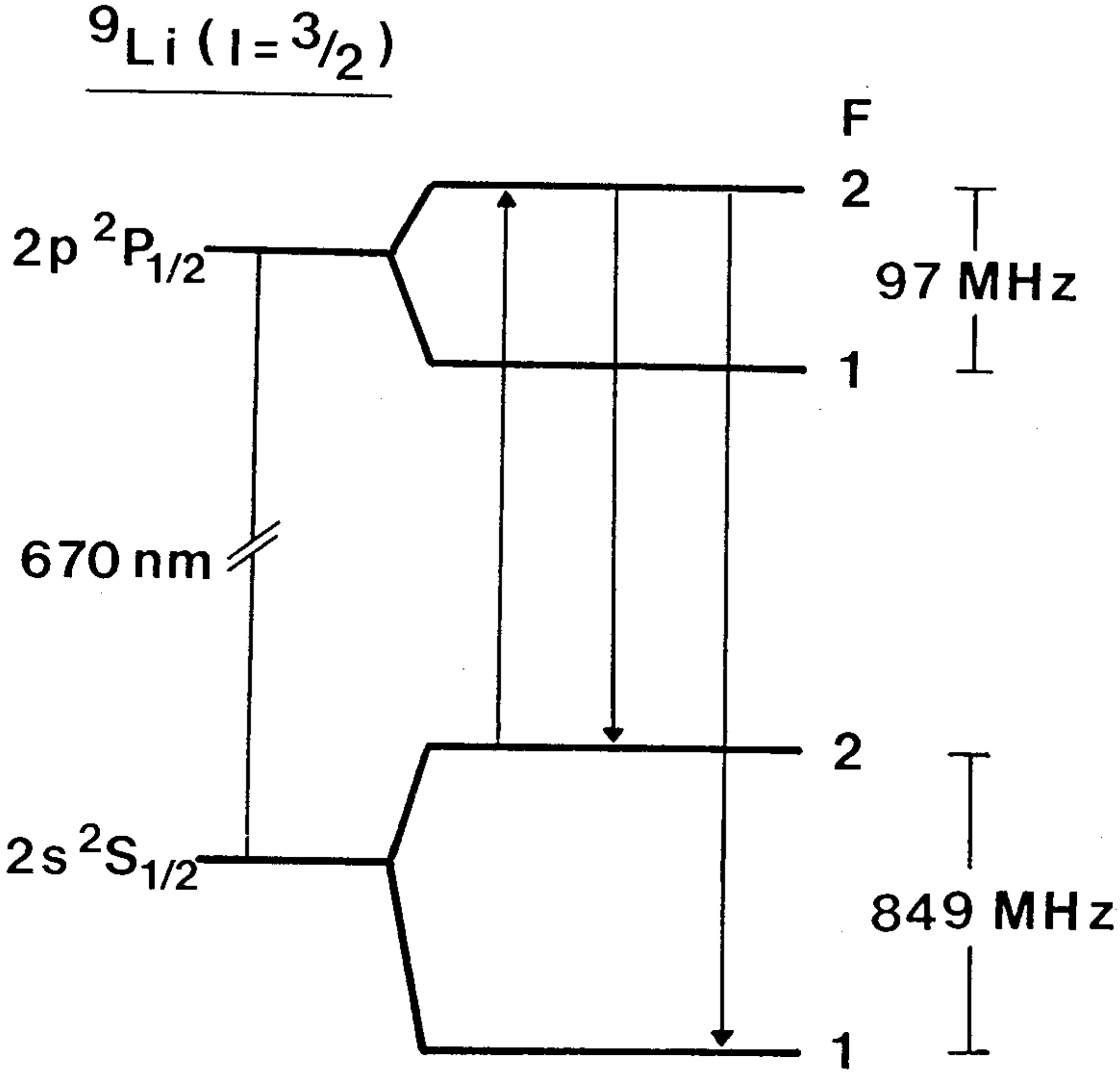

FIGURE 1

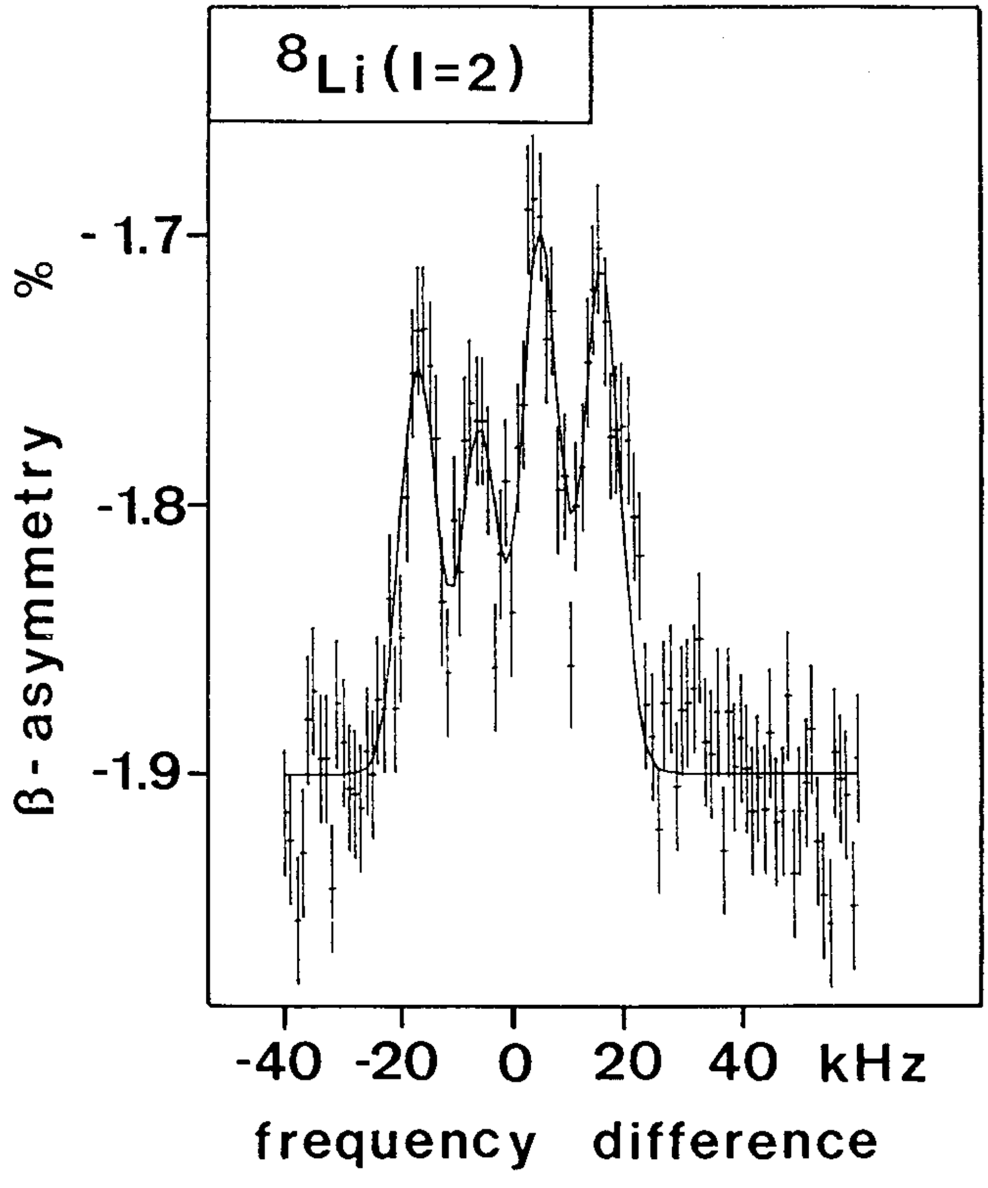
^{8}Li(I=2)
ß - asymmetry %
-1.7
-1.8
-1.9
-40
-20
0
20
40
kHz
frequency difference

FIGURE 2

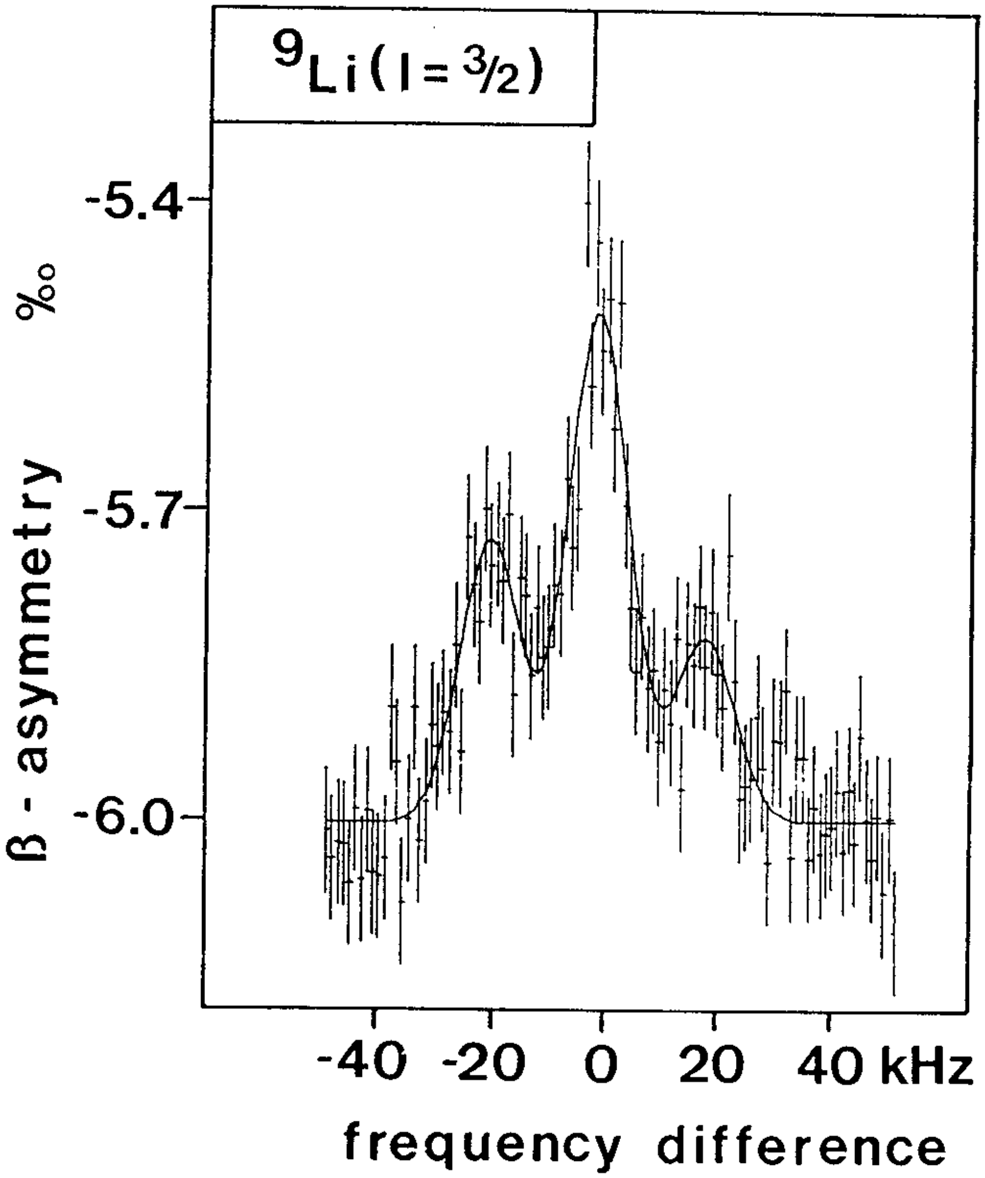
$^9Li(I=3/2)$
β - asymmetry ‰
-5.4
-5.7
-6.0
-40
-20
0
20
40 kHz
frequency difference

FIGURE 3