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Preparation for High-resolution Isotope Shift Measurements on Unstable Lithium Isotopes*

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Abstract: A high-resolution isotope shift measurement of lithium isotopes in a suitable transition, combined with an accurate theoretical evaluation of the mass-shift contribution in the corresponding transition, can be used to determine the root-mean-square nuclear charge radii of these isotopes. For the unstable ^{8,9}Li and the short-lived halo nucleus ^{11}Li, this is the only approach available for obtaining nuclear-model-independent values of the charge radii within the reach of present-day facilities. An experiment of this type is currently underway at GSI and planned for ISOLDE/CERN. The laser spectroscopic scheme and the experimental setup for the isotope shift measurement of lithium isotopes is described. The preliminary results is presented and the accuracy and sensitivity of this method is discussed.

Key words: halo nuclei; isotope shift; charge radius

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1 Introduction

The investigation of halo nuclei has received considerable attention since the mid-eighties and many approaches for a description of this exotic structure have been developed[1]. However, the fundamental question of how much the core nucleons are affected by the presence of the halo-forming nucleons is still open. Hence, an experimental determination of the root-mean-square (rms) charge radius of the neutron halo nucleus ^{11}Li, particularly its change from that of ^{9}Li, is of great interest and would constitute a sensitive test for various nuclear models.

Fundamental nuclear data for all accessible lithium isotopes are listed in Table 1, including the rms mass and charge radii. Though the charge radii of the two stable isotopes of lithium are known from the electron scattering method, this conventional approach is not applicable for ^{8,9,11}Li because of their short lifetimes and low production rates. Other methods like K-X ray or muonic atom spectroscopy are also excluded for the same reason.

A promising approach is based on a combination of atomic physics measurements and recent advances in atomic theory: the frequency of a transition out of the $2s$ ground state of the lithium atom is slightly affected by the finite nuclear charge distribution, and a measurement of the corresponding field shift can provide a nuclear-model-independent value of the charge radius. However, this field shift is accompanied by a mass-dependent shift that

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is 4 orders of magnitude larger and must be calculated with a relative accuracy of better than 10^{-5} to separate it from the overall isotope shift (see Table 2). The calculation has recently been completed for $2s \rightarrow 3s$ and $2s \rightarrow 2p$ transitions in atomic lithium[9]. By performing high-precision variational calculations for lithium and lithium-like ions with the use of multiple basis sets in Hylleraas coordinates, Yan and Drake have achieved the accuracy of ~200 kHz for the mass shift in these transitions. A formula for deducing the nuclear charge radius of a lithium isotope with mass number A is provided as:

$$r_{\mathrm{rms}}^2(^A\mathrm{Li}) = r_{\mathrm{rms}}^2(^6\mathrm{Li}) + \frac{E_{\mathrm{meas}}^A - E_0^A}{C},$$

where E_{meas}^A is the measured isotope shift, E_0^A contains all the calculated contributions to the isotope shift except for the nuclear size contribution. The constant C for the $2s \rightarrow 3s$ transition is $-1.566\ 2$ MHz/fm^2. The calculated values of E_0^A for all lithium isotopes are listed in Table 2.

Table 1 Summary of nuclear spin and parity (J^π), half-life ($T_{1/2}$), magnetic dipole and electric quadrupole moments (μ_I and Q), rms matter and charge radii of the lithium isotopes*

Isotope	J^π	$T_{1/2}$/ms	$\mu_I[\mu_N]$[2]	Q/mbarn	R_m[6,7]	R_c[8]
^{6}Li	1^+	∞	0.822 047 3(6)	−0.83(8)[3]	2.35(3), 2.45(7)	2.55(4)
^{7}Li	$3/2^-$	∞	3.256 426 8(17)	−40.0(3)[4]	2.35(3)	2.39(3)
^{8}Li	2^+	838(6)	1.653 560(18)	31.1(5)[5]	2.38(2), 2.45(6)	?
^{9}Li	$3/2^-$	178.3(4)	3.439 1(6)	−27.4(1.0)[5]	2.32(2), 2.43 (7)	?
^{11}Li	$3/2^-$	8.59(14)	3.667 8(25)	−31.2(4.5)[5]	3.10(17), 3.62(19)	?

Table 2 Expected mass shifts E_0^A between all accessible lithium isotopes for the transition $2s \rightarrow 3s$[9], where the field shift value between ^{7}Li and ^{6}Li is calculated from the electron scattering data with the formula provided in the same paper

	^{7}Li—^{6}Li	^{8}Li—^{6}Li	^{9}Li—^{6}Li	^{11}Li—^{6}Li
Mass shift [MHz]	11 453.07(6)	20 088.23(10)	26 785.18(13)	36 555.34(21)
Field shift [MHz]	−1.24(39)	?	?	?

In the following, a laser spectroscopic scheme and the corresponding setup that will allow the determination of the isotope shift with an accuracy comparable to these calculations are described. We expect to determine the rms charge radii of the unstable lithium isotopes with an uncertainty of less than 2% .

2 Experiment

Fig. 1 shows the level scheme of lithium and the excitation path that has been chosen in order to provide both high accuracy and sufficient excitation and ionization efficiency to compensate the low production rate and short lifetime of ^{11}Li. The $2s \rightarrow 3s$ transition is used to probe the isotope shift with the required accuracy. The Doppler-free excitation offers the advantage that all atoms of the entire velocity distribution fulfill the resonance condition and a narrow resonance line can be observed. Out of the $3s$ state the lithium atoms undergo spontaneous decay into the $2p$ state and are then efficiently ionized via the $3d$ intermediate level. The decay process to $2p$ decouples the $2s$ and $3s$ states from the strong ionizing laser beam , which otherwise

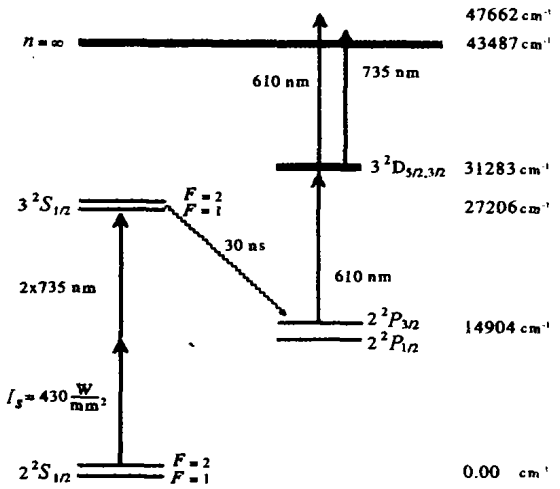

Fig. 1 Level diagram and the excitation scheme for the resonance ionization of an atomic lithium

can cause light shift and broadening. This excitation scheme has been tested for the stable isotopes $^{6,7}Li$[10, 11]. From the results of these measurements an ionization efficiency of $\sim 10^{-3}$ has been estimated.

The experimental setup is shown schematically in Fig. 2 . It shows the laser system on the left side and the vacuum apparatus including the quadrupole mass spectrometer on the right side. Lithium ions created in the tantalum target via proton-induced spallation, fission and fragmentation are accelerated to ~60 keV per nucleon, mass separated, and implanted into a graphite foil, from which they are released as atoms with thermal energies. Resonant laser excitation is used to re-ionize the atoms. The ions are then again mass separated and detected with a commercial quadrupole mass spectrometer. The isotope shift will be measured in the $2s \rightarrow 3s$ two-photon transition, which offers both a narrow line profile for a precise determination of the transition frequency and high efficiency. The subsequent low-background single-ion detection provides a sufficiently high signal-to-noise ratio.

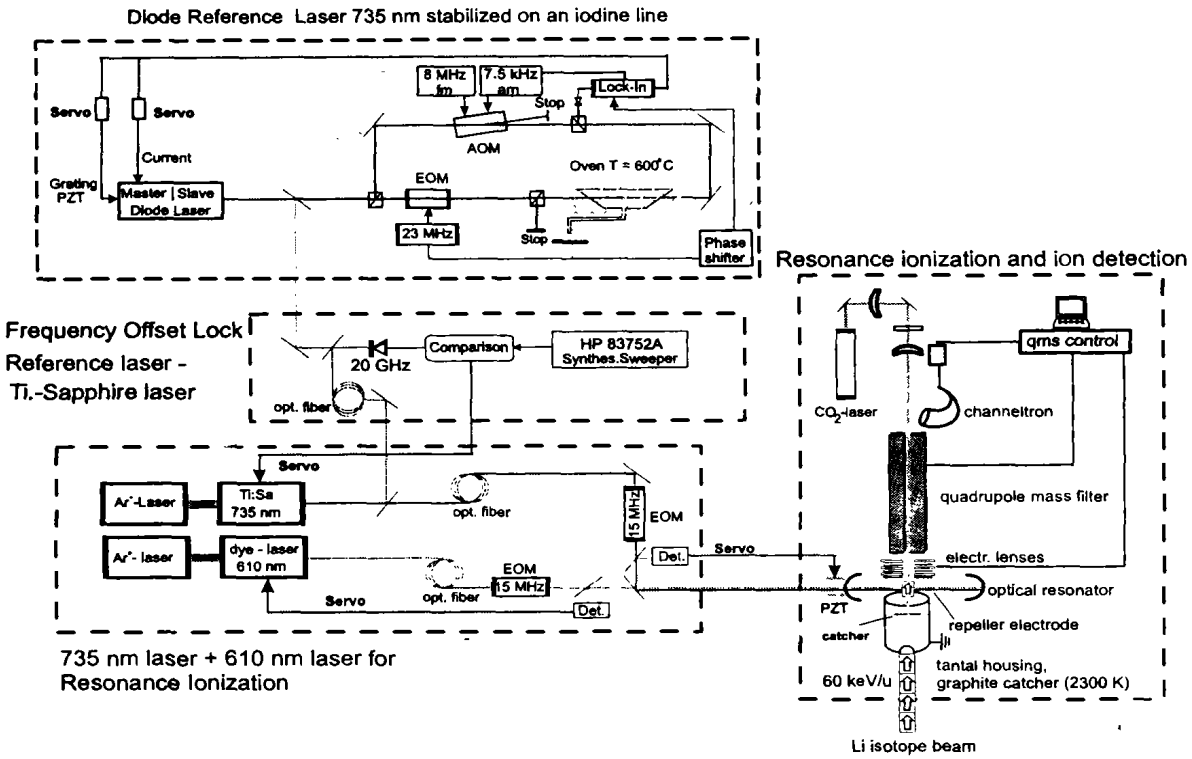

Fig. 2 Experimental setup for the resonance ionization of lithium

To assure the necessary frequency precision of the order of 100 kHz the Ti:Sa laser will be stabilized by RF-offset locking relative to a 735 nm diode laser, which in turn is stabilized to a molecular iodine transition as a fixed frequency reference point. An appropriate transition in iodine has been

located at 13 603.22 cm^{-1} and its hyperfine structure was recorded using FM-saturation spectroscopy. The iodine cell was heated to ~600 °C to provide sufficient population of the lower level of the hot-band transition. A saturation signal recorded with laser powers of 20 mW in the pump and 1mW in the probe beam (1 mm diameter) is shown in Fig. 3 (a). Three groups of unresolved and three single hyperfine lines were observed. The strongest isolated line (a_1) is well separated from all others and will be used for locking the diode laser. A signal-to-noise ratio of about 300 was achieved for this line and it shows a peak-to-peak width of ~10 MHz. Thus an accuracy of about 30 kHz for locking to the reference point can be expected.

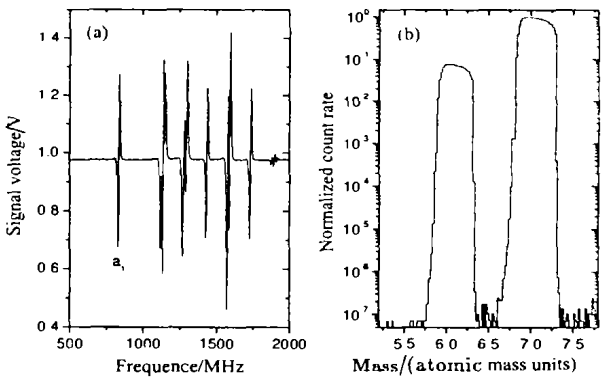

Fig. 3 (a) Hyperfine spectrum of the iodine transition $X^1\Sigma_g^+ \rightarrow B0_u^+$ R(114) 2—11 at 600 °C; (b) shapes of the mass peaks of the stable lithium isotopes ^{6,7}Li

The ions obtained by the resonance ionization process are mass separated and detected with a commercial quadrupole mass spectrometer (QMS). Its axial electron beam ion source was replaced by an ion optics constructed to meet the requirements of our experiment. The mass peak shape of the QMS has been optimized using lithium ions produced by surface ionization to yield an abundance sensitivity of better than 10^{-7}. A recorded mass spectrum is shown in Fig. 3(b).

3 Summary and Outlook

An experimental approach for the measurement of lithium isotope shifts has been presented. The high accuracy and efficiency of this spectroscopic scheme was demonstrated in off-line tests of the excitation path for the resonance ionization of stable lithium atoms. Frequency modulation saturation spectroscopy of the molecular iodine has been performed and its suitability for frequency locking of the lasers was shown. The quadrupole mass filtering and detection system has also been characterized which offers an adequate abundance sensitivity. After the completion of all frequency-locking electronics, the isotope shift measurement for the stable isotopes ^{6,7}Li will be performed off-line and the unstable ^{8,9}Li isotopes will be measured at the GSI on-line separator. The final measurement for the halo nucleus ^{11}Li is planned at ISOLDE/CERN.

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不稳定锂同位素移位的高精度测量实验方案*

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摘　要：对丰中子晕核^{11}Li 的核电荷均方根半径的实验确定，特别是其与^{9}Li 的半径的差值，将对各种核模型进行灵敏的检验. 选择锂的合适跃迁，利用激光光谱技术高精度测量该跃迁的同位素移位，并扣除精确理论计算的质量移位贡献值，可以用来确定有关同位素的核电荷均方根半径. 就目前能够提供的实验设备和手段，对于不稳定锂的同位素^{8,9}Li 和短寿命丰中子晕核^{11}Li 而言，这是能够得到与核模型相独立的电荷半径值的唯一可行的方法. 这类实验正在德国重离子研究中心(GSI)和欧洲核子中心的 ISOLDE/CERN 上计划实施. 描述了锂原子的激光激发共振电离途径和进行锂的同位素移位测量的实验装置，并讨论了采用这种方法测量到的^{6,7}Li 的初步结果及其精度，以及使用该方法研究不稳定核的灵敏性.

关键词：晕核；同位素移位；电荷半径

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