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Measurement of the nuclear charge radii of ^{8,9}Li

The last step towards the determination of the charge radius of ^{11}Li

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Abstract. Nuclear charge radii of ^{6,7,8,9}Li have recently been measured at the GSI on-line mass separator using high-resolution resonance ionization mass spectroscopy. We give a brief description of the experimental method. The results for the charge radii are compared with different theoretical predictions.

PACS. 21.10.Ft Charge distribution – 21.60.-n Nuclear structure models and methods – 32.10.-f Properties of atoms

Model-independent nuclear charge radii can be determined from isotope shift (IS) measurements on electronic transitions. This approach resulted in an impressive number of data on charge radii during the past decades [1,2]. The IS has two origins: the mass shift (MS), due to the change in nuclear mass between the isotopes, and the field shift (FS), which arises from the difference in the charge distribution inside the nuclei. The FS contains the information required to determine the change in the root-mean-square (r.m.s.) charge radius. Unfortunately, the MS is dominant for light isotopes and obscures the small FS, making it virtually impossible to apply this method for very light elements. Progress in atomic theory during the last decade opened the opportunity to apply this method to the lightest elements ($Z \leq 3$). High-precision calculation of the MS in helium- and lithium-like systems are now available and can be used to isolate the FS contribution, provided that the IS can be measured to a relative accuracy of better than 10^{-6}. This approach was used to determine the change in charge radii between the stable isotope pairs ^{3,4}He [3] and ^{6,7}Li [4,5,6]. Recently, first applications to short-lived nuclei were reported: The charge radii of ^{8,9}Li were determined at GSI [7], followed by an experiment on ^{6}He in a magneto-optical trap at Argonne National Laboratory [8]. The experiment at GSI was a precursor for a charge radius determination of the prominent halo nucleus ^{11}Li, which will resolve the long-standing puzzle whether the additional, loosely bound neutrons affect the distribution of the protons inside the ^{9}Li-like core.

The short-lived isotopes ^{8,9}Li were produced at GSI in reactions of an 11.4 MeV/u ^{12}C ion beam impinging on a carbon or a tungsten target. Yields of 200,000 (^{8}Li) and 150,000 (^{9}Li) ions per second were obtained out of the surface ion source, mass separated in a 60° sector magnet and delivered for laser spectroscopy. The ions were stopped and neutralized inside a thin (80 μg/cm^2), hot graphite foil. Atoms, diffusing out of the foil, drift into the ionization region of a quadrupole mass spectrometer (QMS). Here they are resonantly laser-ionized using the following excitation and ionization scheme

$$2s\ ^2S_{1/2} \stackrel{\lambda_1 \lambda_1}{\longrightarrow} 3s\ ^2S_{1/2} \stackrel{\tau}{\rightarrow} 2p\ ^2P_{1/2,3/2}\,,$$
$$2p\ ^2P_{3/2} \stackrel{\lambda_2}{\rightarrow} 3d\ ^2D_{3/2,5/2} \stackrel{\lambda_{1,2}}{\longrightarrow} \mathrm{Li}^+\,.$$

The spontaneous decay from the $3s$ to the $2p$ level with a lifetime of $\tau \approx 30$ ns decouples the precise $2s \rightarrow 3s$ two-photon spectroscopy from the efficient ionization via the $3d$ level. A titanium-sapphire laser (Ti:Sa) provides $\lambda_1 = 735$ nm for the two-photon transition and a dye laser produces $\lambda_2 = 610$ nm for the resonance ionization. Both laser beams are resonantly enhanced in an optical cavity around the interaction region and intensities inside the resonator are monitored with photodiodes placed behind the high-reflector of the cavity. Created ions are mass separated inside the QMS and finally detected with a channeltron-type detector. Details of the experimental setup and the laser system were described previously [7].

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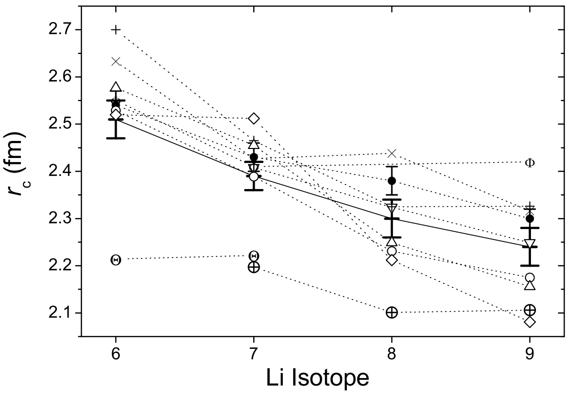

Fig. 1. The r.m.s. charge radii for ^{6,7,8,9}Li: (-) this measurement with $r_c(^7\mathrm{Li})$ from electron scattering as reference; (●) obtained from interaction cross-section measurements using Glauber theory [18]; (⊕) LBSM [11]; (Θ) NCSM [12]; (∇) SVMC [13]; (Φ) DCM [14]; GFMC calculations using AV8′ (×), AV18/UIX (+), AV18/IL2 (○), AV18/IL3 (△), and AV18/IL4 (◇) [15,16,17].

To observe the resonance signals, the Ti:Sa frequency is scanned across the two-photon resonances of the different isotopes. The beat signal between the Ti:Sa and a reference diode laser that is locked to an iodine line is used to obtain an accurate frequency axis. For isotope shift determination, the observed resonance profiles are fitted with an appropriate line profile for a two-photon transition and then corrected for residual AC Stark shift. The results were compared with the mass shift calculations of Yan and Drake [9] to extract the change in the r.m.s. charge radii between the isotopes. In order to calculate absolute charge radii, we took the ^{7}Li charge radius of 2.39(3) fm measured by electron scattering [10] as a reference.

The results of 2.30(4) fm (^{8}Li) and 2.24(4) fm (^{9}Li) are shown in fig. 1 and compared with predictions from different theories. The point-proton radii r_p, given in most theoretical work, have been converted to charge radii r_c by folding in the proton and neutron r.m.s. charge radii. Five different approaches are shown in the figure: large-basis shell-model (LBSM) [11], *ab-initio* no-core shell model (NCSM) [12], stochastic variational multi-cluster (SVMC) [13], dynamic correlation model (DCM) [14] and Greens function Monte Carlo (GFMC) [15,16,17] calculations. The SVMC approach shows excellent agreement with our experimental results. GFMC calculations were carried out using a variety of effective low-energy model potentials for the two-nucleon interaction (AV8′, AV18) and for the three-nucleon interactions (UIX, IL2, IL3, IL4). Here, the combination of AV18 with the IL2 three-body potential results in the best agreement of the calculated radii with those observed in the experiment. On the other hand, the DCM, LBSM and the NSCM calculations do not agree with our results. For comparison, the figure includes model-dependent r_c values derived from experimental interaction cross-sections using Glauber-type calculations [18]. These results show a similar trend of decreasing charge radii, but to a slightly smaller extent.

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