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Nuclear charge radii of potassium isotopes beyond $N = 28$

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ABSTRACT

We report on the measurement of optical isotope shifts for $^{38,39,42,44,46-51}$K relative to ^{47}K from which changes in the nuclear mean square charge radii across the $N = 28$ shell closure are deduced. The investigation was carried out by bunched-beam collinear laser spectroscopy at the CERN-ISOLDE radioactive ion-beam facility. Mean square charge radii are now known from ^{37}K to ^{51}K, covering all $\nu f_{7/2}$-shell as well as all $\nu p_{3/2}$-shell nuclei. These measurements, in conjunction with those of Ca, Cr, Mn and Fe, provide a first insight into the Z dependence of the evolution of nuclear size above the shell closure at $N = 28$.

1. Introduction

Mean square charge radii of nuclei in the calcium region ($Z = 20$) have been the subject of extensive investigation, both experimentally [1–6] and theoretically [5–10]. Although existing data cover the full $\nu f_{7/2}$ orbital, very little is known on the nuclei above $N = 28$ with valence neutrons in the $p_{3/2}$ orbital. Furthermore, substantial structural changes are predicted in this region, including the inversion and subsequent re-inversion of the $\pi s_{1/2}$ and $\pi d_{3/2}$ shell-model orbitals [1,11] and the development of sub-shell closures at $N = 32$ and $N = 34$ [12–16]. Whilst theoretical models of charge radii across the $\nu f_{7/2}$ shell have been successful in describing the trend observed for calcium [8,9], little is known about how this observable would be influenced by the anticipated structural evolution in the region beyond $N = 28$.

The inversion of the odd-A potassium ground-state configuration from $I = 3/2$ ($\pi d_{3/2}$) in $^{39-45}$K to $I = 1/2$ ($\pi s_{1/2}$) for ^{47}K ($N = 28$) was reported by [1] in 1982 and has subsequently been reproduced by nuclear shell-model and mean-field calculations [17–19]. The question of how the $\pi d_{3/2}$ orbital evolves whilst filling the $\nu p_{3/2}$ orbital has been addressed in a recent paper by [11] for the even-N isotopes ^{49}K and ^{51}K, having respectively spin 1/2 and 3/2. In the present work, the ground-state structure of the odd-N isotopes ^{48}K and ^{50}K and a detailed analysis of the spin determination for ^{51}K are presented. With the spin measurements on $^{48-51}$K the contradictory assignments found in decay spectroscopy data [20–24] are resolved. These spins in combination with the magnetic moment of ^{48}K fully define the region of inversion [25].

In this Letter we report on the measurement of optical hyperfine structure and isotope shifts for $^{38,39,42,44,46-51}$K relative to ^{47}K, from which changes in the nuclear mean square charge radii are deduced.

2. Experimental method and data analysis

The measurements were carried out at the collinear laser spectroscopy setup COLLAPS [26] at ISOLDE-CERN [27]. Neutron-rich

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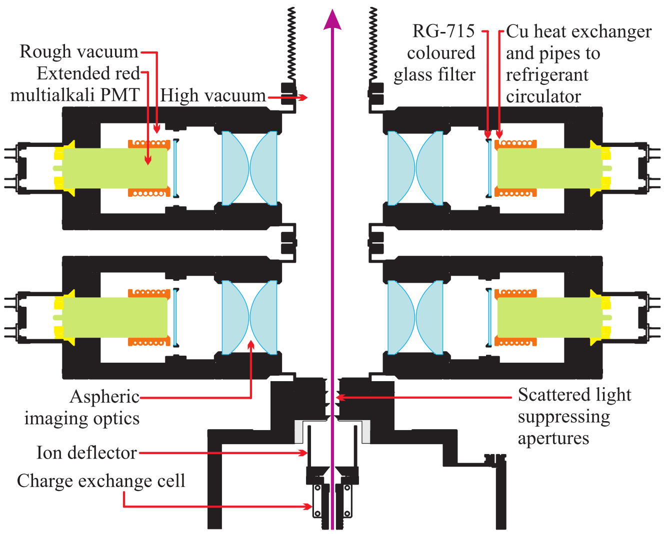

Fig. 1. (Color online.) Cut through the optical detection region (top view). The atom and laser beams enter the detection region through the charge exchange cell (bottom). For details see text.

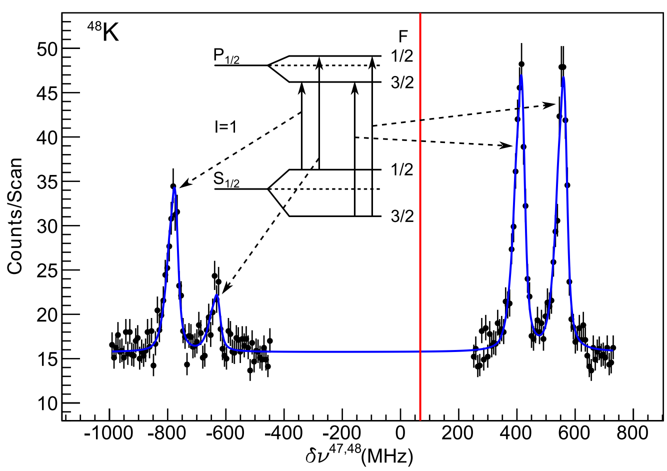

Fig. 2. (Color online.) Optical spectrum of ^{48}K recorded with 0.2 mW laser power. Also shown is the fitted hfs (blue solid line) and the hfs centroid (red vertical line). The ($S_{1/2}$) and ($P_{1/2}$) level scheme is shown as an inset.

potassium isotopes were produced by 1.4-GeV protons impinging onto a thick UC_x target. The isotopes were surface ionized, accelerated to 40 keV, mass separated and directed to the ISOLDE cooler-buncher ISCOOL [28]. After ISCOOL the ion bunches were directed to the collinear laser spectroscopy beam line, where they were neutralized in collisions with potassium vapor. The atomic $4s\ ^2S_{1/2} \rightarrow 4p\ ^2P_{1/2}$ transition ($\lambda = 769.9$ nm) was excited by light generated from a cw titanium-sapphire ring laser. Frequency scanning was performed by applying an additional acceleration potential to the neutralization cell, thus varying the Doppler-shifted laser frequency in the reference frame of the atoms. A light collection system consisting of four separate photomultiplier tubes (PMTs) with imaging optics placed perpendicular to the beam path was used to detect the resonance fluorescence photons. Counts from the PMTs were only accepted during the time in which the atom bunches passed through the light collection system. The background from scattered photons was thus reduced by a factor of $\sim 10^4$ [29,30].

Optical spectroscopy of K isotopes is hindered by the relatively slow decay rate of the atomic transition ($3.8 \times 10^7\ s^{-1}$) as well

Table 1
Spins, isotope shifts referenced to ^{47}K ($\delta\nu^{47,A}$), and changes in mean square charge radii ($\delta\langle r^2\rangle^{47,A}$) of potassium isotopes in the atomic transition $4s\ ^2S_{1/2} \rightarrow 4p\ ^2P_{1/2}$. Statistical errors are shown in round brackets, systematic errors in square brackets. Complementary data $\delta\nu^{39,A}$ from [3] and [1] (published without systematic errors), referenced to ^{39}K, are quoted in the fourth column.

A	I^π	$\delta\nu^{47,A}$ (MHz)	$\delta\nu^{39,A}$ (MHz)	$\delta\langle r^2\rangle^{47,A}$ (fm^2)
37	3/2$^+$		−265.(4)	−0.163(40)[199]
38	3$^+$	−985.9(4)[34]		−0.126(3)[177]
			−127.0(53)	−0.140(51)[174]
39	3/2$^+$	−862.5(9)[30]		−0.037(8)[153]
			0	−0.082(15)[151]
40	4$^-$		125.6(3)	−0.066(16)[129]
41	3/2$^+$		235.3(8)	0.036(17)[108]
42	2$^-$	−506.7(7)[17]		0.034(6)[89]
			351.7(19)	0.026(23)[88]
43	3/2$^+$		459.0(12)	0.049(19)[69]
44	2$^-$	−292.1(5)[10]		0.036(5)[51]
			564.3(14)	0.047(20)[50]
45	3/2$^+$		661.7(16)	0.072(21)[33]
46	2$^-$	−91.6(5)[3]		−0.002(4)[16]
			762.8(15)	0.026(21)[16]
47	1/2$^+$	0	857.5(17)	0
48	1$^-$	67.9(4)[3]		0.186(3)[16]
49	1/2$^+$	135.3(5)[6]		0.342(4)[32]
50	0$^-$	206.5(9)[9]		0.434(8)[47]
51	3/2$^+$	273.2(14)[11]		0.538(13)[61]

as a low (2.5%) quantum efficiency of the PMTs with a high heat-related dark count rate. In order to perform the measurements on a ^{51}K beam of approximately 4000 ions/s, a new optical detection region was developed. Eight 100-mm diameter aspheric lenses were used to precisely image the fluorescence of the laser-excited K atoms onto four extended-red multialkali PMTs in the arrangement shown in Fig. 1. The light-collection efficiency of this system is approximately twice that of the previous standard system described in [31], whilst the background from scattered laser light is an order of magnitude lower. The PMTs were maintained at −40 °C using a refrigerant circulator to reduce dark counts and held under vacuum to prevent ice formation. RG715 colored glass filters were placed in front of the PMTs in order to cut the strong visible beam light originating from stable contaminant beams of Ti and Cr excited in collisions in the charge exchange cell.

Isotope shift measurements were performed relative to ^{47}K. The spectra were fitted with a hyperfine structure (hfs) using a line shape composed of multiple Voigt profiles [32,33], which were found to describe most adequately the asymmetric line shape, using χ^2 minimization (see Figs. 2 and 4). The asymmetry originates from inelastic collisions in the charge exchange process. The reduced χ^2 of the fit could be improved from 2.2 (single Voigt) to 1.5 (multiple Voigt). For the fit a two-parameter first-order hyperfine splitting [34] was used. The magnetic hyperfine parameters A and the centroid of each hfs were extracted. A sample spectrum for ^{48}K is shown in Fig. 2 together with the fitted hfs spectrum. Also shown are the energy levels of the ground state ($S_{1/2}$) and excited state ($P_{1/2}$) with allowed transitions.

In Table 1 we give the ground-state spins deduced from the measured hfs patterns. The spins measured for $^{37-47}$K, previously reported in [1,35], are confirmed by the present analysis. Our new spins measured for ^{49}K and ^{51}K have been published in [11]. The procedure to determine the spins of ^{48}K, ^{50}K and ^{51}K will be described in the following.

3. Spin determination for ^{48,49,50,51}K

For ^{48}K our spin assignment is based on the different relative intensities of the hfs components for ^{46}K ($I = 2$) and ^{48}K. The hfs fits only cannot distinguish between the assumed spins of $I = 1$