EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Study of neutron-rich ^{52,53}K isotopes by the measurement of spins, moments and charge radii.

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Abstract

Experimental results of ground state spins, magnetic moments and charge radii of K isotopes up to $N = 32$ in a previous experiment (IS484) at COLLAPS have demonstrated the re-inversion of the proton single-particle levels at $N = 32$. To extend the study to more exotic isotopes, we propose to perform the measurement of the spins, magnetic moments and charge radii of ^{52,53}K, across $N = 32$ and up to $N = 34$, by using the collinear resonance ionization laser spectroscopy (CRIS) setup. The measured magnetic moments will provide further information on the shell evolution of proton sd shell as the neutron $p_{1/2}$ orbit is filled. Additionally, the charge radii measurements will provide key information on the suggested $N =$ 32 subshell closure. The measurement will provide a prominent test of state-of-the-art theoretical calculations and probe the role of the three-body force, recently included in theory calculations developed in the mid-mass Ca region.

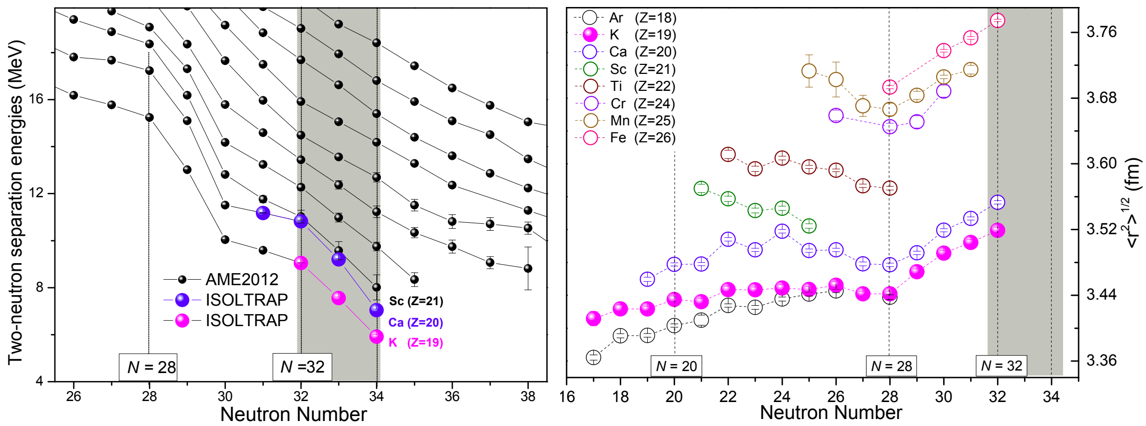
Requested shifts: 11 shifts

1 Introduction and Physics motivations

Investigating and understanding the shell evolution of exotic nuclei using both theoretical and experimental approaches is one of the key issues in current nuclear physics research. In the shell-model framework, the changes of shell structure as a function of neutron and proton numbers in exotic nuclei are thought to be due to the monopole part in the proton-neutron interaction, in particular the tensor component [1]. The effect of the tensor force has been successfully used to explain several experimental observations: the reduction of $N = 20$ shell gap in the region of the "island of inversion" [2, 3], the weakening of the $N = 28$ shell gap in the region below $_{20}$Ca [4, 5], the inversion of proton orbits in odd $_{19}$K and $_{17}$Cl towards $N = 28$ [6] and in odd $_{29}$Cu and $_{31}$Ga towards $N = 50$ [7, 8]. Very recently, three-nucleon (3N) forces were included in different theoretical calculations [9, 10, 11] to describe the experimental observation in the mid-mass Ca region, and were found to provide key mechanisms governing the shell evolution. Laser spectroscopy measurement has already provides indispensable experimental results on the nuclear shell evolution in different mass regions (e.g. Mg, Ca, Cu isotopic chain [2, 12, 7]). More experimental observations, in a few specific mass regions, are needed to test the different theoretical models and probe the behavior of the shell evolution.

Recently, isotopes in the Ca region have been studied intensively, seeking experimental evidence of the proposed subshell closures at $N = 32$, 34 [13, 14, 15, 16]. In the framework of the shell model, the suggested shell closures at $N = 32$, 34 are explained as follows: when protons are removed from the $\pi f_{7/2}$ orbit, the strong attractive interaction with the $\nu f_{5/2}$ decreases, resulting in a shift of the $\nu f_{5/2}$ orbit relative to the $\nu p_{3/2}$-$\nu p_{1/2}$ spin-orbit partners, thus opening a sub-shell gap at $N = 32$ and $N = 34$. The sub-shell effect of $N = 32$ has been observed in the isotopes of Ca [17], Ti [18] and Cr [19] with an energy increase of the first excited 2^+ state, and in neutron-rich K and Ca isotopes with a drop in S_{2n} across $N = 32$, as shown in Figure 1a [13, 20]. A strong $N = 34$ shell gap in ^{54}Ca is predicted by a shell model calculation based on the GXPF1 interaction [21]. Furthermore, a larger shell gap for ^{54}Ca compared with that for ^{52}Ca is also predicted by Holt *et al* [11] with a three-nucleon (3N) forces included. Using the coupled-cluster calculation which employs interactions from chiral effective field theory and includes the effect of 3N force, Hagen *et al* [10] have predicted a ~ 2 MeV $E(2_1^+)$ for ^{54}Ca, suggesting a soft subshell closure. Experimental $E(2_1^+)$ (~ 2 MeV) in ^{54}Ca [13] was measured in RIKEN recently, showing a comparable value with ^{52}Ca and providing direct experimental evidence for the doubly magic nature of ^{54}Ca. This measured $E(2_1^+)$ was reproduced by a shell model calculation performed in the *sd*-*fp*-*sdg* model space using a modified GXPF1B interaction [13].

The mean square charge radii in both the K and Ca isotopic chain were measured recently at COLLAPS, showing no effect of a $N = 32$ sub-shell closure [22, 23]. As shown in Figure 1b, the charge radii of both ^{51}K and ^{52}Ca are increasing with a similar trend as for Mn or Fe, where no subshell closure is predicted. Beyond that, the magnetic moment of ^{51}Ca, having a single-hole with respect to the suggested $N = 32$ subshell closure, indicates an appreciable mixing with configurations above $N = 32$ [12]. To shed more light on the possible magicity or not of neutron numbers 32 and 34, further experimental studies on isotopes in the Ca region, beyond $N = 32$, are needed. We propose therefore



(a) (b)

Figure 1: (a): Two neutron separation energy in the Ca region [14, 20, 24]. (b): Mean square charge radii of isotopes in Ca region around $N = 32$ [22, 23, 25].

to study the neutron-rich ^{52,53}K ($Z = 19$) isotopes, across $N = 32$ and up to $N = 34$, by measuring the spins, magnetic moments and charge radii using collinear resonance ionization laser spectroscopy (CRIS) at ISOLDE.

Previous laser spectroscopy measurements performed on neutron-rich K isotopes (up to ^{51}K) at the COLLAPS beamline have elucidated important aspects of nuclear structure in the Ca region [26, 27]. The measured nuclear spins and magnetic moments up to $N = 32$ demonstrated for the first time the re-inversion of the proton single-particle levels at $N = 32$, and investigated the evolution of proton sd orbits as neutrons filled the fp orbits, by comparison with shell model calculations. In addition to the effect of the tensor component suggested by Otsuka *et al.* [1], the central term of the monopole interaction was found to have the strongest effect in the changing of effective single-particle energies (ESPE) of proton $s_{1/2}d_{3/2}$ orbits beyond $N = 28$. The evolution of the proton $s_{1/2}$ and $d_{3/2}$ shell gap has been discussed systematically based on the shell model and ab initio calculations, showing a difference above $N = 32$ from both SDPF-NR and SDPF-U interactions [27]. Therefore, experimental ground-state spins and magnetic moments of the neutron-rich ^{52,53}K beyond $N = 32$ are highly desired to investigate the evolution of the proton sd levels as neutrons are filling the higher fp orbits in this region. As mentioned, the 3N forces have been included in several theoretical approaches for a better description of the experimental binding energy and $E(2_1^+)$ energies of Ca isotope [10, 11]. Especially, 3N forces provided the first microscopic explanation for the $N = 28$ magic number in ^{48}Ca [11]. Very recently, the NN + 3N interaction derived from chiral effective field theory [28] was used to calculate the ground-state nuclear moments of the neutron-rich Ca isotopes up to ^{51}Ca, showing an excellent agreement for both the magnetic and quadrupole moments [12]. The experimental data on neutron-rich K will provide compelling test for state-of-the-art theoretical calculations developed in the Ca mass region, and will be important for further developments of microscopic interactions and exploring the role of 3N forces.

Figure 1b illustrates the experimental data of charge radii in the Ca region. To verify $N = 32$ as a sub-shell closure, mean-square charge radii measurements of isotopes beyond the proposed closed shell is critical. Therefore, measuring the charge radius of ^{52}K will be the key to understanding the nature of $N = 32$, while the charge radius of ^{53}K will provide important information on the suggested $N = 34$ sub-closed shell. Theoretical

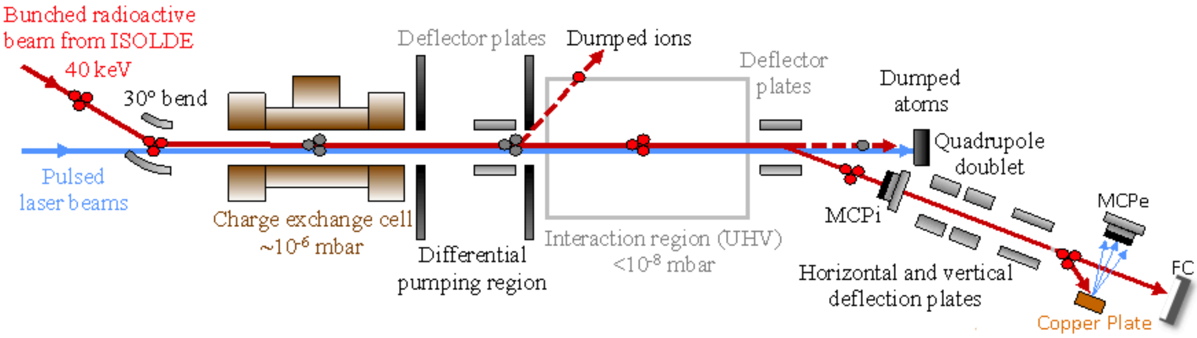


Figure 2: Schematic diagram of the CRIS beam line used for this experiment [32, 34].

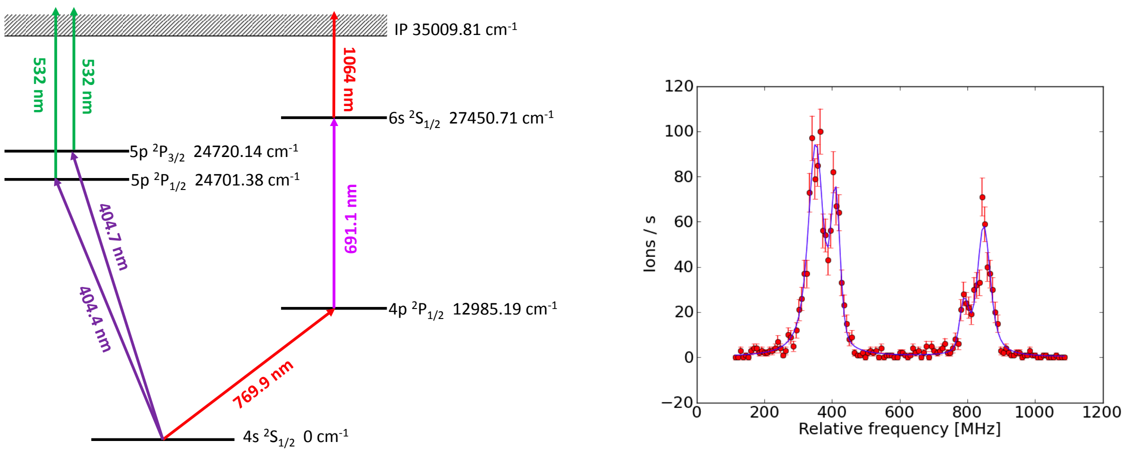
descriptions of charge radii in medium mass nuclei remains a major challenge [29]. Many theoretical approaches are trying to explain the charge radii trend of isotopes in the Ca region, but not a single theoretical model can fully explain the experimental charge radii [22]. Very recently, ab initio calculations with 3N forces included have been successfully applied to describe charge radii of medium mass nuclei in the vicinity of doubly-magic nuclei [22, 30]. As this calculation is ideally suited for nuclei with at most one or two nucleons outside a closed (sub-) shell, charge radii measurements of ^{52,53}K isotopes will be important for testing the role of many-body correlations in such calculations.

2 Experimental method

The hyperfine structure (HFS) spectra and the isotope shift (IS) of neutron-rich K isotopes will be measured by collinear resonance ionization laser spectroscopy (CRIS) at ISOLDE [31, 32, 33]. This technique combines the advantages of the high sensitivity obtained by particle detection of resonantly ionized isotopes, with the high resolution of collinear laser spectroscopy. High efficiency and high resolution (20 MHz for Fr [33]) have been achieved during the Fr experiments in 2012 and 2014, which allowed exotic isotopes to be studied [31] and quadrupole moments to be deduced [33].

In this proposed experiment, the radioactive K ion beams separated by the high-resolution HRS separator, will be cooled and bunched by ISCOOL. The bunched beam at 40 keV will be deflected into the CRIS beam line, as shown in Figure 2. The ions will be first neutralized in a charge exchange cell (CEC) with K vapor. The ions which were not neutralized will be deflected after the CEC, while neutralized atoms are then spatially overlapped and time synchronized with the narrow-band chopped cw laser and pulsed lasers in the interaction region. Recent off-line tests show that more than 80 % neutralization can be achieved for K ions (K II) in the CEC with K vapor.

The resonantly ionized ions in the interaction region are subsequently deflected onto a copper dynode, while the remaining atoms go straight forward to the beam dump. The secondary electrons from the copper dynode, induced by the K II impact, are collected by a micro channel plate (MCPe), as shown in Figure 2. Recording the ion counts by the MCP as a function of the scanned laser wavelength, the HFS of K isotopes will be measured, allowing the ground state nuclear spins, nuclear magnetic moments and changes in the mean square charge radii to be deduced. Recently, a second MCPi has been installed in the beam line (Figure 2) just after the interaction region, which is expected to increase detection efficiency.



(a) (b)

Figure 3: (a): Proposed transition schemes for K. (b): HFS spectrum of ^{39}K taken from the offline test experiment [35].

In the previous COLLAPS experiment, the transition of 769.9 nm, $4s\ ^2S_{1/2}$–$4p\ ^2P_{1/2}$, was used to extract the nuclear spins, magnetic moments and charge radii of K isotopes. The same transition was used in the off-line test experiment in 2012, using a two step RIS scheme (769.9 nm + 355 nm). A resolution of 40 MHz FWHM has been achieved, as presented in Figure 3b. A three step transition is proposed as well, as shown in the right part of Figure 3a. This is accessible using a chopped continuous-wave Ti:Sa laser (first resonant step: 769.9 nm, $4s\ ^2S_{1/2}$– $4p\ ^2P_{1/2}$), a pulsed dye laser (second resonant step: 691.1 nm, $4p\ ^2P_{1/2}$–$6s\ ^2S_{1/2}$) and a Nd:YAG laser (100 Hz) (final non-resonant step: ionization into the continuum, 1064nm, $6s\ ^2\mathrm{S}_{1/2}$–IP). The lasers for all steps are available in the CRIS laser laboratory [34] and were operational during the Ga run in 2015. All three-steps used here are the fundamental frequency and thus with sufficient power, which have been proved to be saturated during the off-line test in 2012 (first step), Ga run (second step) in 2015 and Fr run (last step) in 2014, respectively. Consequently, a better ionization efficiency is expected. In general, a simpler two-step transition scheme is always favorable if it can be easily achieved by the available laser systems and has a comparable ionization efficiency. Therefore, two transitions with two steps are proposed (left side of Figure 3a). It is important to emphasize that a two-step similar transition has been used during the Fr run [33] and thus a comparable ionization efficiency is expected for K (as these elements have a similar electronic structure). The transitions start with a chopped continuous-wave frequency-doubled Ti:Sa laser (404 nm) to obtain the HFS and with a frequency-doubled Nd:YAG laser (100 Hz) to ionize into continuum (532 nm). The offline tests for determining the best ionization schemes using an off-line plasma ion-source are on going.

3 Production yields and beam time estimate

The neutron-rich radioactive K ion beams are produced with a UC_x target and surface ionization. The production yields from the ISOLDE yield database, previous experiments (ISOLTRAP and COLLAPS experiments) and proposal (IDS) are listed in Table 1. The yield for ^{51}K is confirmed from the COLLAPS experiment in 2012 [26], while the yields for ^{52,53}K are taken from the IDS proposal [16] and they are consistent with measurement at ISOLTRAP [36]. However, for the yields of ^{52,53}K, roughly 10 times less production

Table 1: Production yields of ^{51}K, ^{52}K and ^{53}K, taken from the ISOLDE yield database and Ref. [36, 26, 16]

Isotopes	half life	yield (ions/s)	Target/ion source	shifts
^{51}K	365 ms	4500	UC_x /WSI	1 (^{47,48,51}K)
^{52}K	105 ms	560	UC_x /WSI	2
^{53}K	30 ms	$\sim$ 50	UC_x /WSI	6
References				2
Total				**11**
Stable beam				2

rate was measured during the IDS experiment in 2015, which was found to be due to a problem in the ion source [37].

During the Fr experiment in 2012, the HFS spectra of ^{202}Fr isomer and ground state with a production yield of 30 ions/s and 70 ions/s were measured easily within a 2 hours period [31]. In the case of K, a better neutralization efficiency (80 % compared to 50-70 % for Fr) has been confirmed, a comparable laser ionization efficiency is expected (as it has a similar electronic structure), and an updated setup with a second MCP will be used. Thus a better overall experimental efficiency can be expected. Therefore, with the production yields as given in Table 1, measurements of the ^{52,53}K isotopes should be feasible by using the CRIS setup, assuming the quoted yields. A total of 11 shifts are requested, as summarized in Table 1, including 1 shift for re-measuring the previously studied ^{47,48,51}K, 2 shifts and 6 shifts for the new measurements of ^{52}K and ^{53}K, respectively, and 2 shifts for isotope shift reference measurements. Additionally, 2 shifts with stable beam immediately before the run are requested for optimizing the experimental set-up and laser scheme (transmission, ion-laser spatial and time overlap, etc.).

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT
The experimental setup comprises: CRIS

Part of the	Availability	Design and manufacturing
(CRIS)	☒ Existing	☒ To be used without any modification

HAZARDS GENERATED BY THE EXPERIMENT
Hazards named in the document relevant for the fixed CRIS installation.

Additional hazards: None