

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

**Study of neutron-rich  $^{52,53}\text{K}$  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 the previous work (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  $^{52,53}\text{K}$ , across  $N = 32$  and up to  $N = 34$ , by using the collinear resonance ionization laser spectroscopy (CRIS) setup. The measured magnetic moment will afford us further information of the shell evolution of proton  $sd$  orbits as the neutron  $p_{1/2}$  orbit is being filled, and the charge radii measurement will give a key result on the suggested  $N = 32$  subshell closure. Additionally, the measurement will provide a prominent test of state-of-the-art theoretical calculations and probe the role of the three-body force which was recently included in different theory calculations developed in the mid-mass Ca region.

**Requested shifts:** [11] shifts, ([1] run over [1] year)

# 1 Introduction and Physics motivations

Investigating and understanding the shell evolution of exotic nuclei from 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. 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”, the weakening of the  $N = 28$  shell gap in the region below Ca, the inversion of proton orbits in odd K and Cl towards  $N = 28$  and in odd Cu and Ga towards  $N = 50$ . Very recently, three-nucleon (3N) forces were included in different theoretical calculations [1, 2, 3] to describe the experimental observation in the mid-mass region, and were found to provide key mechanisms governing the shell evolution. Experimental observations, in a few specific mass regions, are needed to test the different theoretical models and probe the main role of the shell evolution.

Recently, isotopes in the Ca region have been studied intensively, especially, seeking experimental evidence on the proposed subshell closures at  $N = 32, 34$  [4, 5, 6, 7]. 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 [8], Ti [9] and Cr [10] with an energy increase of the first excited  $2^+$  state, and in neutron-rich K and Ca isotopes with a sizeable drop in  $S_{2n}$  across  $N = 32$ , as shown in Figure 1a [4, 11]. The strong  $N = 34$  shell gap in  $^{54}\text{Ca}$  is predicted by a shell model calculation based on the GXPF1 interaction [12]. Besides that, a larger shell gap for  $^{54}\text{Ca}$  compared with that for  $^{52}\text{Ca}$  is also predicted by Holt *et al* [3] with a three-nucleon (3N) force included. Using the coupled-cluster calculation which employs interactions from chiral effective field theory and includes the effect of 3N force, Hagen *et al* [2] has predicted a  $\sim 2$  MeV  $E(2_1^+)$  for  $^{54}\text{Ca}$ , suggesting a soft subshell closure. Experimental  $E(2_1^+)$  ( $\sim 2$  MeV) in  $^{54}\text{Ca}$  [4] was measured in RIKEN recently, showing a comparable value with  $^{52}\text{Ca}$  and providing direct experimental evidence for the doubly magic nature of  $^{54}\text{Ca}$ . 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 [4].

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 [13, 14]. As shown in Figure 1b, the charge radii of both  $^{51}\text{K}$  and  $^{52}\text{Ca}$  are increasing with a similar trend as for Mn or Fe, where no subshell closure is predicted. Beyond that, the magnetic moment of  $^{51}\text{Ca}$ , having a single-hole with respect to the suggested  $N = 32$  subshell closure, indicates an appreciable mixing with configurations above  $N = 32$  [15]. 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 to study the neutron-rich  $^{52,53}\text{K}$  ( $Z = 19$ ) isotopes, across  $N = 32$  and up to  $N = 34$ , by measuring the spins, magnetic moments and charge radii using collinear resonance

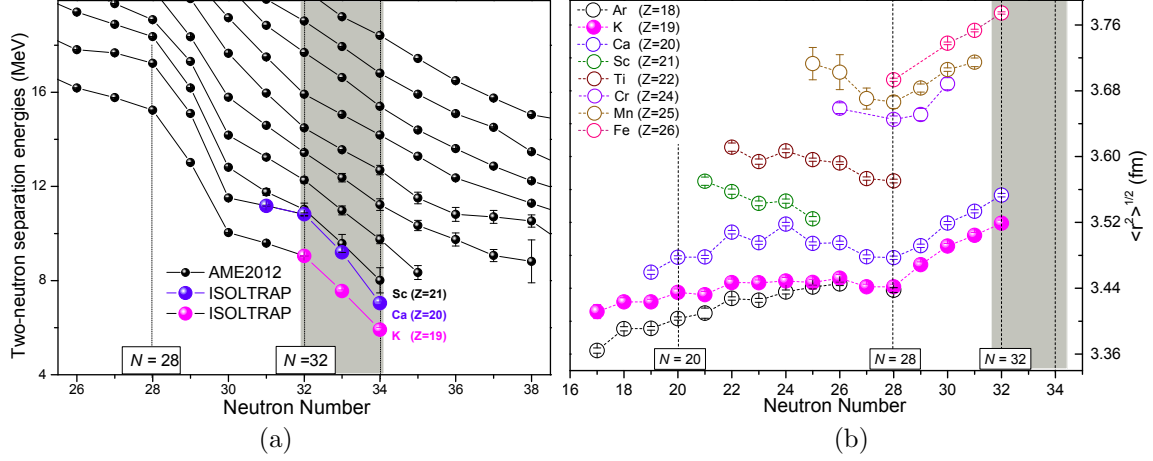


Figure 1: (a): Two neutron separation energy in the Ca region [5, 11, 16]. (b): Mean square charge radii of isotopes in Ca region around  $N = 32$  [13, 14, 17].

ionization laser spectroscopy (CRIS) at ISOLDE.

Previous laser spectroscopy measurements performed on neutron-rich K isotopes at the COLLAPS beamline have elucidated important aspects of nuclear structure in the Ca region [18, 19]. 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 comparing with shell model calculations. In addition to the effect of the tensor component suggested by Otsuka *et al.*, [20], 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  $s_{1/2}$  and  $d_{3/2}$  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 [19]. Therefore, experimental ground state spins and magnetic moments of the neutron-rich  $^{52,53}\text{K}$  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 mention before, 3N force has been included in several theoretical approaches for a better description of the experimental binding energy and  $E(2_1^+)$  energies of Ca isotope [2, 3]. Especially, 3N forces provided the first microscopic explanation for the  $N = 28$  magic number in  $^{48}\text{Ca}$  [3]. Very recently, the NN + 3N interaction derived from chiral effective field theory [21] was used to calculate the ground state nuclear moments of the neutron-rich Ca isotopes up to  $^{51}\text{Ca}$ , showing an excellent agreement for both the magnetic and quadrupole moments [15]. The experimental data on neutron-rich K will provide exciting tests for state-of-the-art theoretical calculations developed in the Ca mass region, and will be an important test for further developments of microscopic interactions and for exploring the role of 3N forces.

Figure 1b gives experimental data of charge radii in the Ca region. To verify whether or not  $N = 32$  appears 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  $^{52}\text{K}$  will be the key to understand the nature of  $N = 32$ , while the charge radius of  $^{53}\text{K}$  will afford important information on the suggested  $N = 34$  sub-closed shell. Theoretical description of charge radii in medium mass nuclei has been a major challenge [22]. 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

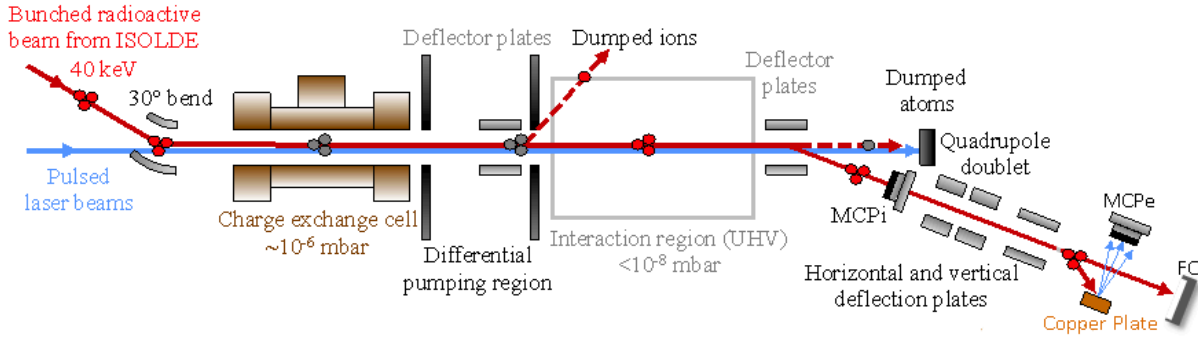


Figure 2: Schematic diagram of the CRIS beam line used for this experiment [25, 27].

charge radii [13]. Very recently, ab initio calculations with 3N force included, have been successfully applied to describe charge radii of medium mass nuclei in the vicinity of doubly-magic nuclei [13, 23]. As this calculation is ideally suited for nuclei with at most one or two nucleons outside a closed (sub-) shell, charge radii measurements of  $^{52,53}\text{K}$  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 [24, 25, 26]. This technique combines the advantages of the high sensitivity and selectivity obtained by particle detection of resonantly ionized isotopes, with the high resolution of collinear laser spectroscopy. A high efficiency and high resolution have been achieved during the Fr experiments in 2012 and 2014, which allowed the exotic isotopes to be studied [24] and quadrupole moments to be deduced [26].

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 30-40 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 away right 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 a more than 80% neutralization factor could be achieved for K ions in the CEC with K vapor, which promises a better efficiency than other elements (50% - 70 % (Fr), 70 % (Cu), 5-20 % (Ga)) measured in CRIS experiments so far.

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 (MCP), 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, which allows the ground state nuclear spins, nuclear magnetic moments and changes in the mean square charge radii to be deduced. Recently, a second MCP has been installed in our beam line (Figure 2) just after the interaction region, which is expected to provide us with better detection efficiency than before.

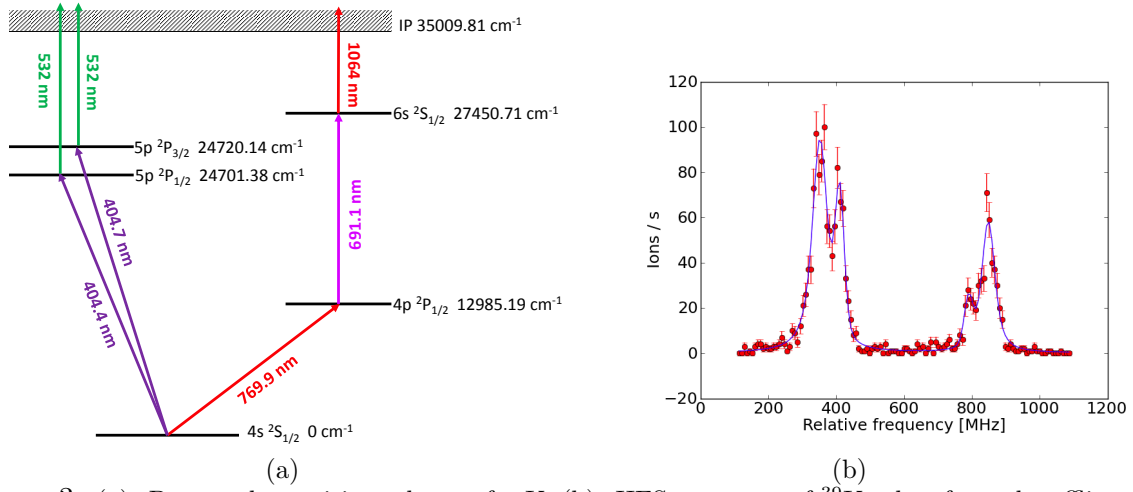


Figure 3: (a): Proposed transition schemes for K. (b): HFS spectrum of  $^{39}\text{K}$  taken from the offline test experiment [28].

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 very promising resolution of 40 MHz FWHM has been achieved, as presented in Figure 3b. However, the second (non-resonant) ionization step could not be saturated due to the rather low power of the frequency-tripled Nd:YAG laser (10 Hz), reducing the efficiency with this scheme. Therefore, a three step transition is proposed, as shown in the right part of Figure 3a, which is accessible by 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,  $4p\ ^2P_{1/2}-6s\ ^2P_{1/2}$ ) and a Nd:YAG laser (100 Hz) (last non-resonant step: the ionization into the continuum, 1064 nm,  $6s\ ^2P_{1/2}-\text{IP}$ ). The lasers for all steps are available in the CRIS laser laboratory and were operational during the Ga run in 2014. In general, the simple two step transition is always favorable if it can be easily achieved by the available laser systems and has a comparable ionization efficiency. Therefore, another two transitions with two steps are proposed as well (left side of Figure 3a). It is important to emphasize that a two-step similar transition has been used during the Fr Run and thus a comparable ionization efficiency is expected for K (as these elements have a similar electronic structure). In addition, the  $4s\ ^2P_{1/2}-5p\ ^2P_{3/2}$  transition might have a better sensitivity to distinguish between the nuclear spins 1/2 and 3/2, and also might provide information on the quadrupole moments (the latter needs to be tested off-line, as it will require a very high resolution). 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 test for determining the best ionization schemes using an off-line plasma ion-source is on going.

### 3 Production yields and beam time estimate

The neutron-rich radioactive K ion beams are produced with a  $\text{UC}_x$  target and surface ionization. The production yields from the ISOLDE yield database and previous experiments (ISOLTRAP and COLLAPS experiment)/proposals (IDS) are listed in Table 1. The yield for  $^{51}\text{K}$  is confirmed from the COLLAPS experiment in 2012 [18], while the yields for  $^{52,53}\text{K}$  are taken from the IDS proposal [7] and they are consistent

Table 1: Production yield from ISOLDE yield database and Ref. [29, 18, 7]

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

with the measurement in ISOLTRAP [29]. However, for the yields of  $^{52,53}\text{K}$ , roughly 10 times less production rate was measured during the IDS experiment in 2015, which was found to be due to a problem in the ion source [30].

During the Fr experiment in 2012, the HFS spectrum of  $^{202}\text{Fr}$  with a production yield of 70 ions/ $\mu\text{C}$  was measured easily [24]. In the case of K, a better neutralization efficiency 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  $^{52,53}\text{K}$  isotopes should be feasible by using the CRIS setup, on the condition that the problem in the ion source is fixed. A total of 11 shifts are requested, as summarized in Table 1, including 1 shift for re-measuring the earlier studied  $^{47,48,51}\text{K}$ , 2 shifts and 6 shifts for the new measurements of  $^{52}\text{K}$  and  $^{53}\text{K}$ , respectively, and 2 shifts for isotope shift reference measurements. Additionally, 2 shifts with stable beam immediately before the run are requested as well 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)	<input checked="" type="checkbox"/> Existing	<input checked="" type="checkbox"/> 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