EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and N-ToF Experiments (INTC) Committee

Ground-state properties of K-isotopes from laser and β-NMR spectroscopy

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Abstract

By combining high-resolution laser spectroscopy with β-NMR spectroscopy on polarized K-beams we aim to establish the ground-state spins and magnetic moments of the neutron-rich ^{48,49,50,51}K isotopes from N=29 to N=32. Spins and magnetic moments of the odd-K isotopes up to N=28 reveal an inversion of the ground-state, from the normal I=3/2 ($\pi d_{3/2}^{-1}$) in $^{41-45}$K to I=1/2 ($\pi s_{1/2}^{-1}$) in ^{47}K. This inversion of the proton single particle levels is related to the strong proton $d_{3/2}$ - neutron $f_{7/2}$ interaction which lowers the energy of the $\pi d_{3/2}$ single particle state when filling the $\nu f_{7/2}$ orbital. Spin-assignments for $^{49-51}$K, combined with recent spectroscopic data and the measured magnetic moment, will provide for the first time information about the evolution of the effective $\pi s_{1/2}$ and $\pi d_{3/2}$ single-particle energies beyond N=28, as the $\nu p_{3/2}$ is being filled. Consequently, these measurements will probe the strength of the $\pi(s_{1/2}d_{3/2})$-$\nu(f_{7/2}p_{3/2})$ tensor interactions. A spin measurement for ^{48}K will help to unravel conflicting spectroscopic data from in-beam and β–decay experiments, while the magnetic moments of these exotic isotopes will give information about their ground-state single-particle structure.

For this research program we ask a total of 24 shifts on the COLLAPS beam line.

Introduction and motivation

In nuclei far from stability strong modifications to the shell structure have been observed in several regions of the nuclear chart. The island of inversion around N=20, the weakening of the N=28 shell gap in isotopes below Ca, the inversion of the ground-state spin of odd K and Cl isotopes towards N=28 and the inversion of the ground-state spin in odd-Cu isotopes towards N=50 are but a few examples which have attracted much experimental and theoretical interest (see e.g. review by Sorlin and Porquet [1]). These modifications have been attributed to the evolution of the effective single particle energies of proton or neutron states when particular proton and/or neutron orbits are being filled or emptied. The origin of this modification as a function of neutron-to-proton ratio is being discussed in several theoretical papers [e.g. 2-4], and it has been related to the tensor part of the nucleon-nucleon interaction. It leads to changes of the effective single particle energies with changing proton and/or neutron number, leading to inversions of ground-state spins, unexpected changes of excited states patterns, appearance of low-lying intruder configurations, and sometimes, resulting in increased nuclear stability due to the appearance of new energy gaps.

In the region below Ca, where protons occupy the *sd*-shell and neutrons occupy mainly the $\nu f_{7/2}$ orbital for isotopes below N=28, this modification leads to a near-degeneracy of the $\pi d_{3/2}$ and $\pi s_{1/2}$ levels when the $\nu f_{7/2}$ orbital is being filled. This gives rise to an inversion of the ground-state spin from $I^{\pi}=3/2^{+}$ (of mainly $\pi d_{3/2}^{-1}$ character) to $I^{\pi}=1/2^{+}$ (of mainly $\pi s_{1/2}^{-1}$ character) at N=28 (^{47}K) [5,6] (figure 1).

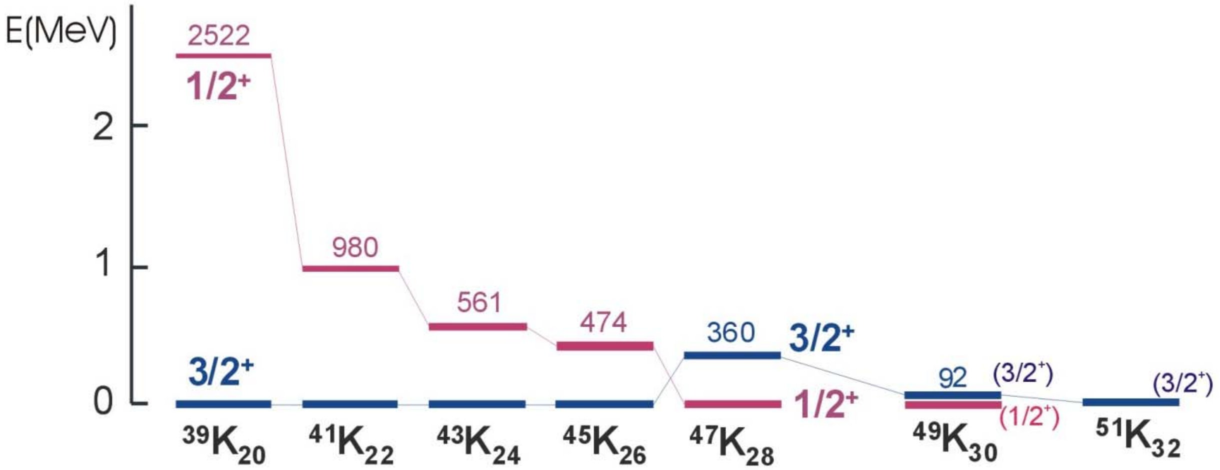

Figure 1: Evolution of the experimental first excited state (½$^{+}$ up to ^{45}K) with respect to the 3/2^{+} ground-state in the odd-K isotopes, with inversion at ^{47}K [4,5]. Levels in ^{49}K are from [7] and no excited states are known in ^{51}K but beta-decay studies suggest a 3/2^{+} ground-state [8].

Nuclear shell and mean field models, with effective interactions fitted to experimental observables, can reproduce the observed evolution of the $\pi d_{3/2}$ and $\pi s_{1/2}$ effective single particle energies (ESPE's) up to N=28, provided that the isospin dependence of the tensor component in the effective interaction is taken into account [3,9-13]. In figure 2 the proton ESPE's calculated with the SDPF-M shell-model interaction from [3] are compared to experimental values. Following the explanation given by Otsuka *et al.* in ref. [3], occupation of the $\nu f_{7/2}$ and $\nu p_{3/2}$ orbits (having j=l+1/2) leads to an increased binding of the $\pi d_{3/2}$ orbital (having j=l-1/2) with respect to the $\pi s_{1/2}$. At N=28 their ESPE's are almost degenerate. This explains the lowering of the first excited ½+ level in the odd-K isotopes with increasing N (Fig. 1), with an inversion at N=28 when the $\nu f_{7/2}$ is maximally filled. According to mean field HFB-calculations using a Skyrme interaction that explicitly includes a tensor component, the ESPE's of these proton levels beyond N=28 (when the $\nu p_{3/2}$ orbit is being occupied) are predicted to repel each other again [12] (dashed line in Fig. 2). However, their exact energy difference as a function of N>28 depends on the strength of the $\pi(s_{1/2}d_{3/2})$-$\nu(p_{3/2})$ interaction, which needs to be determined experimentally. Until now, hardly any experimental data are available which probe this part of the nucleon-nucleon $\pi(s_{1/2}d_{3/2})$-$\nu(f_{7/2}p_{3/2})$ interaction.

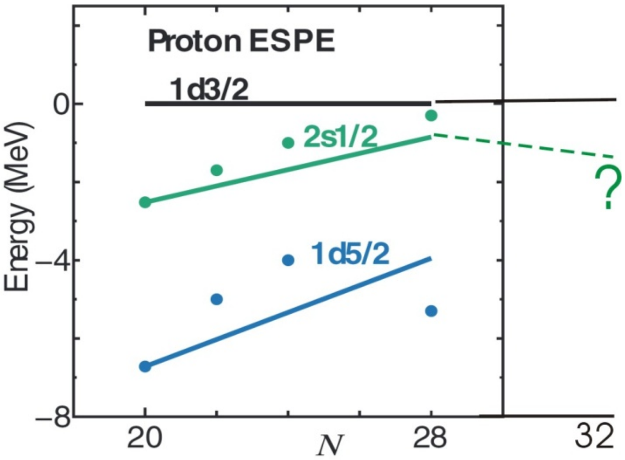

Figure 2: taken from Ref. [3]. Behavior of the proton effective single particle energies (ESPS's) in Ca isotopes (with respect to the $d_{3/2}$ orbital) as a function of N. Points represent the corresponding experimental data from Ref. [10]. The dashed line is a qualitative extrapolation, based on the predictions from HBF with a Skyrme interaction that includes the tensor force [12].

Results from β-decay [8,14-16,19] and recent in-beam measurements using deep-inelastic reactions [17,18] lead to different ground-state spin assignments for the ^{48,49,51}K isotopes.

From the beta-decay of ^{49}K into ^{49}Ca, a spin-parity of $3/2^+$ was suggested for the ground-state of ^{49}K [14]. With deep-inelastic heavy-ion reactions and discrete gamma coincidence techniques excited states in ^{48}K and ^{49}K have been observed recently [7,17]. In ^{49}K, the two lowest levels, differing only by 92 keV in energy, are most likely the $½^+$ and $3/2^+$ states and the γ-decay properties favor the $½^+$ as the ground-state. Shell-model calculations performed with the ANTOINE code [20] in the full sdpf-shell using the recently improved sdpf-U interaction [21] provide excellent reproduction of the first excited state energies over the full neutron-range up to N=28, and predict the spin/parity $3/2^+$ for the ground-state of ^{49}K (Fig. 3). On the other hand, the previous sdpf-NR interaction [9] predicts ^{49}K with $I^\pi=1/2^+$.

Recent beta-decay investigations on ^{51}K completed at ISOLDE using beta, gamma, and neutron spectroscopy [8] revealed that only two states are fed in ^{51}Ca: the ground-state (33.1%) and a state at

3460 keV (3.9%), the remaining decay going into the β-1n channel. A recent in-beam experiment located other levels in ^{51}Ca, including a level at 2378 keV [18] and the authors proposed respectively $5/2^-$ and $7/2^-$ for the levels at 2378 and 3460 keV, based on the observed γ-decay pattern and comparison to shell-model calculations. The beta-decay to the $7/2^-$ level in ^{51}Ca rules out a $1/2^+$ assignment for the g.s. of ^{51}K. The alternative $3/2^+$ assignment would then correspond to a first-forbidden transition to the $7/2^-$ state in ^{51}Ca, but it is unclear in this scenario why the other first-forbidden 5/2- decay is not observed.

Another controversy can be noted in ^{48}K. In this nucleus, investigations of the beta-decay of ^{48}K into ^{48}Ca suggested for the ground-state quantum numbers $J^{\pi}=2^-$ [22,23]. On the other hand, the structure of excited states recently identified in ^{48}K [7,17] seem more consistent with a spin-parity assignment of $J^{\pi}=1^-$. Shell-model calculations predict a $J^{\pi}=2^-$ ground-state, and two levels with $J^{\pi}=2^-$ and $J^{\pi}=1^-$ around 350 keV.

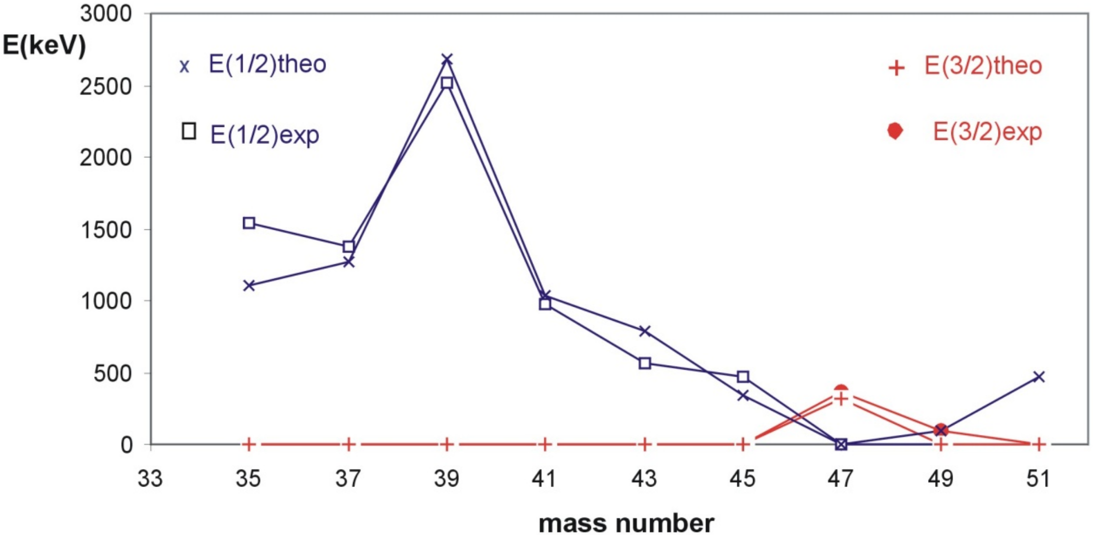

Figure 3: Energy of the first excited states (firmly assigned ½+ from ^{37}K up to ^{45}K) compared to shell-model predictions using the sdpf-U interaction [21].

All questions mentioned above, and the fact that shell-model predictions depend on the effective interaction used, urge for detailed studies of ground-state properties in the $^{48\text{-}51}$K nuclei.

Experimental set-up and methods

With high-resolution collinear laser spectroscopy, the hyperfine structure and isotope shifts of K isotopes can be measured. From this the nuclear ground-state magnetic moment and the change in mean square charge radius may be determined if a nuclear spin is assumed. If the HFS is measured in a transition with an electric field gradient in one of the atomic states, also quadrupole moments can be deduced if the hyperfine levels are resolved (which is not the case for the K isotopes). Sometimes hyperfine structure measurements allow assigning the nuclear spin, but that is case-dependent. Alternatively, β-nuclear magnetic resonance methods can be applied to measure the nuclear g factor once the K atoms have been polarized through optical pumping. The combination of these techniques permits the unambiguous determination of the spin and the consequent extraction of the magnetic moment as described in references [24] and [25].

The K^+ ions provided by the ISOLDE facility are neutralized in a charge exchange cell of the COLLAPS beam line [24] using K vapor (set-up in Fig. 4). The atomic K isotopes are studied in the transition from the 4s $^2S_{1/2}$ ground-state to the 4p $^2P_{1/2}$ and 4p $^2P_{3/2}$ excited states, D1 and D2 lines at 769.9 nm and 766.49 nm respectively.

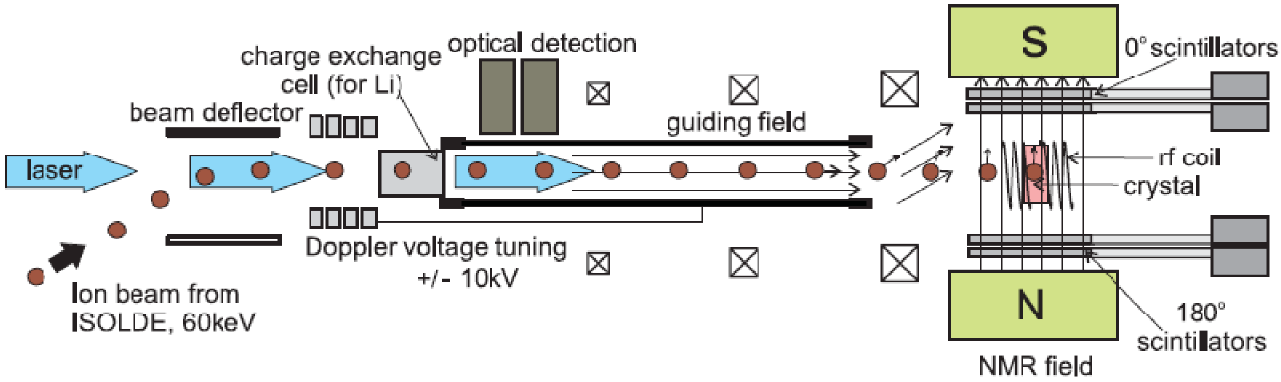

Figure 4: Schematic view of the experimental set-up

The HFS may be detected either by observation of the subsequent fluorescent decay with a photomultiplier tube (PM) or by measuring the asymmetry in the radioactive β-decay after the polarized nuclei have been implanted in a suitable crystal. In the latter case, circularly polarized laser light is used in order to polarize the K-nuclei by optical pumping during the resonant excitation/decay process along the flight path. To maintain the spin-polarization after implantation, the crystal has to be immersed into a static magnetic field of the order of 0.2-0.5 Tesla. When the optical detection is used, the ion beam needs to be bunched using the recently installed ISCOOL ion cooler/buncher [27], in order to allow measurements on beams down to a few times 10^4 ions/μC. Selection of the optimum detection technique for a particular isotope requires knowledge of the optical detection efficiency (probability to observe a fluorescent photon per incident ion), the production rate of the isotope of interest and the β-decay properties.

In table I, the production rates of the neutron-rich K isotopes are presented, as taken from the ISOLDE data base using a UC_x target (no laser ion source). In the initial commissioning tests of ISCOOL (nov. 2007) a series of measurements were conducted on K isotopes. In these tests an optical detection efficiency of the order 1 observed photon per 100 000 ions was common. The PMT used in these tests is known to have a quantum efficiency in the region of 1% for this wavelength region. As PMT's with GaAs photocathodes exhibit a quantum efficiency in excess of 10% for this wavelength region and are commercially available we may confidently expect an optical detection efficiency in the region of 1 observed photon in 10 000 ions. With this efficiency optical detection can be considered for all isotopes considered in this proposal, provided the optical background can be reduced to below 1/s, which is achievable using the ISCOOL ion cooler/buncher. Especially for ^{51}K, an efficient background reduction will be needed to allow optical measurements within a reasonable timescale of 2 to 3 shifts. In this particular case, β-asymmetry detection might be better suited.

The feasibility of a β-asymmetry measurement depends critically on the β-decay properties of the isotope, and more in particular on the nuclear lifetime and on how much asymmetry can be observed.

Table I: production rates (ions/μC) of the neutron-rich K isotopes (from data base)

K	45 - g	17.3 m 6	SC	2.0E+07	UC_x
K	47 - g	17.50 s 24	SC	2.8E+06	UC_x
K	48	6.8 s 2	PSB	1.3E+06	UC_x
K	49	1.26 s 5	PSB	2.7E+05	UC_x
K	50	472 ms 4	PSB	5.0E+04	UC_x
K	51	365 ms 5	PSB	4.5E+03	UC_x
K	52	105 ms 5	PSB	5.6E+02	UC_x

The β-decay properties of the K-isotopes of interest are given in Table II. The half lives of all isotopes are suited for β-asymmetry detection (τ should be smaller than the spin-lattice relaxation time in the implantation crystal, and varies typically from 1s up to several seconds). A possible problem lies in the fact that most isotopes have a very strong β-delayed neutron branch. Because this β-decay branch populates states in the continuum, it has most probably a very low β-asymmetry parameter. Especially for ^{49,51}K, where this branch is respectively 90% and 65% of the decay, it will be necessary to enhance the sensitivity to the asymmetry (A) in the normal β–decay branch by placing an energy degrader in front of the β-detectors to cut out the low-energy branch into the continuum as much as possible. That should enhance the asymmetry, but of course will reduce also our count rate (N). However, in an asymmetry measurement the sensitivity of the detection is proportional to N.A^2.

Table II: β-decay properties of the isotopes of interest.

A	**I^π**	**$T_{1/2}$**	**P_n (%)**	**Q_β (MeV)**	**Q_β–B_n (MeV)**	**references**
48	(2-,1-)	6.8 s	1.14 (15)	12.1	2.0	[15,20]
49	(1/2+,3/2+)	1.26 s	90(14)	11.0	5.2	[7,14]
50	0-	472ms	29(3)	14.1	7.6	[15,16]
51	(3/2+)	365 ms	63(8)	13.9	9.6	[18]

a. Measurement of the ground-state spin and magnetic moment.

Unambiguous spin determinations are achieved by combining hyperfine-structure measurements with nuclear magnetic resonance [24,25]. However, in many cases a HFS measurement alone is sufficient to assign a ground state spin. E.g. the HFS pattern (number of transitions and line shapes) is very different for a spin I=1/2 and I=3/2 in the D1 line. Additionally, the nuclear magnetic moment and isotope shift are deduced from the measured HFS assuming a certain spin. Thus both these quantities, when compared to systematic trends or model calculations and if significantly different for the possible ground state configurations, allow in some cases assigning a certain ground state spin with good confidence. In Figure 5 the experimental magnetic moments of the odd-K isotopes are compared to shell-model calculations with the ANTOINE code using the recently improved sdpf-U interaction [21]. Free-nucleon g-factors and effective g-factors ($g_s^{eff}=0.75\ g_s$, $g_l^{eff}(\pi)=1.1$ and $g_l^{eff}(\nu)=-0.1$) have been used and calculations are performed for the I=3/2 and for the I=1/2 level. The experimental trend of the moments is perfectly reproduced. This means that we have a rather good predictive power for the magnetic moments of the ^{49}K and ^{51}K isotopes for either I=3/2 or I=1/2 as the ground-state (two most likely ground state candidates). Note that in ^{49}K the two levels are calculated within less than 100 keV, and experimentally a level was observed at 92 keV but a firm spin assignment could not be made (a ground state spin ½ is preferred). As these moments are very different, a simple HFS measurement will be sufficient to give strong evidence for a particular nuclear ground-state spin and magnetic moment.

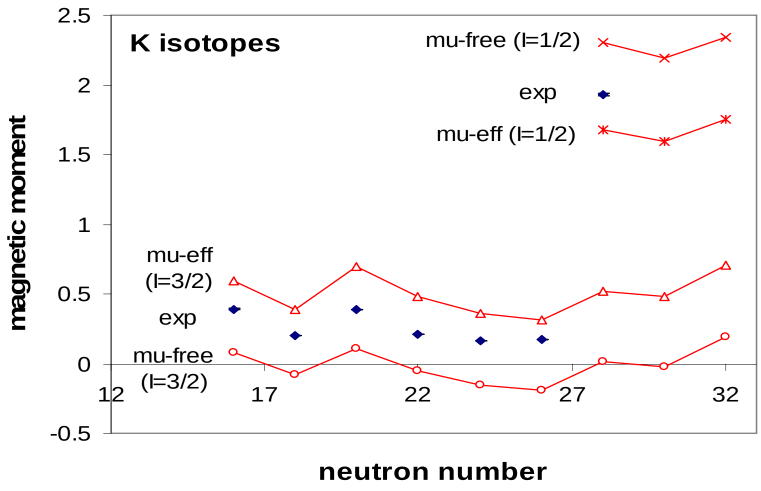

Figure 5: experimental magnetic moments of odd-K ground-states compared to shell-model calculations with the sdpf-U interaction.

For ^{48}K, simulated HFS spectra (both in D1 and D2 line) show that a firm spin-assignment might be difficult based on the HFS and deduced magnetic moments assuming different spins. Also the line shapes are not very distinctive because the transitions are not resolved. In this case a g-factor measurement using the β-NMR method will certainly be needed to make a firm spin-assignment.

The ground-state spin of ^{50}K has been established as I=0 (through β-decay arguments) [16], but a recent in-beam spectroscopy experiment as MSU seems to prefer a $I^{\pi}=1^{-}$ ground-state (private communication F. Nowacki). In case the spin is indeed 0, the nuclear spins cannot be polarized and thus no β-asymmetry can be observed (and the magnetic and quadrupole moment are zero). Thus ^{50}K needs initially to be investigated by optical detection: a single line in the HFS will confirm the spin zero. In case a structure is observed in the optical spectra, β-NMR detection of the g-factor might be needed to firmly assign a spin.

b. Measurement of the quadrupole moments

Due to the small splitting in the 4p $^2P_{3/2}$ multiplet (quadrupole moments are calculated to be of the order of 60 mbarn), HFS measurements will not be sufficiently sensitive to deduce quadrupole moments. It is possible to extract these moments with high precision using the β-NMR method (by implantation in a crystal with a suitable electric field gradient). However, at this stage we do not plan quadrupole moment measurements as this requires dedicated beam time.

c. Measurement of the changes in mean square radii

Isotope shifts of K isotopes between N=20 and N=28 have been measured by Touchard et al. [5], and the deduced changes in mean square charge radii were revised in [26]. A very strong shell effect has been observed beyond N=28 in the $_{20}$Ca isotopes just above and it would be interesting to see whether this effect persists in the $_{19}$K-isotopes. Furthermore, the existence of a new magic number N=32 has been predicted by some theories (e.g. Honma et al., PRC69-034335, 2004), and recent spectroscopy studies in ^{52}Ca, ^{54}Ti and ^{55}V support this new magicity. From the measured HFS of each of the above isotopes (with either β-asymmetry or optically) with respect to a reference isotope (e.g. stable ^{39}K) it might be possible to deduce the change in mean square charge radius once the spin has been established. However, the field shift in the K-isotopes is very small, estimated at about 10-20 kHz only, so accurate and precise isotope shift measurements will be required to deduce the changes in mean square charge. With the method of optical detection using the ISCOOL cooler/buncher we need to investigate in more detail if systematic effects can be reduced to this precision. With the β-asymmetry measurements, the line-shape analysis is not obvious in case of the K-isotopes, because the atom is at resonance with the laser beam also in the transitional magnetic field region during adiabatic spin rotation, which affects the line shape and is difficult to model. Thus isotope shift measurements will most likely require dedicate beam, once the performances of the ion cooler are fully under control. In the present requested beam times, we aim to measure isotope shifts with both methods, in order to compare the results.

Feasibility and beam time request

We plan to perform two experiments using a UC$_x$ target (no need for laser ion source), with following goals:

Experiment 1: Optical detection of the HFS of ^{48,49,50,51}K using ISCOOL at the HRS mass separator + test of the β-asymmetry for ^{48,49,51}K.

As motivated above, for most of these isotopes an optical measurement of the HFS in the D1 should be sufficient to assign their ground state spin and to measure their magnetic moment (with sign). Optical detection of the HFS, using improved PM's with quantum efficiency of 10%, is possible certainly up to ^{50}K in less than 1 shift per isotope using a bunched beam provided by ISCOOL. For ^{51}K we foresee 3 shifts. In order to verify the possibility to extract changes in mean square charge radii, we will measure at regular intervals also the HFS of a less exotic reference isotope during these measurements (total 8 shifts for optical detection).

Because the β-asymmetry for the isotopes with large β-delayed neutron branch (^{49}K and ^{51}K) will most likely be very small, we plan in this experiment to optimize the conditions for β-asymmetry detection (which will certainly be needed for a firm spin-assignment in ^{48}K, and possibly also in ^{51}K in case the spin is larger than 1/2). Measurements of β-asymmetry after implantation in different crystals will be undertaken in order to determine the appropriate conditions for the maintenance of nuclear spin-polarization whilst obtaining information on the optical detection background associated with the introduction of crystals of varying optical transparency. (4 shifts).

We ask **12 shifts** to measure the HFS of the 4 isotopes with respect to a reference case and to perform tests for improving the sensitivity of the β-asymmetry detection.

Experiment 2: β-asymmetry detection on ^{48,49,51}K for β-NMR and isotope shift measurements at GPS.

As the background in β-asymmetry detected spectroscopy is typically dominated by daughter decay, little improvement is expected from the use of a bunched beam. Consequently the experiment can be performed with the GPS. The relatively fast settling time of this separator permits a rapid mass change between the measurement of the radioactive isotope using β-asymmetry detection and the reference isotope using optical detection, thus minimizing possible systematic uncertainties associated with voltage variations at the ion source or cooler.

For measuring the HFS with β-asymmetry for ^{48,49,51}K relative to that of stable ^{39}K (optically), we request 6 shifts. Comparison of the isotope shifts extracted from run 1 and run 2 will allow to pinpoint possible systematic or other errors which are related on one hand to the non-simultaneous measurement of the two HFS (in case of cooler usage) and on the other hand related to the need for careful line shape analysis in case of β-asymmetry detection. For the isotopes that require an independent g-factor measurement in order to firmly assign a ground state spin (^{48}K and probably also ^{51}K), we ask 6 shifts to perform β-NMR measurements. We can also consider to measure quadrupole moments using the multiple-rf NQR method, in case time would be available.

This means a total of **12 shifts** for the second experiment.

Summary of requested beamtime

In total we ask for **24 shifts**.

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