EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

β-decay spectroscopy with laser-polarised beams of neutron-rich potassium isotopes

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Abstract:

The proposed experiment aims to investigate the β decay of neutron-rich potassium isotopes ($Z=19$), including ^{49}K ($N=30$) and ^{51}K ($N=32$), for which reinversion of the ground-state spin driven by the evolution of the proton πsd orbitals was observed in laser spectroscopy. We will apply a novel technique that utilises anisotropic β decay of oriented nuclei to firmly assign spins and parities of states populated in daughter nuclei through allowed transitions. Our experiment, which combines the strengths of β-decay spectroscopy and collinear laser spectroscopy, will be performed at the VITO beamline. A new β-decay spectroscopy station that accommodates β-particle, γ-ray, and neutron detection following the decay of laser-polarised nuclei will be commissioned.

Requested shifts: 15 (to be scheduled in a single run).

Introduction — Experimental β-decay studies contribute significantly to improving our understanding of exciting nuclear phenomena emerging far from the stability, such as β-delayed multiple-particle emission [1–3], evolution of shell structure [4], and appearance of so-called "islands of inversion" [5]. The great success of β-decay experiments in probing ground- and excited-state properties is due to the high angular-momentum selectivity of the β decay that populates states with particular "allowed" configurations in the daughter nuclei. Such measurements often allow excited states in exotic nuclei to be observed for the first time, especially from precursors produced with yields as low as a few ions/s. However, there is a fundamental limitation of the conventional β-decay spectroscopy, namely the limited ability to deduce spins and parities of states involved in the β decay. Experimental β-decay feedings allow for the determination of logft values that suggest the type of transition [6]. Only tentative assignments, i.e. range of spin values and the most probable parity, can be made based on them. Consequently, drawing a definitive conclusion from experimental logft values on the structure of states involved in the particular transition is often difficult in conventional β-decay experiments.

β-decay spectroscopy becomes an even more powerful technique when oriented nuclei are utilized, i.e. when the nuclear spin of the β-decay emitter has a directional orientation with respect to the axis of an applied magnetic field. In this way, one can benefit from the parity non-conserving nature of the weak interaction and exploit the directional distribution of radiation emitted from polarised beams [7]. A novel approach to β-decay measurements was pioneered by a group from the University of Osaka [8]. The technique uses the anisotropic β decay of oriented nuclei to unambiguously assign spins and parities of states populated in daughter nuclei through allowed transitions. This is achieved by measuring the β-decay asymmetry of excited state in coincidence with β-delayed radiation depopulating this state. The angular distribution of β particles emitted from a polarised nucleus depends on the β-decay asymmetry parameter and polarisation of the parent nucleus. While the asymmetry parameter can take different discrete values depending on the spins of the initial parent state and final daughter state, the polarisation is common for all β-decay transitions. If the initial-state spin and one of the final-state spins are known, the degree of polarisation can be easily evaluated and then used to find asymmetry for other transitions and from them, spins of the fed levels. If only the spin of the initial state is known, it is still possible to determine final-state spins. In this case, a proper combination of asymmetry values for each transition, giving a consistent polarisation value has to be determined simultaneously [8]. The above method has already been successfully applied to several polarised beams of light and medium mass isotopes, including β-delayed neutron emitters [8–13].

Our goal is to adopt this novel technique at the VITO beamline for laser-induced nuclear orientation by combining the strengths of β-decay spectroscopy and collinear laser spectroscopy. We plan to launch a new research programme with a dedicated β-decay spectroscopy station at VITO that accommodates β-particle, γ-ray, and neutron detection following the β decay of laser-polarised nuclei. The commissioning experiment presented in this proposal aims to investigate the β decay of neutron-rich potassium isotopes ($Z = 19$), including ^{49}K ($N = 30$) and ^{51}K ($N = 32$), for which reinversion of the ground-state spin driven by the evolution of the πsd orbitals was observed in high-resolution collinear laser spectroscopy [14, 15]. Since allowed transitions proceed preferentially to states of similar configuration in daughter nuclei, β decays of these nuclei offer a great opportunity to detect various excitations of the ^{48}Ca core and, therefore, to benchmark particle-hole interactions in this mass region.

Physics cases — The selection of three neutron-rich potassium isotopes, ^{47}K, ^{49}K, and ^{51}K, for the commissioning experiment is motivated by three main aspects.

The first is related to the beam preparation. The use of a beam of abundantly produced nuclei will facilitate the demonstration of the reliability of the experimental approach and help to develop its possible extensions. High production yields for potassium isotopes at ISOLDE can compensate for the lowered detection efficiency when measuring the β-decay asymmetry in coincidence with delayed radiation. Two of these isotopes, ^{47}K and ^{49}K, were already polarised at the VITO setup in 2022. Their hyperfine spectra and degree of asymmetry were measured in recent β-NMR campaigns [16–18].

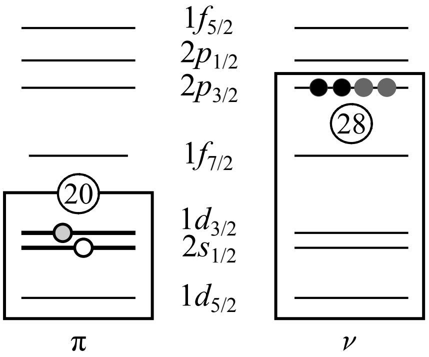
The known properties of the radiation emitted from ^{47}K [19], ^{49}K [20, 21], and ^{51}K [21, 22], are the second reason for the choice of those nuclei for the first β-decay spectroscopy measurement at VITO. The most comprehensive experimental study was performed for ^{47}K [19] and therefore, this isotope will be used to calibrate the observed β-decay asymmetries according to known spins and parities of the levels populated in ^{47}Ca. Measurements with ^{47}K will validate our experimental approach for determining β-decay asymmetries in coincidence with γ rays. The β decay of ^{47}K with spin $1/2^+$ proceeds in 80% through an allowed transition, in which the fed $1/2^+$ state in ^{47}Ca depopulates mainly by the E1 586-keV γ-ray transition in cascade with a 2013-keV E2 transition [19]. These two transitions take 94% of the β-decay intensity, thus allowing to easily monitor key parameters in the online analysis and optimise the laser-induced polarisation of the beam. Moreover, these two well-known transitions are a perfect case to demonstrate the feasibility of determining the multipolarity of γ rays from the observed asymmetry in γ-ray emission. The anisotropy of β-delayed radiation from spin-oriented nuclei is proportional to its angular momentum (ℓ) [7,23,24], in this case $\ell = 1$ for the $E1$ 586-keV line, and $\ell = 2$ for the $E2$ 2013-keV line. By comparing the degree of γ-ray asymmetry observed with transitions of different multipolarity, we will investigate the degree of sensitivity of this method to angular momenta of the emitted radiation.

In comparison to ^{47}K, heavier potassium isotopes, being strong β-delayed neutron (βn) emitters, serve as a perfect ground for applying β-decay asymmetry measurements in coincidence with neutrons. Energy spectra of β-delayed neutrons emitted from ^{49}Ca and ^{51}Ca contain several well-resolved lines, facilitating their attribution to particular β-decay transitions.

Based on the above-mentioned considerations, we conclude that the choice of the nuclei for the commissioning experiment guarantees a clear demonstration of the capability to measure β-decay asymmetry in coincidence with γ rays and neutrons and, thus, to determine spins and parities of excited states using the method developed by the group from the University of Osaka.

Moreover, β decays of selected precursors offer great potential for obtaining new experimental information on both parent and daughter nuclei that will enrich the discussion on the nuclear structure in the region around ^{48}Ca. This prospect is the essential and third aspect motivating our choice of nuclei for the proposed experiment. Compared to the doubly magic ^{48}Ca, potassium isotopes have only one proton less, while the neut-

Figure 1: Schematic drawing showing the ground-state configuration of ^{49}K ($I^{\pi} = 1/2^{+}$) and ^{51}K ($I^{\pi} = 3/2^{+}$). The location of the proton hole (neutron particles) in ^{49}K and ^{51}K is indicated by white (black) and light grey (black and grey) circles, respectively. Evolution of the $\pi 2s_{1/2}$ and $\pi 1d_{3/2}$ orbitals (in bold) emerges with filling of the $\nu 2p_{3/2}$ orbital.



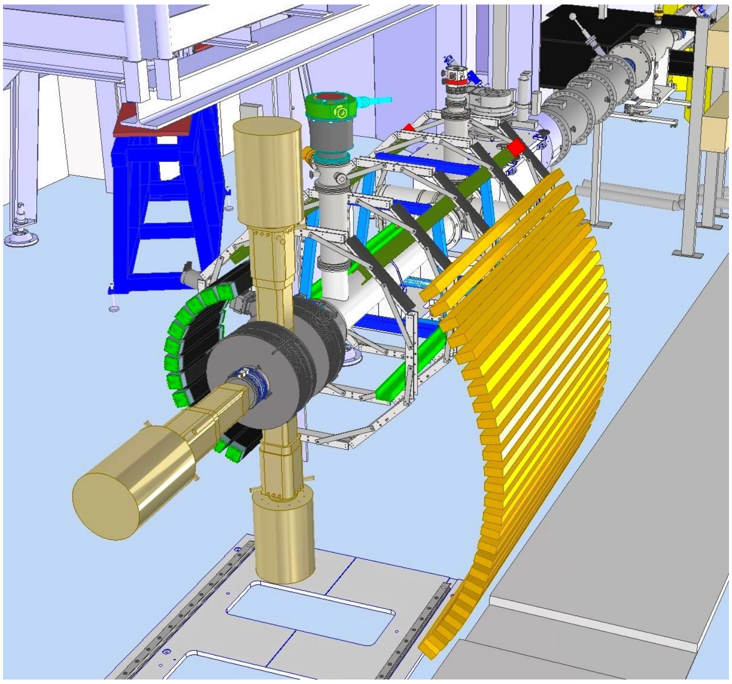
ron number ranges from $N = 28$ to 32. Their ground-state spins were firmly established from hyperfine spectra measured using laser spectroscopy that yielded $I^{\pi} = 1/2^{+}$ for ^{47}K and ^{49}K and $I^{\pi} = 3/2^{+}$ for ^{51}K [14, 25], respectively. The observed inversion of spins, from $3/2^{+}$ to $1/2^{+}$ at $N = 28$, and then, the remarkable reinversion to $3/2^{+}$ at $N = 32$, is driven by the the evolution of the proton orbitals (πsd) emerging with the filling of subsequent neutron orbitals (νpf) [14,15,26]. The ground-state wave function of ^{47}K ($N = 28$) and ^{49}K ($N = 30$) is dominated by the $\pi 2s^{-1}_{1/2} \otimes \nu(pf)$ configuration. For ^{51}K, the dominant $\pi 1d^{-1}_{3/2} \otimes \nu(pf)$ configuration was deduced [15], as expected from a "normal" ordering of the $\pi 2s_{1/2}$ and $\pi 1d_{3/2}$ orbitals (see Figure 1).

The comparison of the experimental and predicted magnetic moments suggests that the ground-state wave function is of high-purity in ^{51}K, while it is significantly mixed in ^{49}K due to almost degenerate $\pi 2s_{1/2}$ and $\pi 1d_{3/2}$ orbitals [14, 15, 27]. To reproduce the measured magnetic moment of the $1/2^{+}$ ^{49}K ground state, at least 25% mixing with the $\pi 1d^{-1}_{3/2} \otimes \nu(pf)_{2^{+}}$ state is needed. Since the ground-state configuration of the parent nucleus serves as the initial condition for the course of the β decay, excitation spectra in ^{49,51}Ca, resulting from allowed transitions of ^{49,51}K, can provide further experimental information about the pure or mixed nature of the ground-state wave function of potassium isotopes. Possible weakening of the energy gap between the shells can be inferred from the comparison of these spectra, dominated by core excitations. In particular, the main allowed transitions will populate $1/2^{+}$ and $3/2^{+}$ in ^{47,49}Ca and $1/2^{+}, 3/2^{+}$ and $5/2^{+}$ states in ^{51}Ca. These states, in turn, can be understood, in a simple shell model picture, to be dominated by the $\nu 2s^{-1}_{1/2}/1d^{-1}_{3/2}(pf)^{+2}$ in ^{49}Ca and $\nu 2s^{-1}_{1/2}/1d^{-1}_{3/2}/1d^{-1}_{5/2}(pf)^{+4}$ configurations in ^{51}Ca, respectively. These configurations involve orbitals below the $N = 20$ shell closure, causing the energies of the corresponding states to be increased by the $N = 20$ shell gap energy. The main allowed transitions are therefore expected to populate states above the neutron separation energies in daughter nuclei, explaining the large P_n values and increasing the difficulty of the experiment. Here, by combining the Osaka method with the neutron detection capability afforded by INDiE, we will be able to identify these states unambiguously, and obtain their β-decay strength B(GT). By comparing the experimental B(GT) with calculations using modern large-scale shell-model interactions, such as SDPF-MU or SDPF-U-MIX, we will be able to provide an estimate of the ground state and daughter states wavefunction mixing independent of the previous magnetic moment measurements [14, 15, 27].

Another important topic addressed in the proposed experiment is the emission of β-delayed neutrons. Decays of ^{49}K and ^{51}K, for which βn emission probabilities (P_n) are 86(9)% and 65(8)% [28], respectively, offer great testing grounds for theoretical models describing this process. Such examination will be facilitated by the recent experimental and theoretical advances in the region around ^{48}Ca – the lightest doubly-magic neutron-rich nucleus. The unique information about βn emitters obtained through the Osaka method will serve as a benchmark for the theoretical approaches for modelling β-decay strength and predicting P_n values for r-process nucleosynthesis simulations. Interestingly, for ^{49}K, which is recommended as a "standard" for P_n measurements [28], the predicted P_n values, 21% [29], 14% [30], and 29% [31], are significantly lower than the experimental result (86(9)%). Theoretical models provide higher P_n values for ^{51}K, 62% [29], 77% [30], or 59% [31]. These predictions do not reflect the experimental trend [32], i.e. lower P_n for ^{51}K (65(8)%) having the βn-emission window 2.5 MeV larger than ^{49}K. Determining spins and parities of the neutron-emitting states in ^{49,51}K, which subsequently decay to levels in βn daughter nuclei ^{48,50}K with well-established spin-parity assignments, will provide crucial information on neutron angular momenta. This will provide a robust experimental dataset to test βn emission models, which were recently challenged with the remarkable neutron-spectroscopy data obtained at IDS for two neutron-rich indium isotopes: ^{133}In, ^{133m}In, and ^{134}In [33, 34]. The spin and parity of neutron-emitting states are crucial quantities in these theoretical considerations. Moreover, in the simple shell-model picture, ^{49}K is a nucleus analogous to ^{133}In – both have one proton hole and a pair of neutrons with respect to the core. The obtained data will allow us to compare the details of the βn emission for these analogous nuclei from two regions around neutron-rich doubly magic nuclei. The heavier indium isotope, ^{135}In, with configuration analogous to ^{51}K, i.e. one proton hole and two neutron pairs, will soon be measured at IDS [35]. In the near future, we will propose an experiment with laser-polarised beams of neutron-rich indium isotopes to establish the spins and parities of neutron-emitting levels and finally answer critical questions about the mechanism of βn emission in this astrophysically relevant region [36, 37].

Experimental details — The experiment will take place at the VITO beamline [38, 39]. Polarisation of potassium atoms will be achieved using the D2 line at 766.49 nm [18]. A new pair of Helmholtz coils will be installed behind the optical pumping section (see Figure 2) to provide a magnetic field that adiabatically decouples the atomic and nuclear spins, and therefore to maintain the nuclear spin polarisation following the beam implantation into a crystal. These coils were designed to produce an 800 gauss field in the central position under conservative operating conditions. Copper hollow conductors are used as the magnet material to provide flexibility for on-demand adjustment of the magnetic field, with the capability of up to 1200 gauss, which is sufficient for decoupling the spins of the majority of nuclei. Construction of the coils began in January 2023 at the CERN mechanical workshop. Inside the coils there will be an aluminium chamber, hosting an implantation crystal (KCl or KF) and two plastic scintillators (50×50 mm^2, 10-mm thickness) coupled to SiPM readout boards. The detectors will be placed at 0° and 180° angle with respect to the polarisation (and beam-axis) direction. They will cover a 20% solid angle, which is a trade-off between detection efficiency and decay asymmetry (the latter is largest for smallest solid angle). Outside

Figure 2: A new β-decay spectroscopy station integrated with the VITO beamline. The drawing shows its planned location in the experimental hall relative to the WIZARD platform (left). The detection system includes three Clover detectors and two neutron spectrometers: INDiE (yellow) and NEXT (black). Two plastic detectors (not visible) are inside the chamber between the Helmholtz coils (grey).



the main chamber, three to six Clover detectors (from IFIN-HH) will be placed, each with a γ-ray detection efficiency of about 0.8% (at 1 MeV, 5 cm). For neutron time-of-flight measurements, two detectors will be used: the local IDS neutron spectrometer INDiE (based on the VANDLE array design [40]), consisting of 26 plastic scintillator bars, with an efficiency of 6% for 1 MeV neutrons; and the high-resolution neutron detector NEXT recently developed by the authors of this proposal at the University of Tennessee [41], consisting of 14 segmented plastic scintillator modules with neutron pulse shape discrimination and 11% efficiency at 1 MeV. The XIA Pixie-16 DAQ system already present at the VITO beamline will be used to collect signals from all the detectors.

Beam time request — The number of requested shifts was governed by the number of β-γ and β-n coincidence events required to measure β-decay asymmetries (and later also γ-ray and neutron-asymmetries) with a precision that enables to distinguish between different discrete values that can take the decay asymmetry factor depending on the spin change and radiation multipolarity. The required number of events depends on the following properties of the experimental system (based to a large extend on previous IDS and VITO experiments): beam transport efficiency to implantation point (70%), neutralisation fraction in the charge-exchange cell (70%), solid angle covered by all radiation detectors and their intrinsic efficiencies. Also the properties of the used potassium beam and implantation host were considered: half-life, initial spin polarisation obtained via optical pumping (40 - 50%) and its relaxation time in the crystal, β-decay branching ratios, expected asymmetry factors for different possible transitions.

The resulting number of coincidence events were then compared to the experimental yields using a UC$_x$ target with surface ionisation. The following production yields have been assumed, based on the ISOLDE yield database and VITO experiments in 2022 [42]: 1×10^7 ions/μC for ^{47}K, 1×10^5 ions/μC for ^{49}K, and 4.5×10^3 ions/μC for ^{51}K.

As a result, we request 15 shifts with UC_x target, surface ionisation, and potassium mass marker:

(a) 2 shifts for establishing laser polarisation and optimising laser-atom overlap using ^{47}K beam;

(b) 0.5 shift with laser-polarised ^{47}K beam;

(c) 2 shifts with laser-polarised ^{49}K beam;

(d) 8 shifts with laser-polarised ^{51}K beam;

(e) 1 shift for optimising laser polarisation after the change of the isotope (0.5 shift for ^{49}K and ^{51}K);

(f) 1.5 shifts (in total) for measurements without laser polarisation using ^{47}K, ^{49}K, and ^{51}K beams.

Summary of requested shifts: 15 shifts in total, to be scheduled in a single run in 2023.

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DESCRIPTION OF THE PROPOSED EXPERIMENT

Please describe here below the main parts of your experimental set-up:

Part of the experiment	Design and manufacturing
VITO	☐ To be used without any modification ☒ To be modified
New Helmholtz coils	☐ Standard equipment supplied by a manufacturer ☒ CERN/collaboration responsible for the design and/or manufacturing

HAZARDS GENERATED BY THE EXPERIMENT

Additional hazard from flexible or transported equipment to the CERN site:

Domain	Hazards/Hazardous Activities		Description
Mechanical Safety	Pressure	☐	[pressure] [bar], [volume][l]
	Vacuum	☐	
	Machine tools	☐	
	Mechanical energy (moving parts)	☐	
	Hot/Cold surfaces	☐	
Cryogenic Safety	Cryogenic fluid	☐	[fluid] [m3]
Electrical Safety	Electrical equipment and installations	☐	[voltage] [V], [current] [A]
	High Voltage equipment	☐	[voltage] [V]
Chemical Safety	CMR (carcinogens, mutagens and toxic to reproduction)	☐	[fluid], [quantity]
	Toxic/Irritant	☐	[fluid], [quantity]
	Corrosive	☐	[fluid], [quantity]
	Oxidizing	☐	[fluid], [quantity]
	Flammable/Potentially explosive atmospheres	☐	[fluid], [quantity]
	Dangerous for the environment	☐	[fluid], [quantity]
Non-ionizing radiation Safety	Laser	☐	[laser], [class]
	UV light	☐	
	Magnetic field	☒	0.12 T
Workplace	Excessive noise	☐	
	Working outside normal working hours	☐	
	Working at height (climbing platforms, etc.)	☐	
	Outdoor activities	☐	
Fire Safety	Ignition sources	☐	
	Combustible Materials	☐	
	Hot Work (e.g. welding, grinding)	☐	
Other hazards			