EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Study of neutron-rich $^{51-53}$Ca isotopes via beta-decay

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Abstract

The high Q-beta values in certain neutron-rich regions of the chart of nuclides opens up the possibility to study states in the daughter nuclei which lie at high excitation energy, above the neutron separation threshold. We propose to perform spectroscopy of the beta-delayed neutron emission of the $^{51-53}$K isotopes to study the population of single-particle or particle-hole states both below and above the neutron separation threshold. The VANDLE neutron detector will be used in combination with the IDS tape station setup and Ge detectors.

Requested shifts: 22 shifts

Introduction

With the increasing availability of neutron-rich beams, the isotopes that can be reached experimentally are approaching regions with low neutron-separation energies (S_n). When combined with the high Q_β value for beta decays this leads to a dominance of beta-delayed neutron emission for regions sufficiently far from stability, in particular near the shell closures, see Fig 1. The aim of this proposal is to investigate discrete states in neutron-rich nuclei in the calcium region. The states of interest will be populated by beta decay. From the previous studies in less exotic nuclei it is known that the high-energy states which will be explored will provide an insight into the single-particle energies going towards more neutron-rich nuclei.

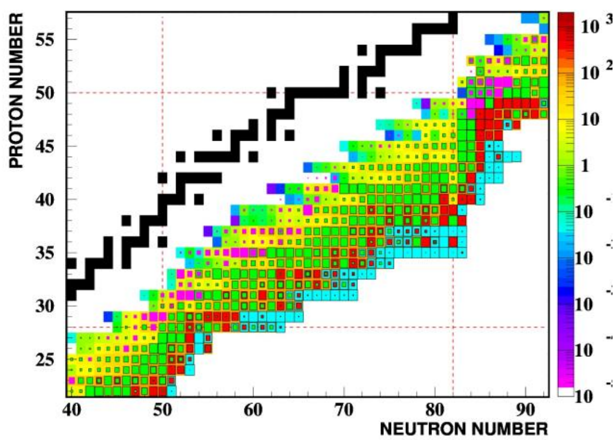

Fig. 1: The chart of the nuclei indicating the dominant beta-delayed neutron emission channels.

Physics motivation

Multiple studies of exotic (neutron-rich) calcium isotopes have been done in the past with multi-nucleon transfer from ^{48}Ca [1], but the reaction cross sections drop quickly as more neutrons are added, and thus the spectroscopic studies reached their limits at ^{52}Ca. More recently, the N=34 ^{54}Ca was produced and studied with the in-flight technique (^{70}Zn beam fragmentation) at Riken [2], and with the ISOL technique at CERN-ISOLDE (^{238}U spallation/fission) [3]. The N=33 ^{53}Ca was also measured at Riken [2] together with ^{54}Ca.The ensuing discovery of a subshell closure at N=34 in Ca isotopes [2, 3] has drawn renewed interest towards the neutron-rich calcium isotopes. The existence of this subshell closure has been explained as due to effects of three-body forces driving the monopole part of the nuclear Hamiltonian [4, 5], which are also necessary to reproduce the well-known N=28 shell closure in ^{48}Ca. The isotope ^{54}Ca is at the closure of the neutron $p_{1/2}$ orbital, with a large energy gap to the next $f_{5/2}$ orbital. Figure 2 shows some of the most recent shell-model calculations in this region, using a Hamiltonian incorporating nucleon-nucleon interaction from chiral effective-field theory together with schematic approximation of three-body forces as in-medium two-nucleon interactions. Coupling to the continuum is also taken into account. The 2^+ state of ^{54}Ca predicted at slightly below 2 MeV excitation energy, was found in Ref. [2] to be located at 2.1 MeV in excellent agreement with prediction. A

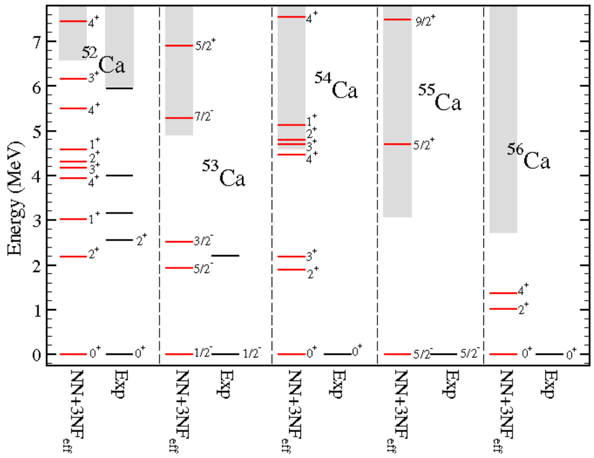

Figure 2: Shell-model calculations with three-body forces and coupling to continuum for neutron-rich calcium isotopes. The grey area indicates states above the neutron-separation energy. Figure is taken from Ref. [4]

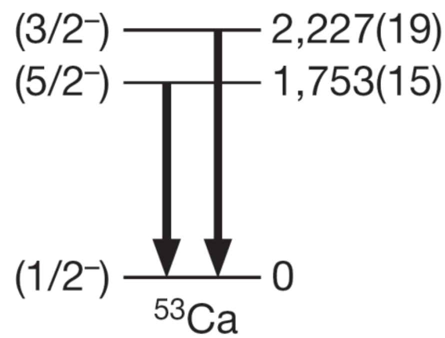

Fig. 3: The level scheme of ^{53}Ca deduced in Ref. [2]. Picture is taken from Ref. [3]

few other known states in lighter Ca isotopes are very well reproduced. However, a precise measurement of the effective single-particle energy evolution in this region is still lacking. It is thus of uttermost importance to test the shell-model predictions, and in particular the role played by the monopole part of the Hamiltonian which drives the change in the effective single-particle energies (ESPE).

In this proposal we want to study both the neutron unbound and bound states in $^{51\text{-}53}$Ca populated in the beta-decay of $^{51\text{-}53}$K, and from them to try to track the evolution of ESPE. In a past measurement at ISOLDE [6] the 7/2$^-$ level in ^{51}Ca and an unassigned level in ^{53}Ca were measured by gamma spectroscopy. Many other unbound levels were reconstructed by combining neutron and gamma spectroscopy for ^{51}Ca, but the statistics was not sufficient to draw definite conclusions on ^{53}Ca. The position of the 7/2$^-$ level is a measure of the energy necessary to make a vacancy in the neutron $f_{7/2}$ orbital (N=28 shell closure) and, calculations shown in Fig. 2, predict it to be unbound and to be placed at much higher in energy in ^{53}Ca. The occupation of the $p_{3/2}$, $p_{1/2}$ orbitals by five neutrons in ^{53}K should also enable the population of the 3/2$^-$ and 5/2$^-$ levels by first-forbidden beta decays. These are predicted to have relatively little configuration mixing from large-scale shell-model calculation, thus providing an effective measurement of the ESPE of the $p_{3/2}$, $f_{5/2}$ orbitals and of the gap between them at N=33. The state observed previously in ^{53}Ca [6], could be either of the two, but the 3/2$^-$ assignment seems more probable considering the string occupation of the $p_{3/2}$ orbital in the ^{53}K mother nucleus. More recently, two states were observed in ^{53}Ca via the proton knockout from ^{54}Sc in Riken [2], as shown in Fig. 3. One of the states corresponds to the level already measured in beta decay at ISOLDE, while the other is about 500 keV lower. They attributed the two states to the 5/2$^-$ and 3/2$^-$ levels mainly considering the shell-model predictions and systematics.

The spin-parity assignment was also supported by the theoretical calculations with the interactions KB3G [7] and a modified (adjustment to the strength (–0.15 MeV) of the $p_{3/2}\,f_{5/2}$

monopole interaction between neutrons) GXPF1B [2,8], which both predict the two levels in the described sequence. A previous version of this interaction GXPF1A [8], was predicting a reversed order. However, the spin-parity assignment is still tentative and its confirmation in another measurement can finally answer this question.

We propose to populate via beta decay ^{53}Ca with more statistics than previous measurements , thus achieving a more reliable beta decay feeding intensity measurement, in order to evaluate the *logft* values as well as to observe both $3/2^-$ and $5/2^-$ states. This will also allow us to more definitely assign their spin. In fact, we expect a higher population of the $3/2^-$ state due to the predicted properties of the wave function of the mother ^{53}K nucleus. We expect to see the M1 gamma ray connecting the $5/2^-$ and $3/2^-$ states: the comparison of the branching ratio with shell-model calculation will further constrain the spin-parity assignment. Recently, at Riken, ^{53}Ca was also produced and studied via proton-knockout of a ^{54}Sc beam [3].

Figure 2 also shows some states placed above the neutron-separation energy, in shaded areas, and the neutron-separation threshold lowers as the system becomes more neutron rich. The energy of these states can thus be estimated only by measuring the energy of the emitted neutrons in combination with gamma spectroscopy of the levels populated after neutron-emission. The observation of states which are particle-hole through the Ca core will give a unique insight into the shell structure between N=40 and N=50, at the very limit of isospin in this region. Besides the neutron-emission channels following first-forbidden transitions, 2n emission will also occur in ^{53}Ca [6], with a 10% probability. The Gamow-Teller (GT) decay of K isotopes is dominated by the transformation of the fp neutrons into their respective proton spin-orbit partner states. In the neutron-rich K isotopes (Z=19) the proton states near Fermi energy occupy the N=20 sd shell with one proton vacancy. The GT transformation will most likely create a proton in the $f_{7/2}$ orbital, as a consequence such a state will have an excitation energy of the order of the size of the shell gap at Z=20: about 6 MeV, see e.g. Ref. [10]. Additional extra excitation energy, of about 4-5 MeV, is due to the fact that the most likely decay channel $\nu f_{7/2} \rightarrow \pi f_{7/2}$ will generate a deeply bound neutron hole below N=28 shell closure. As a result, the Gamow-Teller states populated in the calcium isotopes will have about 10 MeV excitation energy. This is close to the two-neutron separation energy in the beta-decay daughter, hence such states will likely be decaying via two-neutron emission. Experimental evidence for this decay mode was observed by Perru et al. [6], but without detailed spectroscopic information. In this experiment we will exploit the large yields at ISOLDE, large P_{2n} values and VANDLE efficiency to search for 2 neutron events. Low statistics in the attempt to measure the beta-2n branch of ^{11}Li at ISOLDE made it impossible to observe true n-n coincidences over the mu-n and mu-gamma background [11]. Given the estimated branching ratios in [6] we expect for ^{52,53}K about or more than 10 000 true n-n coincidence events to be detected in VANDLE. This puts this experiment in a substantially better situation to identify n-n coincidences using kinematics cuts. We will exploit VANDLE to measure their energies and thus to determine the excitation energy of the particle-hole states, which are in this case generated across proton Z=20 and N=28 shell closures. The calculations presented below do not factor in the effects of shell evolution.

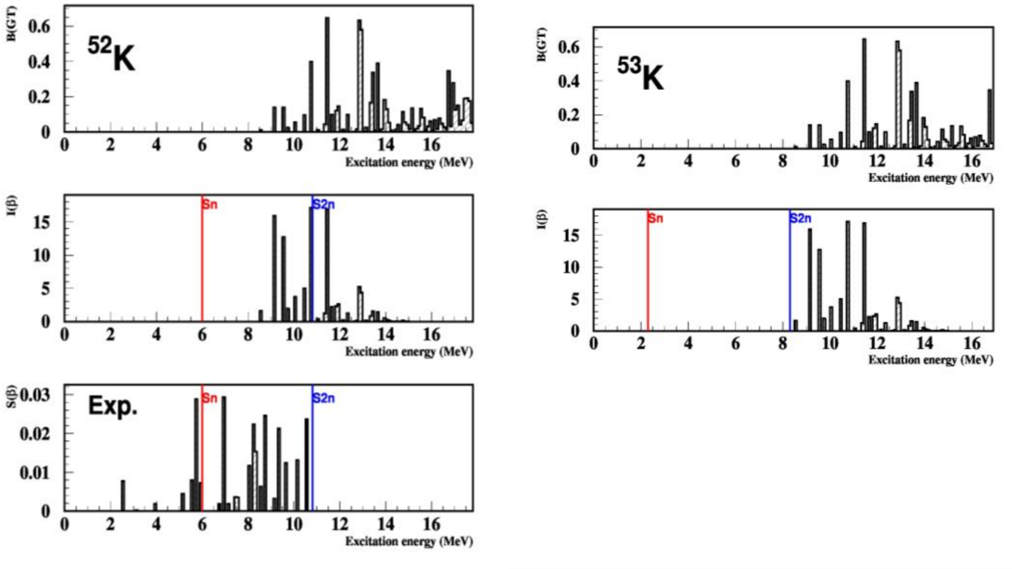

Fig. 4: (Left) Calculated Gamow-Teller strength distribution for the ^{52}K decay with 6 MeV Z=20 shell gap (top). Beta decay feeding intensity in arbitrary units, corresponding to the theoretical B(GT) (middle). Observed beta-decay strength distribution [6] predominantly due to first forbidden transitions. (Right) Calculated B(GT) (top) and resulting beta decay feeding pattern for ^{53}K decay. Notice, that entire B(GT) for ^{53}K is located above two-neutron separation energy in ^{53}Ca.

Experimental procedure

The experimental setup needed for the studies of interest at ISOLDE will consist of the IDS tape station with detectors for gamma and beta spectroscopy, surrounded by neutron detectors at 1m distance in order to achieve a good time-of-flight (TOF) resolution, from which the neutron energy has to be derived. The gamma detection system will be composed by germanium array. The HPGe detectors are necessary for the gamma spectroscopy of both the beta-daughter states below neutron emission and of the nucleus produced after beta-delayed neutron emission (^{52}Ca in the previous example of ^{53}Ca spectroscopy). This last measurement is also essential to reconstruct the energy of the states populated in the beta-daughter nucleus, by summing the energy of the neutron and the energy of the gamma rays in coincidence. Considering a typical gamma efficiency of 2% and a neutron efficiency of 10% at energies around 1 MeV, the combined neutron-gamma detection efficiency is 0.2%. In Fig. 4, we show the kind of setup we would like to use: it is similar to the TONNERE setup which was installed in the past at ISOLDE [6], to study beta-delayed neutron emission in the $^{51-53}$K isotopes. We propose to utilize the new detector VANDLE [12]. VANDLE will be available at ISOLDE starting from December 2014. Figure 5 shows the simulated neutron energy spectrum from VANDLE, considering the energies measured from K isotopes decay in Ref. [6]. The energy resolution, for 1 MeV neutrons, should be around 80 keV.

In Ref. [6] it was not possible to reconstruct the level structure above the neutron separation threshold due to the low statistics for the ^{53}K nucleus. The beta-delayed neutron emission probability was indeed measured to be around 75%. The ^{53}K yield at ISOLDE is around 50 pps from fission reactions in a UC_x target [13]. Table 1 shows the expected implantation rates assuming 80% transmission efficiency using the yields in [13]. Further improvements could be achieved for the shortest lived species ^{53,54}K using the new nano-structure UC_x target with a rhenium source. Considering a population of the state of interest in ^{53}Ca of 5%, four days of measurement should be sufficient to achieve the desired goal. For ^{51}Ca (^{51}K beam), we ask for one day of beam time. A try may also be given for the investigation of ^{54}K (whose yield may be in the order of 3 pps [13]) in order to populate ^{54}Ca: for this last part we require three shifts.

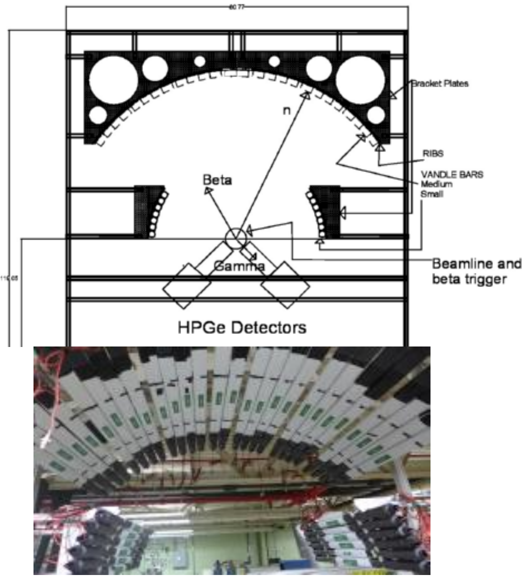

Fig. 4: The VANDLE setup which will be employed at CERN

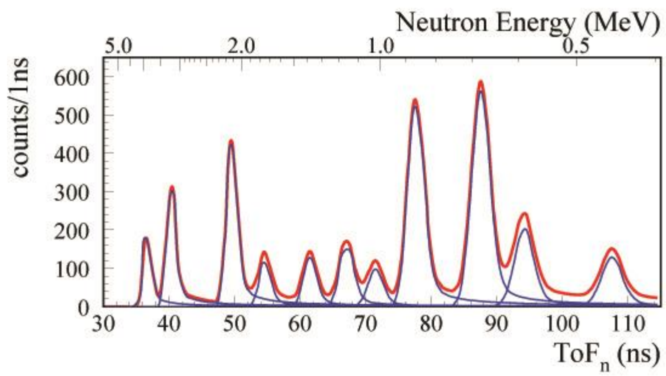

Fig. 5: The neutron-energy spectrum simulated for VANDLE taking into account the neutron energies measured in Ref. [6]

Summary of requested shifts:

Isotope	Rate on tape /s [13]	Time	Expected n. counts	Expected 2n coincidences
^{51}K	32000	3 shifts	$5.67\cdot10^{7}$	-
^{52}K	3200	4 shifts	$1.35\cdot10^{7}$	$3.2\cdot10^{4}$
^{53}K	40	12 shifts	$5\cdot10^{5}$	$6.9\cdot10^{3}$
^{53}K	1	3 shifts	$3\cdot10^{3}$	-

References:

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Symposium of Nuclei in the Cosmos, vol. 138, 1 (2008). || [13] A. Gottberg and T. Stora, UC480 and UC447 (2012).

Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: *(name the fixed-ISOLDE installations, as well as flexible elements of the experiment)*

Part of the Choose an item.	Availability	Design and manufacturing
[if relevant, name fixed ISOLDE installation: COLLAPS, CRIS, ISOLTRAP, MINIBALL + only CD, MINIBALL + T-REX, NICOLE, SSP-GLM chamber, SSP-GHM chamber, or WITCH]	☒ Existing	☒ To be used without any modification
		Tape station (with Ge) IDS, VANDLE
[Part 1 of experiment/ equipment]	☐ Existing	☐ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[Part 2 experiment/ equipment]	☐ Existing	☐ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[insert lines if needed]		

HAZARDS GENERATED BY THE EXPERIMENT

(if using fixed installation) Hazards named in the document relevant for the fixed [COLLAPS, CRIS, ISOLTRAP, MINIBALL + only CD, MINIBALL + T-REX, NICOLE, SSP-GLM chamber, SSP-GHM chamber, or WITCH] installation.

Additional hazards:

Hazards	*[Part 1 of the experiment/equipment]*	*[Part 2 of the experiment/equipment]*	*[Part 3 of the experiment/equipment]*
Thermodynamic and fluidic			
Pressure	[pressure][Bar], [volume][l]		
Vacuum			
Temperature	[temperature] [K]		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	[fluid], [pressure][Bar], [volume][l]		
Electrical and electromagnetic			
Electricity	[voltage] [V], [current][A]		
Static electricity			
Magnetic field	[magnetic field] [T]		
Batteries	☐		
Capacitors	☐		

Ionizing radiation			
Target material	[material]		
Beam particle type (e, p, ions, etc)			
Beam intensity			
Beam energy			
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☐		
• Open source	☐		
• Sealed source	☐ [ISO standard]		
• Isotope			
• Activity			
Use of activated material:			
• Description	☐		
• Dose rate on contact and in 10 cm distance	[dose][mSV]		
• Isotope			
• Activity			
Non-ionizing radiation			
Laser			
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300MHz)			
Chemical			
Toxic	[chemical agent], [quantity]		
Harmful	[chemical agent], [quantity]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chemical agent], [quantity]		
Corrosive	[chemical agent], [quantity]		
Irritant	[chemical agent], [quantity]		
Flammable	[chemical agent], [quantity]		
Oxidizing	[chemical agent], [quantity]		
Explosiveness	[chemical agent], [quantity]		
Asphyxiant	[chemical agent], [quantity]		
Dangerous for the environment	[chemical agent], [quantity]		
Mechanical			
Physical impact or mechanical energy (moving parts)	[location]		
Mechanical properties (Sharp, rough, slippery)	[location]		
Vibration	[location]		
Vehicles and Means of Transport	[location]		
Noise			
Frequency	[frequency],[Hz]		
Intensity			
Physical			
Confined spaces	[location]		
High workplaces	[location]		
Access to high workplaces	[location]		
Obstructions in passageways	[location]		
Manual handling	[location]		

Poor ergonomics	[location]		

0.1 Hazard identification

3.2 Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): *(make a rough estimate of the total power consumption of the additional equipment used in the experiment)*