EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Addendum to IS599 to the ISOLDE and Neutron Time-of-Flight Committee

Study of neutron-rich $^{53-54}$Ca isotopes via beta-decay of ^{54}K

[11/01/2016]

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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 ^{54}K isotope 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.

CERN-INTC-2016-012 / INTC-P-425-ADD-1
11/01/2016

Requested shifts: 22 shifts

Introduction

The calcium region is one of the most paradigmatic for the shell model. The nature of the N=28 shell closure has been long debated, leading to the conclusion that it can only be explained with three-body interactions. The recent discoveries of the N=34 subshell closure, together with the availability of first-principle calculations including three-body forces, has drawn even more attention to this crucial region [Steppenbeck].

The aim of this proposal is to investigate the N=34 subshell closure by measuring discrete states in neutron-rich calcium isotopes around N=34 and the lifetime and Gamow-Teller strength distribution of ^{54}K. The states of interest will be populated by beta decay directly or after beta-delayed neutron emission. This measurement is an addendum to IS599, which was performed last year. The test for ^{54}K production was a part of that proposal, and we managed to observe its decay at the IDS station. Therefore, we are requiring here beam time dedicated to the continuation of IS599.

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.

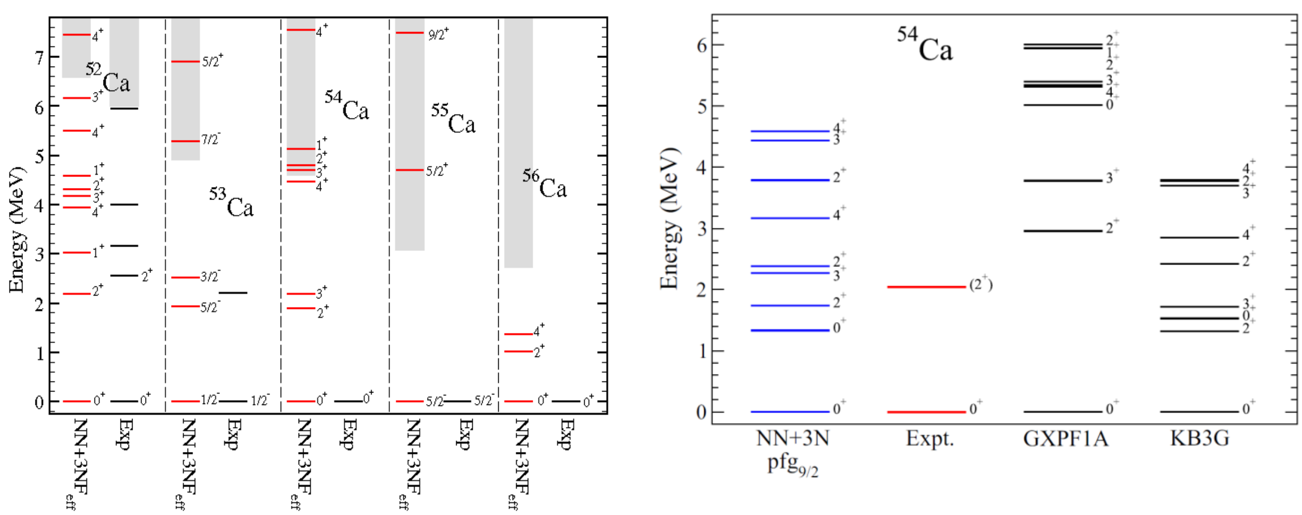

Figure 1. On the left: shell-model calculations with three-body forces renormalized to the Ca region and coupling to continuum for neutron-rich calcium isotopes. The grey area indicates states above the neutron-separation energy [Hagen]. On the right: shell-model calculations with three-body forces renormalized to the light nuclei [Holt]

More recently, the N=34 ^{54}Ca was produced and studied with the in-flight technique (^{70}Zn beam fragmentation) at Riken [Steppenbeck], and with the ISOL technique at CERN-ISOLDE (^{238}U spallation/fission) [Perrot]. The N=33 ^{53}Ca was also measured at Riken [Steppenbeck] together with ^{54}Ca. The discovery of a subshell closure in this nucleus [Steppenbeck, Wienholtz] 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 [Hagen, Zuker], 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 1 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. [Steppenbeck] to be located at 2.1 MeV, in excellent agreement with the calculation. A 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).

We therefore proposed to this PAC an experiment, IS599, to be able to reconstruct the neutron-unbound states of ^{53}Ca and the GT distribution in ^{52,53}Ca. We successfully performed the experiment last year, getting results on ^{52,53}Ca (see Figs. (4,5) in the next section) and proving the production of ^{54}K, as shown by the detection of its β-delayed neutron branch, see Fig. 2. In the present proposal we want concentrate on the study of the decay of ^{54}K to better understand the shell evolution around N=34. In fact, with a single measurement of the decay of ^{54}K, we can have at the same information on ^{54}Ca and ^{53}Ca, thanks to beta-delayed neutron emission.

^{53}Ca was studied in β decay in Ref. [Perrot]: one state was observed and tentatively assigned as $3/2^-$. More recently, two states were observed in ^{53}Ca via the proton knockout from ^{54}Sc in Riken [Steppenbeck], 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.

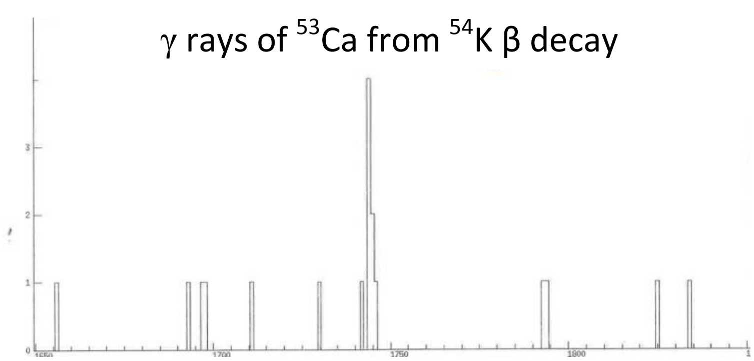

Fig. 2: γ ray of ^{53}Ca from ^{54}K β decay from Exp. IS599

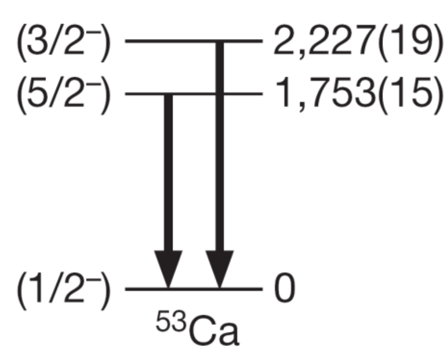

Fig. 3: The level scheme of ^{53}Ca deduced in Ref. [Steppenbeck]. Picture is taken from Ref. [Wienholtz].

The spin-parity assignment was also supported by the theoretical calculations with the interactions KB3G [Poves] and a modified (adjustment to the strength (–0.15 MeV) of the $p_{3/2}$ $f_{5/2}$ monopole interaction between neutrons) GXPF1B [Steppenbeck,Honma], which both predict the two levels in the described sequence. A previous version of this interaction GXPF1A [Honma], was predicting a reversed order.

The measurement we propose here can help to clarify the strength of the N=34 shell closure as well as to confirm previous assignments and observations. We propose to measure the beta-delayed neutron and gamma emission from ^{54}K with the following motivations:

1) On the one hand, the β decay will populate the N=34 ^{54}Ca. The spin of ^{54}K has not been measured, but it is predicted to be 2^- or 3^- (in ^{52}K it is 2^-) [Audi]. This implies a negligible feeding of the ^{54}Ca 0^+ ground state, and excited levels up to spin 3-4 should be visible. The comparison of the level scheme with calculations with different models of three-body forces (see Fig. 1) will help to disentangle among different renormalization of such forces, helping to understand their derivation from first-principles. Also, it could be possible to observe the transition between the 2^+ and the second 0^+, which in Ref. [Steppenbeck] was outside the observational limit due to its low energy. The second state found in Ref. [Steppenbeck] was interpreted as a 3^-, so it would be an allowed GT transition in our case. We will then be able to confirm or refute the tentative spin assignment. The interest of such state lies in the fact that the position in energy of 3^- is linked to excitations to the shells below and above the pf space. Therefore being a precise test of how interactions can correctly reproduce the shell gaps evolution [Utsuno].

2) On the other hand, the study of neutron emission to ^{53}K will provide crucial information on this region. At the first place, the coincidence between neutron emission and gamma rays will enable to reconstruct the level scheme or ^{54}Ca even above the neutron separation threshold. In this way a good part of the GT strength will also be measurable, considering the Q-value of nearly 20 MeV: the GT strength will go mainly through the $\nu f_{7/2} \rightarrow \pi f_{7/2}$ channel, requiring only about 10 MeV. These states are interesting because they can help us to understand, in comparison to the ^{52}Ca situation, how the N=28 shell gap is behaving when adding neutrons (it should increase [Holt]). At the second place, the analysis of the states populated in ^{53}Ca after neutron emission will also provide significant information. In fact, given that GT operator acts on deeply-bound neutrons, the unpaired $f_{5/2}$ neutron will the one to be emitted after ^{54}Ca is left in a highly-exited configuration. In Fig. 2, from our previous test run, we can indeed see that we likely populate the state tentatively identified as $5/2^-$ in [Steppenbeck], which is exactly what one expects if the 35th neutrons is in the $f_{5/2}$ shell. With more statistics, we will be able to see whether there are other states populated by neutron emission, inferring information on the role of the $f_{5/2}$ orbital at N=34.

Moreover, we point out that the decay lifetime of ^{54}K, today known with a 50 % error (10±5 ms) from a measurement performed 30 years ago [Langevin], and its P_n and possibly P_{2n} , will also be observables directly influenced the orbital spacing at N=34. Therefore, their comparison with theoretical estimates will complement the picture at the subshell closure.

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 (^{53}Ca). 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 8% at energies around 1 MeV, the combined neutron-gamma detection efficiency is 0.2%. We propose to exploit the neutron detector VANDLE [12] we already successfully employed in our previous run. Figure 4 shows the neutron energy spectrum from VANDLE from the decay of ^{53}K (Exp. IS599). The energy resolution, for 1 MeV neutrons, should be around 80 keV. For the same case, Fig. 5 presents the matrix of neutron-gamma coincidences: the two gamma transitions after neutron emission are clearly visible.

The ^{54}K yield we measured at ISOLDE was around 0.3 pps from fission reactions in a UC_x target. However, the rates we were observing were lower by a factor 10 with respect to the one obtained in the past [Gottberg], possibly due to the fact that the target was a used one. We thus expect an improvement in the counting rate, but we take a value of 0.5 pps in a conservative way. In 7 days of measurement this means 302000 event implanted. Considering a 90 % β efficiency, and a 90 % β-delayed neutron emission branch, we should have around 500 counts in the gammas of ^{54}Ca. If we neglect 2n emission, the number of detected neutrons should be 20000, or 500 in neutron-gamma coincidences. If the 2n branch is strong, we will have a chance to detect it.

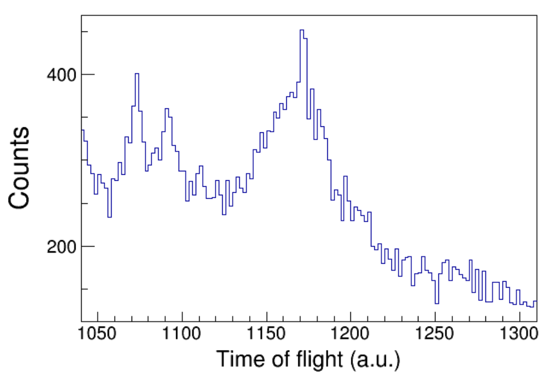

Fig. 4: The neutron spectrum from the VANDLE detector in the β decay of ^{53}K. Exp. IS599 (partial stat.)

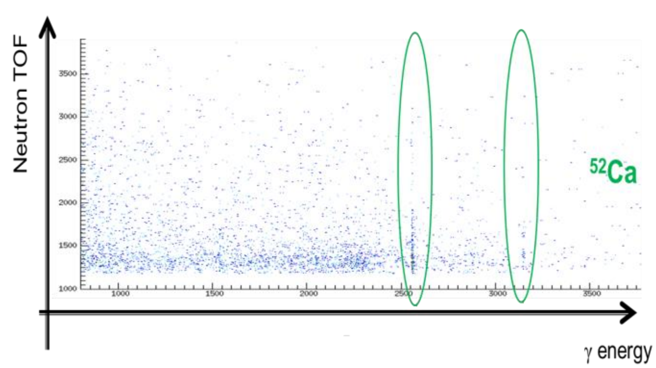

Fig. 5: The neutron-gamma coincidence matrix from VANDLE and IDS in the β decay of ^{53}K. Exp. IS599 (partial stat.)

Table 1 shows the expected implantation rates. Considering the short half-life of ^{54}K, 10 ms, further improvements could be achieved using the new nano-structure UC_x target. We also ask for 1 shift for debugging the setup and beam transport, and to check rates on less exotic

Ca isotopes. **In total we ask for 22 shifts for the β decay of ^{54}K at IDS with the VANDLE neutron detector**.

Summary of requested shifts:

Isotope	Rate on tape /s	Time	Expected neutron counts
^{54}K	0.5	21 shifts	$2.0 \cdot 10^4$

Tab 1

References:

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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)*