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EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE Committee

Beta-delayed 1- and 2-proton decay of ^{35}Ca

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Abstract

In this experiment, we propose to measure the decay of the beta-delayed two-proton emitter ***^{35}Ca***. The delayed proton(s) emission is a unique tool to perform spectroscopy of the drip-line nuclei involved in the process, in particular ***^{34}Ar***, which is relevant for nuclear astrophysics. In addition, we propose to use an experimental setup that may allow us to search for a possible direct 2-proton branch in the decay in order to study the mechanism of such an emission process.

Requested shifts: **<u>33 shifts</u>**

1 INTRODUCTION

At the proton drip-line, due to the increase of the Q_{EC} energy window, the beta decay populates states in the daughter nucleus at high enough energy to allow for one or several proton emission. For such isotopes, the decay spectroscopy from emitted protons measurements offers the most precise way to study low energy structure of the involved nuclei [1].

In addition, the strong feeding of the isobaric analog state (IAS) delayed proton(s) emission allows the identification of transitions from this state, which is relevant to study the Fermi strength, to estimate masses at the drip-lines with isobaric multiplet mass equation (IMME), and also to study isospin mixing, since the proton emission from IAS is isospin forbidden [2].

Due to the large Q_{EC} window, an important fraction of the Gamow-Teller (*GT*) strength is also accessible with beta decay. The measurement of the *GT* strength distribution B(*GT*) can thus be used to test the nuclear interactions and nuclear structure models far from stability [1].

The beta delayed 2-proton emission was observed for the first time in the decay of ^{22}Al [3]. Since then, more than 10 isotopes have been observed with this decay mode, the most studied one being ^{31}Ar [4]. In this type of decay mode, only sequential decays have been established, while there is no evidence for direct 2-proton transitions up to now. Nevertheless, a small fraction of the 2-proton branch could proceed via direct emission [5]. Such a case would be an interesting complement to the 2-proton radioactivity [1] to study the emission mechanism, since high statistics could be more easily accessible, and the Coulomb barrier effect would vanish.

The richness of the decay of such drip-line nuclei is illustrated in figure 1. The βp and $\beta\gamma$ measurements allow for a comparison of proton and gamma emission strengths. Gamma coincidences may also be measured in coincidence with protons to determine the feeding of ground and excited states in the 1-proton and 2-proton daughters.

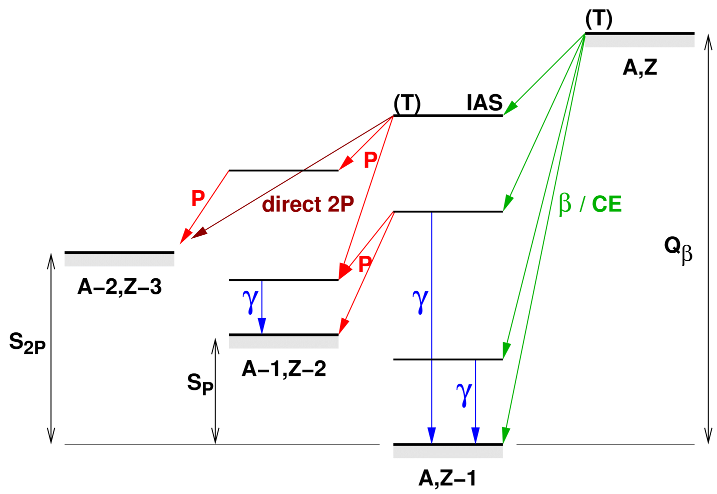

figure 1. Schematic picture of the delayed 1- and 2-proton emission of very proton rich isotopes.

This proposal is a continuation of the program to study such decaying isotopes, after ^{31}Ar [6]: ^{35}Ca is a similar beta-delayed two-proton precursor (see below).

2 THE DECAY OF ^{35}CA

The decay of ^{35}Ca was first observed in a gas-jet experiment performed at Berkeley [7]. The beta delayed 2-proton emission to the ground state and to the first excited state in ^{33}Cl was identified. The 2-proton emissions from the IAS in ^{35}K were discovered to be sequential emissions. The half-life was estimated to be $T_{1/2} = 50 \pm 30$ *ms*. The excitation energy of the IAS in ^{35}K allowed to determine the mass excess of the ^{35}Ca ground-state from IMME: $\Delta m = 4453 \pm 60$ *keV*.

Another experiment was performed at GANIL [8] (projectile fragmentation) where the decay of 6×10^4 ions was registered, leading to a more precise half-life: $T_{1/2} = 25.7 \pm 0.2$ *ms*. In this experiment, 19 ***β***-proton transition were identified and the B(*GT*) strength distribution was extracted. The total ***β***-proton(s) branching was found to be close to 100%, and no ***β***-gamma transition could be observed. The ***β-2p*** fraction was estimated to 4.2% of the decay, but no indication have been found for 2-proton emission to excited states in ^{33}***Cl***. The Fermi transition strength B(*F*) was found to be much lower than expected: the proposed explanations are either a very strong isospin mixing, either missed gamma transitions de-exciting the IAS. From the IMME, the mass excess was determined as: $\Delta m = 4530 \pm 66$ *keV*. It should be noticed that the mass excesses from both experiments are in good agreement, but differ significantly from the 2012 atomic mass evaluation [9] that gives the estimated value $\Delta m = 4788 \pm 196$ *keV*.

We propose to perform a full decay spectroscopy of ^{35}***Ca***, by mean of coincident gamma-proton(s) measurement. The ISOLDE facility has the advantage of providing a contaminant free radioactive beam, which was not the case in previous experiments. In addition, the high efficiency and high granularity set-up (described below) should allow us to improve significantly the experimental conditions. Under these conditions, the purposes of the experiment are:

- to measure with better resolution the ***β-p*** decay, trying to resolve previously observed proton groups;
- to try to observe ***β-γ*** decay, that could explain the low B(*F*) previously measured;
- to measure the ***β-2p*** decay and confirm or not the transition to the 1st excited state in ^{33}***Cl***, and search for a direct (non sequential) 2-proton component;
- comparing ***β-p-γ*** and ***β-2p***, to obtain information on the relative proton and gamma width of populated states in ^{34}***Ar*** (daughter of ^{35}***Ca*** in ***β-p*** decay): such information is relevant for nuclear astrophysics, where the ^{33}***Cl***(***p***,***γ***)^{34}***Ar*** reaction rate for *rp*-process is estimated from statistical model [10];
- build an improved decay scheme from protons and gamma coincidences.

These proposed measurements include new determinations of the half-life, the mass excess and the B(GT) distribution.

3 DETECTION SET-UP

We propose to perform the measurement with the “Silicon-Cube” device [11] (see figure 2). It is an assembly of six ***ΔE-E*** silicon telescopes made of a thin front double-sided strip detector, backed with a single silicon diode. Each telescope is 48x48 mm^2, with 16x16 strips. The telescopes are mounted in a close geometry, resulting in a geometrical efficiency around 50%.

The radioactive ions are deposited at the centre of the “cube”, either on a mylar tape from a tape transport system, either on a simple catcher (a thin mylar foil) since there is no long-lived proton decay from the daughter nuclei.

The front detectors are used for low energy lines measurement, and to determine the emission angles of emitted protons with high granularity (with an angle precision around 5 degrees).

They are equipped with low noise pre-amplifiers for a better energy resolution (typically 15 *keV* for 5 *MeV* alpha particles).

The back detectors allow to perform sum energy for higher energy protons, and to veto beta particles pile-up and avoid the broadening of the proton peaks energy lines.

The silicon cube will be surrounded by 3 clover germanium detectors to perform the β-γ, β-**p**-γ and β-**2p**-γ coincidence measurements. The gamma detection efficiency at 1 *MeV* will be around 15%.

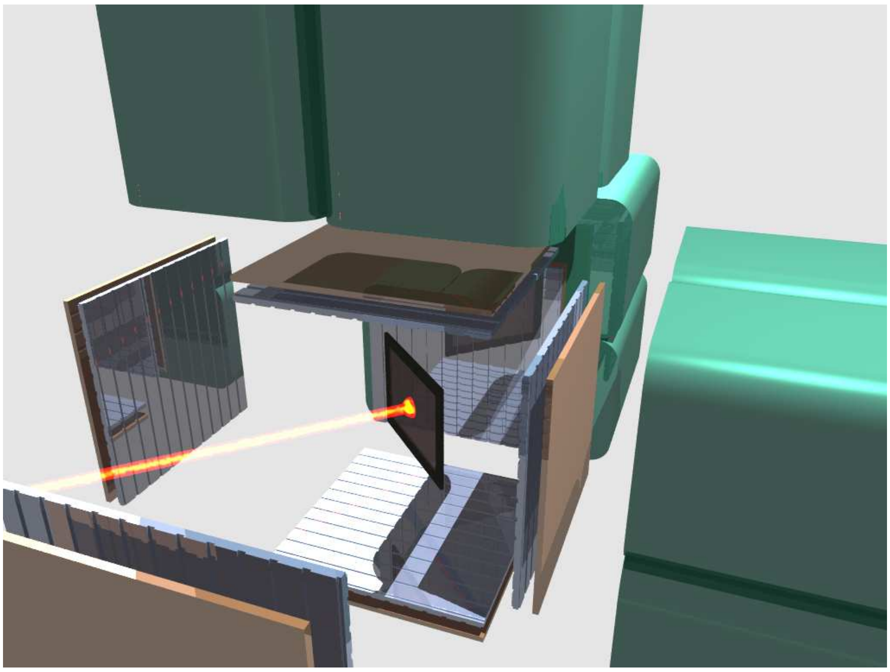

figure 2. Schematic view of the detection set-up, presented here with a "catcher" to collect ions. Two silicon telescopes (strip detectors backed with large single silicon detectors) are shown at shifted positions for presentation reasons. To measure gamma rays in coincidence with betas and protons in the decay, 3 germanium clovers (4 crystals each) are installed around the cube.

4 BEAM-TIME REQUEST

The ^{35}***Ca*** production at ISOLDE requires ***TiC*** targets that are currently under test. The proposed experiment can be achieved with average rates in the order of 0.1 ion per second.

For the set-up tuning and the calibration with known beta delayed proton emitters (mainly with ^{37}***Ca*** but also ^{36}***Ca*** and optionally ^{31,32}***Ar***, that will also be produced with the target), we ask for 1 days of beam time.

The ^{35}***Ca*** beam time request is determined with the following parameters:

- measurement cycle (collection / decay): 20% (1 shift for $T_{1/2}$ measurement), or 100% in continuous running mode;
- experiment dead-times (technical stops): 75%;
- proton detection efficiency: 50% for 1p; 25% for 2p.

With a production rate for ^{35}***Ca*** of 0.1 ion/second, within 1 day, we should obtain in the order of 3000 ***β-p*** decays and 60 ***β-2p*** decays. We need few counts to identify that part of the **2*p*** emission which does not proceed via an intermediate state to assign a direct emission. Assuming a 1% fraction of the **2*p*** decay being a direct emission, 8 days beam time is required to identify such a transition. This time will be sufficient for proton and gamma width comparisons in ^{34}***Ar*** and to establish a better decay scheme.

Summary of requested shifts:

Beam and separator tuning:	3 shifts
Set-up tuning and calibration (with radioactive beam)	3 shifts
Experiment (^{35}***Ca*** beam)	24 shifts
Total	**30 shifts**

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
[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] Silicon Cube	☒ 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 3 experiment/ equipment] Germanium clovers	☒ 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	[Bar], [volume][l]		LN2, 1.5 bar
Electrical and electromagnetic			
Electricity	[V], [A]	220[V], 10[A] (crates)	

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]		☒ [ISO standard]
• Isotope		60Co, 137Cs, 152Eu	3-alpha source
• Activity		2 kBq	5 kBq
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

The safety considerations for the realisation of the experiment described here are the ones from any standard nuclear physics experiment.

The experiment requires electrical power for standard NIM / VME crates and for detectors. For the germanium detectors, we use high voltage (5 kV) power supplies. The electrical current required is in the order of 10 A.

We need to fill the germanium detectors with liquid nitrogen. We plan to use the ISOLDE tanks. The usual safety issues with liquid nitrogen apply here.

For silicon detectors calibration we will use 3-alpha source, with an activity in the order of 5 kBq. For germanium detectors, standard gamma sources like ^{60}Co, ^{137}Cs, … will be used (with an activity around 2 kBq). The activity from calibration source is thus very low. In addition, the activity from the experiment it-self should remain extremely low, since isotopes considered here have a very short half-life (less than a second) and very low production rates (lower than 1 to 100 per second for ^{35}***Ca*** and ^{37}***Ca***).

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)*

Electronic crates and power supplies : ~ 5kW