EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Study of the β-delayed one- and two-proton decay of ^{35}Ca

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B. Blank[1], M.J.G. Borge[2,4], H.O.U. Fynbo[3], M. Gerbaux[1], J. Giovinazzo[1], S. Grévy[1], H. Guérin[1], T. Kurtukian-Nieto[1], E. Nacher[2], A. Perea[2], V. Pesudo[2], K. Riisager[3], O. Tengblad[2]

1 Centre d'Etudes Nucléaires de Bordeaux Gradignan – UMR5797 CNRS/IN2P3 – Université de Bordeaux, Chemin du Solarium, BP 120, 33175 Gradignan Cedex, France

2 Instituto de Estructura de la Materia, CSIC, E-28006 Madrid, Spain

3 Department of Physics and Astronomy, University of Aarhus, DK-8000 Arhus, Denmark

4 PH Department, CERN, CH-1211 Geneva 23, Switzerland

Spokesperson(s): J. Giovinazzo (giovinaz@cenbg.in2p3.fr), O. Tengblad (olof.tengblad@csic.es)

Local contact: M.J.G. Borge (mj.borge@csic.es)

Abstract

In this experiment, we propose to measure the decay of ***^{35}Ca***. This nucleus decays by β-delayed emission of γ rays and one or two protons. Our study will allow us to establish a complete decay scheme of this nucleus and compare the experimentally determined Gamow-Teller strength to model predictions, to study states in ***^{34}Ar***, which are relevant for the astrophysical ***rp*** process, to search for Fermi decay strength missing according to a previous study, and for the first time, to study two-proton emission with an adequate detection system which will allow us to search for a possible direct 2p branch predicted by a theoretical work and to study thus the mechanism of the two-proton emission process.

Requested shifts: **30 shifts**

1 INTRODUCTION

At the proton drip-line, due to the large Q_{EC} energy window, β decay populates states in the daughter nucleus at high energy producing a complex emission pattern including the emission of one or several protons. Decay spectroscopy of these nuclei offers the high sensitivity and precision to study low spin structures in the daughter nuclei [1].

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

Due to the large $\boldsymbol{Q_{EC}}$ window (~22 *MeV* from systematics), an important fraction of the Gamow-Teller (*GT*) strength is also accessible with β decay. The measurement of the *GT* strength distribution, B(*GT*), can thus be used to test the nuclear interaction and nuclear structure models far from stability [1].

Beta-decay studies proved also to be a unique tool to search for astrophysically relevant states in nuclei involved in proton capture reactions [3]. These states are located close to the proton emission threshold of these nuclei and allow thus the capture of a proton (in the present case for the $^{33}Cl(p,\gamma)^{34}Ar$ reaction of the *rp*-process). Beta-decay studies allow to search for such states and to determine their spin and parity. The observation of proton and γ emission from these states allows one also to determine relative proton and γ widths relevant for the capture process.

Beta-delayed 2-proton emission was observed for the first time in the decay of ^{22}Al [4]. Since then, more than 10 nuclei show this decay mode, the most studied one being ^{31}Ar [5]. 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, according to shell-model predictions, a small fraction of the 2-proton branch could proceed via a direct emission [6]. Such a case would be an interesting complement to 2-proton radioactivity [1] to study the emission mechanism, since high statistics could be more easily accessible. In addition, the two-proton emission process might be influenced by the spin of the decaying system (e.g. 5/2+ for ^{31}Ar [7] and an expected 1/2+ for ^{35}Ca).

The richness of the decay of such drip-line nuclei is illustrated in Figure 1.

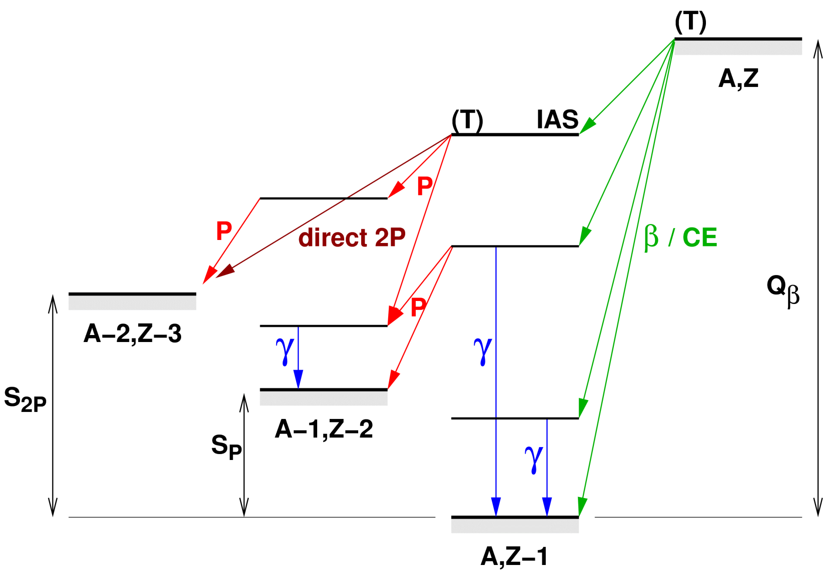

Figure 1: Schematic decay scheme for a proton drip-line nucleus by β-delayed γ as well as 1- and 2-proton emission.

After an extensive study of ^{31}***Ar*** ([5] and references therein), this proposal is a continuation of the program at ISOLDE [3] dedicated to study such decaying isotopes: ^{35}***Ca*** is, from the decay pattern point of view, a similar beta-delayed two-proton precursor, however, most likely with a different ground state spin (see below).

2 THE DECAY OF ^{35}CA

The decay of ^{35}***Ca*** was first observed in a gas-jet experiment performed at Berkeley [8]. Beta-delayed 2-proton emission to the ground state and to the first excited state in ^{33}***Cl*** was identified. 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 by means of the IMME: $\Delta m = 4453 \pm 60$ *keV*.

Another experiment was performed at GANIL [9] (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 transitions were identified and the B(*GT*) strength distribution was extracted. The total β-proton(s) branching ratio was found to be close to 100%, and no β-γ transition were observed. The β-**2*p*** fraction was estimated to be 4.2% of the decay, but no indication was found for 2-proton emission to excited states in ^{33}***Cl***, in contradiction with the result from the previous experiment. The Fermi transition strength B(*F*) was found to be much lower than predicted: the explanations proposed were either an extremely strong isospin mixing or unobserved γ 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 excess values from both experiments are in good agreement, but differ significantly from the 2012 atomic mass evaluation [10] that gives an estimated value of $\Delta m = 4788 \pm 196$ *keV*.

We propose to perform for the first time a complete study of the decay of ^{35}***Ca***, including β-delayed γ, one-proton and two-proton emission with the possibility to observe for the first time a direct 2p branch, by means of a coincident β - γ- proton 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 purpose of the experiment is as follows:

- to measure with much better resolution the β-***p*** decay, trying to resolve previously observed proton groups;
- to try to observe β-γ decay from the IAS, that would explain the low Fermi strength previously measured;
- to measure the β-**2*p*** decay and confirm or not the transition to the 1st excited state in ^{33}***Cl***, as well as to search for the first time for a direct (non sequential) 2-proton component. This will be achieved by searching for two protons with similar energy for a given sum energy (equal energy sharing between the protons). Sequential decay is characterised by well-defined single-proton lines, typically with a different energy between the two protons. If statistics is high enough, we can also measure the protons relative angular distribution.

- to compare ***β-p-γ*** and ***β-2p*** decays in order to obtain information on the relative proton and γ widths of states populated in ^{34}Ar (daughter of ^{35}Ca in ***β-p*** decay): such information is relevant for nuclear astrophysics, where the $^{33}Cl(p,\gamma)^{34}Ar$ reaction rate for the *rp*-process is estimated from statistical model calculations [11];
- to build an improved decay scheme from proton and γ decay measurements and to determine thus the half-life, the mass excess and the B(GT) distribution;
- to determine the spin of ^{35}Ca.

3 DETECTION SET-UP

We propose to perform the measurement with the “Silicon-Cube” device [12] (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 has a surface of 48x48 mm^2, with 16x16 strips. The telescopes are mounted in a close geometry, resulting in a geometrical efficiency of about 50%.

The radioactive ions are deposited at the centre of the “cube”, either on a Mylar tape from a tape transport system, or on a simple catcher (a thin Mylar foil). Most likely we will chose this second option, since there is no long-lived β-delayed proton emitter among the daughter nuclei.

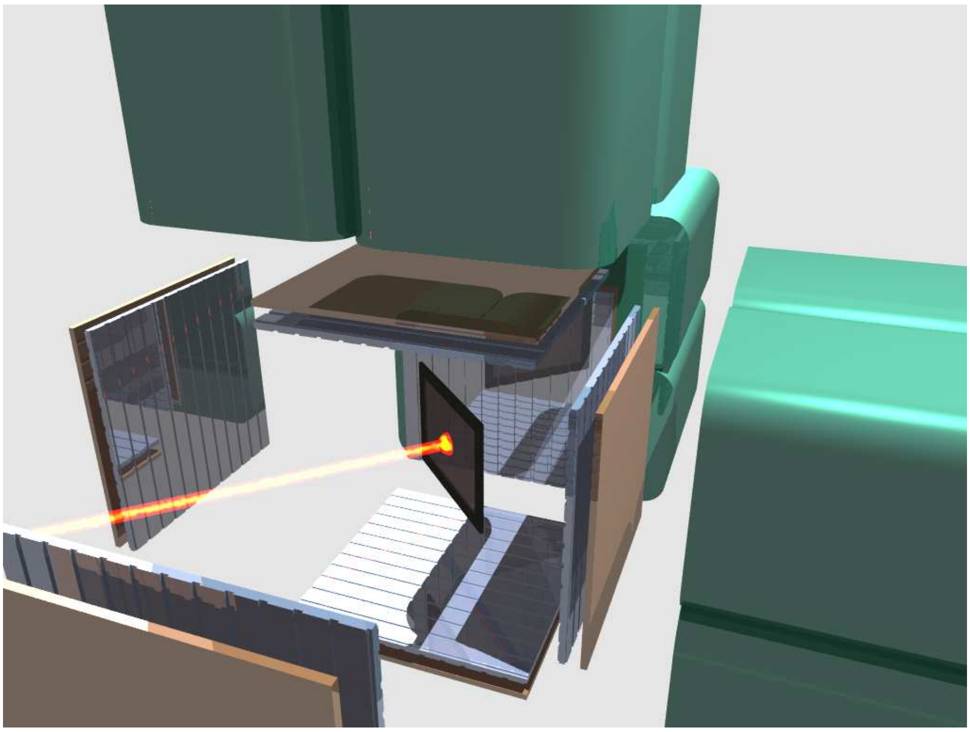

Figure 2: Schematic view of the detection set-up, presented here with a “catcher” to collect ions. Two silicon telescopes (strip detectors backed with large-area silicon detectors) are shown at shifted positions for presentation reasons. To measure γ rays in coincidence with β particles and protons in the decay, three germanium clovers (four crystals each) are installed around the cube.

The front detectors are used for low-energy proton lines and to determine the emission angle of between two protons with good resolution (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 measure the residual energy for high-energy protons punching through the front detector, and to veto β particles to avoid the broadening of the proton energy lines.

The silicon cube will be surrounded by three clover germanium detectors to perform the β-γ, β-p-γ and β-$2p$-γ coincidence measurements. The γ-ray detection efficiency at 1 *MeV* will be around 15%. These detectors may be either the Miniball clovers (used for ^{31}Ar experiment), some EXOGAM clovers, or detectors from the decay station (IDS).

4 BEAM-TIME REQUEST

The proposed experiment can be performed with average rates in the order of 0.1 to 1 ion per second. The ^{35}Ca production at ISOLDE requires ***TiC*** targets that are currently under test. While estimated production is about 0.05 particles per second (pps), some developments are going on, which may increase this rate 10 times [13].

For the set-up tuning and the calibration with known β-delayed proton emitters (mainly with ^{37}Ca but also ^{36}Ca), we ask for 1 day 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 interrupts, beam re-tuning, set-up checking, nitrogen filling,…): 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 of the order of 3000 β-p decays and 100 β-$2p$ decays. We need a 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 of beam time are required to identify such a transition. This time will be sufficient for all the other research topics mentioned above.

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:

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] Users' own data acquisition	☒ 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 of the order of 10 A.

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

For silicon detector calibration, we will use a 3-alpha source, with an activity in the order of 5 kBq. For germanium detectors, standard γ sources like ^{60}Co, ^{137}Cs, … will be used (with an activity around 2 kBq). The activity from calibration sources is thus very low. In addition, the activity from the experiment itself 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