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

β3p spectroscopy and proton-γ width determination in the decay of ^{31}Ar

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Abstract: We propose to perform a detailed study of the β-decay of the dripline nucleus ^{31}Ar. This will allow a detailed study of the β-delayed 3p-decay as well as provide important information on the resonances of ^{30}S and ^{29}P, in particular the ratio between the proton and γ partial widths relevant for astrophysics.

Requested shifts: 24 shifts, (split into 1 run over 1 year)

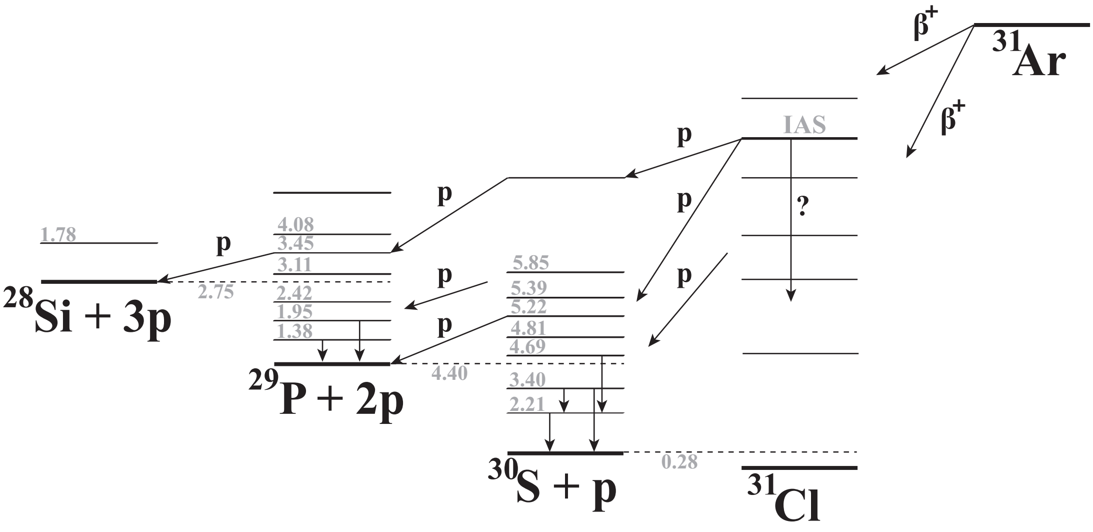

Figure 1: The decay of ^{31}Ar not to scale. Different proton and γ decays are drawn as an illustration. The proton separation energy are marked with dashed lines.

1 Introduction

The decay of the dripline nucleus ^{31}Ar is the most thoroughly studied β-delayed multi-particle decay, to a large extend due to earlier experiments performed at ISOLDE. Recent developments on the CaO target and ion source [1], and detection capabilities (the new ISOLDE Decay Station), as well as results from the nearly completed analysis of the previous experiment IS476, makes it timely to return to this decay at ISOLDE. As will be argued below, these recent developments allow for the first time to explore the physics of β3p-decays with spectroscopic precision, to provide unique information requested by nuclear astrophysics on decay widths of resonances in ^{29}P and ^{30}S, and an unprecedented in-depth view of the β-strength in a dripline decay.

2 Physics motivation

The decay of ^{31}Ar is a prototype of the decays of the most extreme dripline nuclei. It has a large Q_β-window of 17.34(21) MeV and as a consequence many different β-delayed decay channels are open: $\beta\gamma$, βp, βpγ, β2p, β2pγ, β3p and perhaps also β3pγ, see Fig. 1. All, but the latter, have been observed in previous ISOLDE experiments [2, 3, 4]. A proper understanding of the ^{31}Ar decay will give us a better ground for predicting decay patterns further up the proton dripline.
Results from the previous experiment at ISOLDE on this decay, IS476, are now either published or being written up. The main points are:

1. We have demonstrated that the β2p- and βpγ-decay can be used to study the levels of ^{30}S, especially the astrophysically interesting states just above the proton threshold. We have added the use of particle-particle angular correlations as a tool for determining spin of the individual levels of ^{30}S.

2. Identification of β3p-decays in the decay of ^{31}Ar, although with very limited statistics. This four-particle decay mode is identified not only from the strongly populated isobaric analogue state (IAS), but also from higher lying states. Since these states are at high excitation energy, they represent a large Gamow-Teller strength.

These results were obtained with a total number of produced ^{31}Ar only half that of the previous study in 1997, which was possibly only due to a significantly better solid angle for charge particle detection in IS476.
As will be presented in section 3, by using a Nano-structured CaO target material the ISOLDE target group has demonstrated a yield larger by at least an order of magnitude over the previous design. In addition the initiative of the *ISOLDE Decay Station* (IDS), will enable a measurement with much higher efficiency for γ-detection, which when combined with a charged particle detection system similar to or better than that of IS476 provides a new window of opportunity. Specifically, we aim to increase the reach of the ^{30}S study to the point where the radiative and particle partial widths can be determined at the level of sensitivity required by nuclear astrophysics, and via the β3p channel achieve the same for resonances in ^{29}P. In addition, we will go from simply *identifying* the β3p branch in the decay of ^{31}Ar to actually *studying* it; much like what was achieved for the β2p decay mode 16 years ago. The goal of identifying non-sequential decay modes both in β2p and β3p remains and will be pursued also in the new experiment with increased sensitivity. Finally, a new measurement will provide a much better measure of the β-strength distribution both in the Fermi and Gamow-Teller part in particular with the better measurement of the β2p and β3p branches to high lying states, which represent relatively large β-strength per decay. These points will be discussed in more detail below.

2.1 Levels of ^{30}S

When IS476 was proposed in 2008 the levels just above the proton threshold in ^{30}S had not all been identified, but were only inferred from the mirror nucleus. These levels are important for determining the reaction rate of $^{29}\mathrm{P}(p,\gamma)^{30}\mathrm{S}$, which influences the silicon abundances. The latter can be directly studied from presolar dust grains believed to be produced in classical novae. In the last two years the relevant levels in ^{30}S have been studied intensively [3, 5, 6, 7, 8], such that the energies are now known for the relevant levels, while some disagreements about the spin assignment remain. In IS476 we have developed a method that makes it possible to determine the Γ_p/Γ_γ ratio from the decay of ^{31}Ar and verified its applicability by placing limits on the Γ_p/Γ_γ ratio for three ^{30}S levels [3]. Furthermore, we have shown that by choosing specific transitions from ^{31}Cl to ^{30}S it is possible to determine the spin of the states from particle-particle angular correlations [4]. With more statistics it will be possible, using these methods, to not only place limits, but to determine the Γ_p/Γ_γ ratios for at least four of the relevant levels, including the levels predicted to have the strongest influence on the astrophysical reaction rate. It will also be possible to resolve some of the open questions regarding spin assignments.
The two levels predicted to have the strongest influence on the $^{29}\mathrm{P}(p,\gamma)^{30}\mathrm{S}$ reaction are situated at 4689 keV and 4809 keV. The γ-decay of the lowest of the two was identified in IS476 and from that an upper limit on the Γ_p/Γ_γ ratio was found to be 0.26 (95 % C.L.).

This, however, is two orders of magnitude higher than what is expected from calculations, and therefore not a sufficiently small limit. IS476 suffered from a large contamination of ^{16,17}N produced as a molecule at mass A=31, which gave a disturbing background from both β-particles and γ-rays. This hampered to some extend the detection of low-energy protons. During the experiment it became clear how this background could be reduced by operating the target and line temperature appropriately. Together with the improvements discussed above, it should therefore be possible to reach at least a factor of ten increase in sensitivity such that a value for Γ_p/Γ_γ can be provided not only for the 4689 keV level, but also for the 4809 keV level. In IS476 the latter was not clearly identified in the γ-spectrum, but there were indications for a signal around the expected energy. With a better γ-detection and a higher yield, it should be clearly within reach, if it is populated in the decay, and in turn a value for Γ_p/Γ_γ achievable.
Currently there are still some disagreements with the spin assignment of the level around 5.2 MeV, or if there are in fact two levels; a 0^+ and a 3^+ level. This is the level in ^{30}S that is populated the most in the β2p-decay of ^{31}Ar. We have shown, using particle-particle angular correlations, that the level we populate is either a 3^+ or a 4^+. We have found an upper limit on the Γ_γ/Γ_p ratio of 0.5 (95 % C.L.), which is two magnitudes higher than found from calculations of a 3^+ level [8]. With the setup here and the requested beam time it should be possible to determine the spin of this level and to detect γ-rays from it and thereby get a value for Γ_γ/Γ_p.
In the same way as the β2p- and βpγ-decays can be used to investigate the levels of ^{30}S, the β3p- and the β2pγ-decays can be used to investigate the levels of ^{29}P. As will be further discussed below, the analysis of the IS476 experiment shows indications of sequential β3p-decay through at least two levels above the proton threshold in ^{29}P. The experiment suggested here will provide sufficient statistics on the 3p- and the 2pγ-decay to make it possible to study the Γ_p/Γ_γ ratio at the percent level. Up until now only the $\Gamma_p\Gamma_\gamma/\Gamma$ have been measured [9]. With the measurements of the Γ_p/Γ_γ ratio it will be possible to improve the currently known total lifetimes of these levels in ^{29}P.

2.2 β3p-decay

The β3p-process has only been seen from two nuclei until now: ^{45}Fe [10] and ^{43}Cr [11, 12]. It was recently discovered from ^{31}Ar by Pfützner *et al.* [13] and it has also been observed during the analysis of IS476, but not yet published. The 3p-decay of the IAS was clearly seen and also indications of 3p-decays from other, higher lying levels in ^{31}Cl. The statistics was, however, very limited and only about 60 three-particle decays were observed, where about half of them are assumed to be background from 2pβ-decays. The amount of data available gave rise to a number of questions: Which states do the 3p-decay go through in ^{29}P? Are the decays only sequential or are there simultaneous components? What other states in ^{31}Cl decay by 3p-emission? If the decay goes through states in ^{30}S, they have higher energy than any previously observed levels in ^{30}S. Is it possible to identify any of those specific states in ^{30}S?
The β3p-decay of ^{31}Ar is thus interesting in it self, but also as a tool for determining the Gamow-Teller strength at high energy. As for ^{43}Cr, the β3p-decay of ^{31}Ar takes the isospin asymmetric initial system towards an isospin symmetric system. The final nuclei,

^{28}Si, is semi-magical with two closed $d_{5/2}$ shells.

2.3 β-strength

The Fermi strength of the decay has previously been found using the 2p- and 1p-decay of the IAS. In the analysis of IS476, which had a better resolution than previous experiments, only about 75 % of the expected strength is found. Only 2p-decays to the three lowest states in ^{29}P were identified, but the analysis of the 3p-decay gives strong indications of decays to both the fifth and the sixth excited states. This means that there are several other 2p-decay channels that also need to be included together with the 3p-decay channel. This will be possible with an experiment measuring the γ-rays in coincidence with the 1p- and 2p-decays, i.e. an experiment with a good efficiency for both γ and particle detection. A good γ-efficiency will also open the possibility for detection of direct γ-decays from the IAS.

It is known that the position of the main part of the Gamow-Teller strength for ^{33}Ar and ^{32}Ar is sensitive to the exact shell model interaction used [14, 15]. It is thus natural to investigate ^{31}Ar to see if this is also the case here. The main problem is to identify the strength going to highly excited levels in ^{31}Cl where many channels are open. The problem is the same as for the Fermi strength: The final states must be known. It is seen from the 3p-decay that several excited states in ^{31}Cl above the IAS are populated, but it is not possible to assign the 2p-decay of these correctly without detection of the γ-transition in coincidence.

3 Detection system and ^{31}Ar production

We propose to use the IDS for this study, with a custom built chamber hosting an array of 6 Double Sided Si strip detectors. We aim for a charged particle detection solid angle close to 70 %, while the Ge-detectors of the IDS provide a solid angle around 25 % using a combination of clover- and Miniball like Ge-detectors.

We ask for a CaO target with the new nano-structured target material. This target unit has been tested by the ISOLDE target group partly in collaboration with IS476, with very promising results. The deduced yield for ^{31}Ar determined by a combination of measurements of several Argon isotopes with both the tape station and a spectroscopy setup at La1 is of the order of 30 ions/μC, which is a factor 10 or more higher than the average yield obtained in IS476.

4 Summary and Beam request

The beam time request is based on the following reasoning. We assume an average yield on the collection foil of 10 ions per second, which is factor ten above the yield obtained in the previous experiment, IS476. Assuming 8 days of beam time with this yield we expect a total number ions at the foil of 5×10^6, which again is a factor 10 higher than the corresponding number for IS476. This beam time estimate includes time for calibrations using ^{32,33}Ar.

Including the increased detection efficiency for both protons and γ-rays we expect the following: From the theoretically estimated proton- and γ-partial widths we expect 40 protons from the 4689 keV-level. A definite measurement is also within reach for the 4809 keV-level that currently is estimated to be the most important resonance for astrophysics. We expect from the theoretically calculated proton and γ partial widths to detect four 3 Mev γ-rays in total from the 5.2 MeV level. Hence, with the requested beam time and the suggested setup we will be able to provide the astrophysically required information for the mentioned levels.
For the β3p decay of the IAS we expect a total of 500 measured events.
Summary of requested shifts: 24 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	Availability	Design and manufacturing
ISOLDE Decay Station (IDS)	☒ Existing	☒ To be used without any modification safety procedure for the IDS will be done independently of the proposals

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 experiment/ equipment]	[Part 2 of experiment/ equipment]	[Part 3 of 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]	Carbon foil		
Beam particle type (e, p, ions, etc)	^{31,32,33}Ar		
Beam intensity	1-1e4 /s		
Beam energy			

Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☐		
• Open source	☐		
• Sealed source	☐ [ISO standard]		
• Isotope	Standard sources for calibration of Ge-detectors		
• 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 (1-300 MHz)			
Chemical			
Toxic	[chemical agent], [quantity]		
Harmful	[chem. agent], [quant.]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chem. agent], [quant.]		
Corrosive	[chem. agent], [quant.]		
Irritant	[chem. agent], [quant.]		
Flammable	[chem. agent], [quant.]		
Oxidizing	[chem. agent], [quant.]		
Explosiveness	[chem. agent], [quant.]		
Asphyxiant	[chem. agent], [quant.]		
Dangerous for the environment	[chem. agent], [quant.]		
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]		

Hazard identification:

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]