

Proposal to the INTC

**Studies of β -delayed two-proton emission : The cases
of ^{31}Ar and ^{35}Ca**

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Abstract

We propose to perform detailed studies of the decays of the two dripline nuclei ^{31}Ar and ^{35}Ca . This will allow an in-depth study in the process of β -delayed two-proton emission ($\beta 2p$); as well as provide important information on resonances in ^{30}S and ^{34}Ar relevant for the astrophysical rp-process.

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1 Physics motivation for studying ^{31}Ar and ^{35}Ca

As the driplines are approached Q-values for β -decay increase whereas the separation energies for particle emission in the daughter-nuclei decrease - this leads to the phenomenon of β -delayed particle emission. As the driplines are approached more and more decay modes are energetically allowed; presently delayed emission of neutrons, protons, two protons, two neutrons, deuterons, three-protons, three neutrons, tritons, alpha-particles as well as fission have been observed, see the recent review [1].

ISOLDE has historically played a central role in these studies due to the unique properties of the radioactive beams from the ISOL method, in particular the low energy and small emittance of the beam. Indeed, many of the mentioned types of delayed particle emission were first observed at ISOLDE.

Here we propose to perform detailed studies of two nuclei at the proton dripline, ^{31}Ar and ^{35}Ca , which are both prolific β -delayed particle emitters, and which in particular have the β -delayed two-proton channel open.

We first give the common physics motivation for the two proposed studies and then briefly outline the present knowledge for each isotope and finish with a discussion of the proposed setup and production method.

1.1 Common physics motivation

Fig. 1 is a schematic decay scheme of a generic nucleus with an open $\beta 2p$ channel, where the nomenclature used in discussing β -delayed particle emission is also given. The

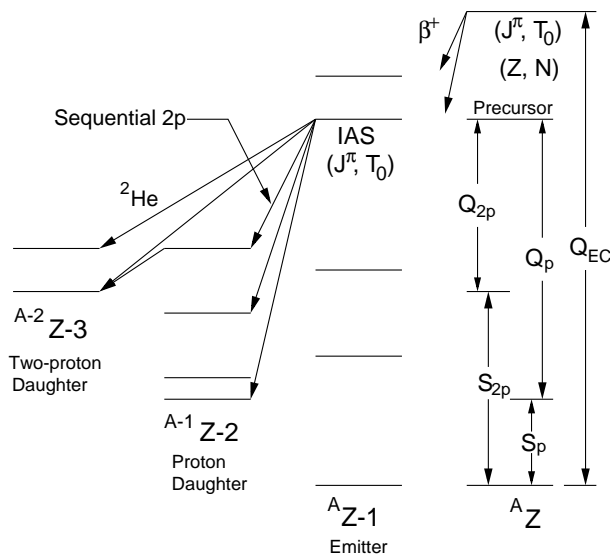


Figure 1: Schematic view of β -delayed two-proton emission with the nomenclature indicated. Two-proton emission occurs from highly excited states fed in the β -decay (typically the IAS, but also from states with the isospin of the emitter). The ^2He is symbolizing direct two-proton emission.

$\beta 2p$ decay channel has presently only been observed in 10 isotopes ^{22}Al , ^{23}Si , ^{26}P , ^{27}S , ^{31}Ar , ^{35}Ca , ^{39}Ti , ^{43}Cr , ^{45}Fe and ^{50}Ni (see [1] for a detailed discussion and references therein).

We are here interested in two physics questions open for such nuclei :

- what is the mechanism of two-proton emission ?
- what is the relative proton and gamma width of levels in the proton daughter just above the proton threshold ?

These two points will be discussed below.

1.1.1 *The mechanism of two-proton emission*

When more than one particle is emitted in a break-up process the kinematics is not fully determined by energy and momentum conservation, and it becomes possible to study the mechanism of the break-up. Two-proton emission from a nucleus is an example of this general problem. If the two protons are emitted (i.e. penetrate the Coulomb barrier) sequentially leaving a long lived (depending on the barrier) intermediate state, two-body kinematics applies and the break-up process is again fully determined. The search for non-sequential two-proton emission is most sensitive when there are few (or ideally no) intermediate states available for the competing sequential decay mechanism. In this case the two protons have to penetrate the barrier together and the hope is that the correlations of the protons after break-up will give information on the correlated barrier transition.

Last year, 2007, saw the first long awaited measurement of two-proton correlations in a nucleus (^{45}Fe) decaying by two-proton emission in its ground state [2, 3]. In the first of these, a few decay events were recorded by a time projection chamber, while in the second 87 two-proton decay events were observed with an optical time projection chamber, which had a quite low energy resolution of 20%, but allowed for studying the decay mechanism. The two-protons were observed to share the energy equally with a quite broad distribution in energy.

Initially the non-sequential two-proton emission was termed " ^2He emission" and simple predictions of the energy and angular correlations were made from semi-classical calculations. In the last years quite a number of detailed three-body quantum mechanical calculations have been published with detailed predictions for the lifetime of two-proton emission and the energy and angular correlations in two-proton emission [5, 6] and other three-body breakups (such as 3α breakup of ^{12}C [7]). See also [1] for a detailed discussion and references. A recent example is discussed in [3] where it is shown that structure information can be extracted by comparing measured and calculated correlations. The theoretical calculations are very challenging and new energy and angular correlation measurements would be very valuable for testing which approach is most precise.

Two-proton emission from excited states is much easier to observe experimentally - β -delayed two-proton emission is an example. For studies of the mechanism of the emission, states fed at low excitation energy in the emitter, just above the $\beta 2p$ threshold, are most interesting since there the number of possible sequential channels is smallest. Such transitions have presently only been observed in the decay of ^{31}Ar , where several such states are relatively strongly fed. In all other cases the $\beta 2p$ channel has only been observed from the strongly fed isobaric analogue states (IAS) situated at high energy in the emitters. From simple barrier penetration arguments direct two-proton emission should be suppressed relative to sequential emission by two to three orders of magnitude depending on the available energy [8]. Hence, with enough statistics we should be able to study the direct emission, or at least place a limit on its strength relative to sequential emission.

1.1.2 *Proton and gamma widths of specific states in the proton daughter*

The neutron deficient part of the nuclear chart, where β -delayed two-proton emission occurs, is also relevant for the astrophysical rp-process. For example, the properties of excited levels in ^{30}S (the βp daughter of ^{31}Ar) just above the proton separation energy determine the reaction rate for the bottleneck reaction $^{29}\text{P}(p,\gamma)^{30}\text{S}$. These levels were studied recently at Oak Ridge [9] and NSCL [10], but no information on the proton and gamma widths of the resonances were given - only the resonance energies were provided.

In the last experiment on ^{31}Ar decay at ISOLDE [11] it was demonstrated that very detailed information on ^{30}S excited states can be obtained from this decay. With the improved setup suggested here, we can measure the relative proton and gamma width of the states seen at Oak Ridge and NSCL and thereby provide for the first time important information to reduce the uncertainties in the determination of the $^{29}\text{P}(p,\gamma)^{30}\text{S}$ reaction rate. Similarly in the decay of ^{35}Ca we can reach information on ^{34}Ar , which would reduce the uncertainties in the determination of the $^{33}\text{Cl}(p,\gamma)^{34}\text{Ar}$ reaction rate.

1.2 ^{31}Ar

The decay of ^{31}Ar has been studied in previous experiments at ISOLDE in 1990, 1995 and 1997. Data from the $\beta 2p$ channel from the 1997 experiment is shown in Fig. 2. ^{31}Ar is clearly the best studied $\beta 2p$ -emitter and the isotope with the highest ratio of delayed two-proton emission to one-proton emission.

The reason for the much better data for ^{31}Ar is in part the fact that it can be produced as an ISOL beam at ISOLDE, and in part that it was studied with a large area segmented Si-array (state of the art at the time). The search for direct two-proton emission is best performed for the strong peaks at 2-3 MeV Q-value. Each diagonal line in the plot corresponds to the population of a resonance in ^{30}S . By combining information from the diagonals with proton- γ coincidences the astro-physically needed information can be extracted. The setup envisaged for the present updated experiment is a factor 7 more

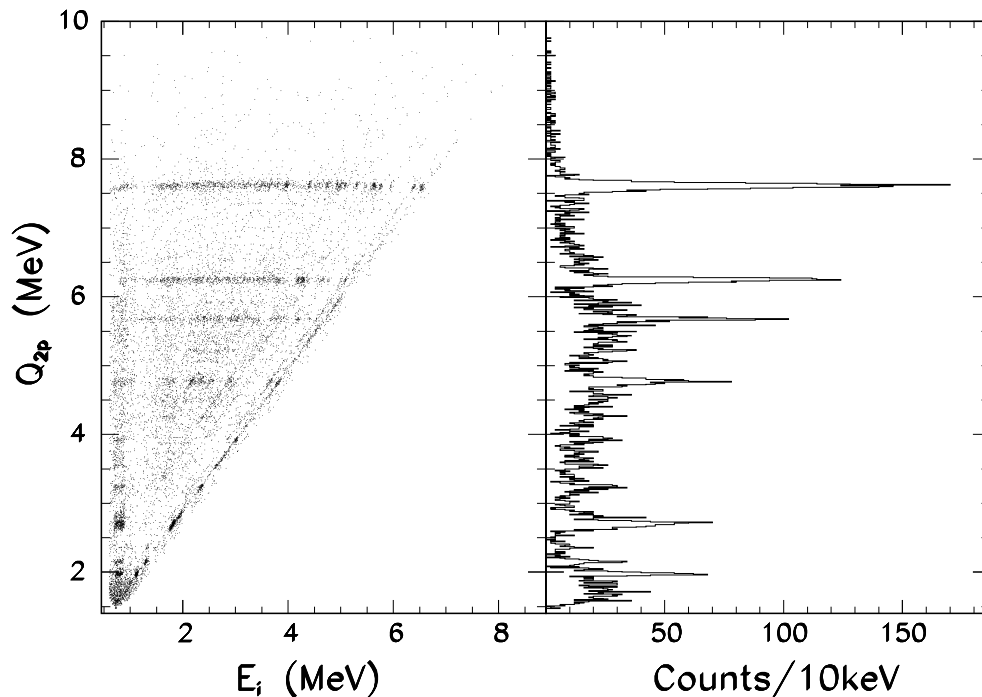


Figure 2: The figure gives an overview of the multiplicity-two events from the 1997 experiment. To the left is shown Q_{2p} against the energy E_i of the individual protons. Each event is represented by two points lying on the same horizontal line. The right part is the projection onto the Q_{2p} -axis. (from [11])

efficient for two-proton detection than the 1997 experiment, which will allow us to address the questions mentioned above. The setup will of course also permit addressing a number of other open questions concerning the decay of ^{31}Ar , such as the possible existence of a delayed three-proton branch similarly to that recently reported in the decay of ^{45}Fe [4],

and a detailed study of the Gamow-Teller strength distribution and its possible quenching. Detailed spin assignments can be performed using the β -neutrino recoil method [12].

1.3 ^{35}Ca

The decay of ^{35}Ca was studied in a pioneering work at Berkeley [13] where the $\beta 2p$ channel from the IAS was observed, and has since been studied with improved statistics at GANIL [14], but with a setup which did not permit a study of the mechanism of the $\beta 2p$ process. In the latter work it was specifically stated that this decay should be studied again, with a setup like the one used for the 1997 work on ^{31}Ar discussed above. Such a study could shed light the mechanism of the two-proton emission, as suggested here, but also elucidate why a large part of the Fermi-strength was unobserved as well as permitting a detailed study of the Gamow-Teller distribution.

In the work at GANIL the decay of 6×10^4 ^{35}Ca ions was studied (from a yield of 0.3 ions/s).

Due to the very efficient setup envisaged here, the required minimum yield for a successful experiment is of the order of 0.05-0.1 ions/s. Note that the beam development work required for this experiment could also be beneficial to other experiments requiring short-lived beams from this target, e.g. co-linear laser spectroscopic studies of ^{35}K , and studies of the super allowed β -decay of ^{38}Ca (IS437).

1.4 Detection system

The set-up, shown in Figure 3, will consist of 6 telescopes placed at the faces of a cube with DSSSD (16×16 strips) detectors of different thickness each covering approximately 8% of 4π each backed by thick detectors for detecting punch-through protons and for vetoing β -particles. Three four-leaf high purity Ge clover detectors will surround the cube. The efficiency for one- and two-proton detection will be respectively 2-3 and 7

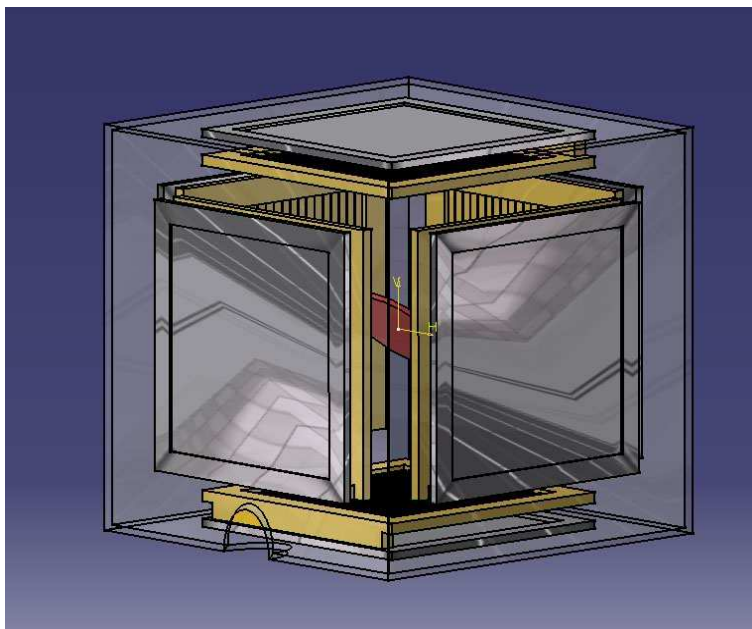


Figure 3: The proposed experimental set-up for the measurement of the β -decay of ^{31}Ar and ^{35}Ca .

times larger than for the setup used for ^{31}Ar at ISOLDE in the last experiment there. The

angular coverage will be much more uniform than previously which will be an advantage for reliably measuring the two-proton angular distribution.

2 The proposed production method

For ^{31}Ar we require a CaO target with a cooled plasma ion-source. The yield from this combination is of the order of 1-3 ions/s with a current of $2.4\mu\text{A}$. This yield has been measured on several occasions from different CaO targets and should be considered to be very reliable.

For ^{35}Ca , we require some beam development. A measurement of Ca isotopes was performed in 1990 at the SC on a Ti foil target (Ti318), and later on in 1993 at the PS-Booster. That target sintered rapidly with the pulsed proton beam at the PSB, and hence a new robust design is required for use at the PSB. This could be achieved by using $5\mu\text{m}$ Ti disks, spaced by $20\mu\text{m}$ Ta or W rings, which should release faster, and should not sinter too rapidly due to the spatial decoupling and good evacuation of the deposited beam power [15]. This requires the development of a method to produce and pack 10000 of these disk+rings in a target container. The estimated yield from such a target is a few $^{35}\text{Ca}/\text{s}$ with standard beam on target, which is well above the requirement for a successful experiment.

3 Summary and Beam request

For ^{31}Ar we ask for 9 days of beam time including time for calibrations using $^{32,33}\text{Ar}$. This will permit us to measure the decay of the order of 10^{6-7} ^{31}Ar nuclei, which should be sufficient to see direct two-proton emission with the efficient setup suggested here. Also, we can study the properties of the astro-physically important resonances in ^{30}S with good precision.

For the ^{35}Ca part we ask for 2 days for a target test. Depending on the achieved yield of ^{35}Ca we will subsequently submit an addendum for beamtime for the study of that decay.

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