MULTI-PARTICLE EMISSION FROM ^{31}Ar AT ISOLDE*

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A multi-particle decay experiment was successfully performed at the ISOLDE Decay Station. In this new permanent station, devoted to β-decay studies, the novel MAGISOL Si-Plugin Chamber was installed to study the exotic decay modes of the proton drip-line nucleus ^{31}Ar. The motivation was to search for $\beta 3p$ and $\beta 3p\gamma$ channels, as well as to provide information on resonances in ^{30}S and ^{29}P relevant for the astrophysical rp-process. Description of the experimental set-up and preliminary results are presented.

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1. Introduction

β-delayed proton emission consists in the emission of protons following the de-excitation of resonant states populated in the β-decay of exotic nuclei, near the proton drip-line. Two processes take place: first, the parent nucleus or precursor undergoes β-decay, which is followed by the proton emission from excited states of the emitter nucleus. Drip-line nuclei

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have large Q_β values and, therefore, high-lying unbound states are accessible [1]. In the case of ^{31}Ar, ($Q_{EC} = 18.38(10)$ MeV, $S_p = 282.8(44)$ keV, $T_{\frac{1}{2}} = 15.1(3)$ ms [2]), many decay channels are open: $\beta\gamma$, βp, $\beta p\gamma$, $\beta 2p$, $\beta 2p\gamma$, $\beta 3p$ and perhaps also $\beta 3p\gamma$. The nucleus ^{31}Ar has been studied in previous experiments at GANIL (1987 [3], 1991 [4], 1992 [5]) and at ISOLDE (1988 [6], 1995 [7, 8], 1996/1997 [9–11], 2009 [2, 12, 13]). However, the $\beta 3p$ branch has been observed only with limited statistics and $\beta 3p\gamma$ remains unobserved. In order to measure these decay channels, the MAGISOL Collaboration (Madrid–Aarhus–Göteborg) performed a new experiment using a compact set-up optimized for multi-particle emission at the ISOLDE Decay Station (IDS) [14]. The analysis of this experiment is on-going and the first results are discussed below.

2. Experimental set-up

The experiment was carried out at the ISOLDE facility at CERN [15], where pulses of 1.4 GeV protons from the PS Booster impacted in a thick CaO powder target coupled to a cooled plasma source (VADIS [16]). The radioactive beam, produced by fragmentation reactions, was extracted in charge state (+1). The ions were separated on-line by the ISOL method [17], transported to the IDS beam line (see Fig. 1), and collected in a 20 μg/cm^2 carbon foil located in the middle of the detector set-up. The ^{31}Ar yield (3 atoms/s) was stable during the running period of 7 days, despite the power outage that occurred at the CERN Meyrin site, affecting all systems at ISOLDE. The CaO target was operated at a low temperature ($\sim 500°$C) in order to withstand the high proton intensity of 3×10^{13} ppp [18]. The IDS is a new initiative to have a permanent station dedicated to β-decay studies allowing to measure with high efficiency γ rays and charged particles.

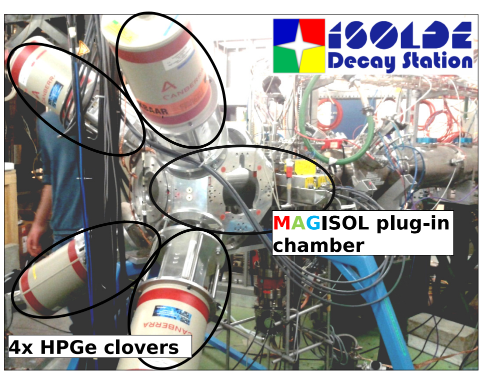

Fig. 1. IDS during the IS577 experiment; surrounding the detection chamber there are four clover detectors, each consisting of four germanium crystals.

The MAGISOL Si-Plugin Chamber contains an array of 5 Double-sided Silicon Strip Detectors (DSSD) backed by unsegmented silicon-pad detectors (PAD) in ΔE–E configuration for β and charged particle detection. The detectors are directly plugged into a Printed Circuit Board (PCB) that is further plugged into second lateral PCBs, which act as vacuum feedthrough.

In order to define the beam entering the chamber and to be able to optimize it onto the target, there is a collimator and a movable Faraday cup at the entrance as well as a second Faraday cup at the exit. The preamplifiers, on the outside, are plugged directly into the previously mentioned vacuum-feedthrough PCB, see Fig. 2. To complete the set-up, 4 High-Purity Germanium (HPGe) clover detectors surround the chamber to provide high γ-ray detection efficiency.

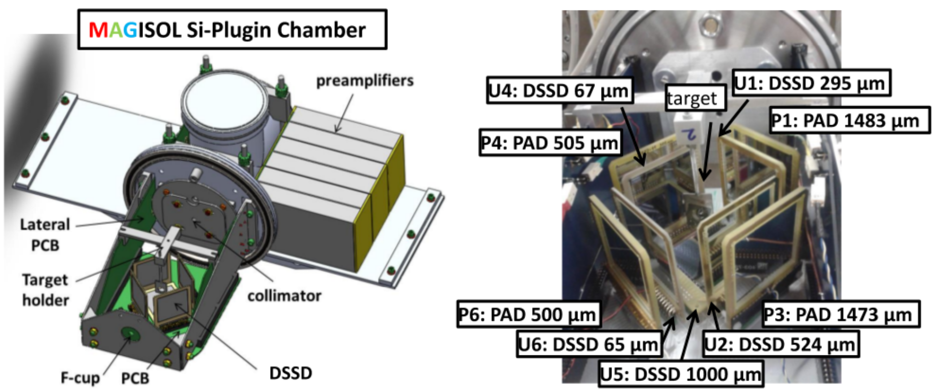

Fig. 2. Left: MAGISOL Si-plugin Chamber. Right: A view of the silicon array detector inside the chamber.

Regarding the silicon array detector, the four silicon telescopes are of different thickness in order to optimize the detection of protons impacting at different energies (Figs. 3 and 4). Thin DSSDs are chosen to be insensitive to β radiation but thick enough to fully stop low-energy protons. The thick DSSDs will fully stop high-energy protons, while a 5^{th} thick horizontal DSSD is mainly dedicated to β detection. The PADs have been used for β detection. In addition, this telescope configuration gives the possibility to separate protons and betas: thin telescopes allow us to identify high-energy protons, while thick telescopes are used in anti-coincidence mode in order to separate β events from low-energy proton events.

In conclusion, a compact set-up with high efficiency for detection of multi-particle emission with a low cut-off energy (150 keV) and with a good energy (25 keV) resolution is available for measurements at the IDS. The total proton-detection efficiency, estimated as the total solid angle covered by the silicon array set-up, is 45% of 4π. The Si-array comprises 1280 pixel detectors (5×5 cm, 16×16 strips) resulting in an angular resolution of (3°) needed to characterize the different proton-emission channels of ^{31}Ar.

3. Preliminary results

3.1. ^{31}Cl levels

The charged particle set-up was calibrated on-line in energy and solid angle, by using produced ^{33}Ar during the run from the same target and ion-source.

In the calibrated raw-spectra shown in Fig. 3, multiplicity-one proton events arising from the decay of ^{31}Ar to excited levels of the daughter (^{31}Cl) are easily identified.

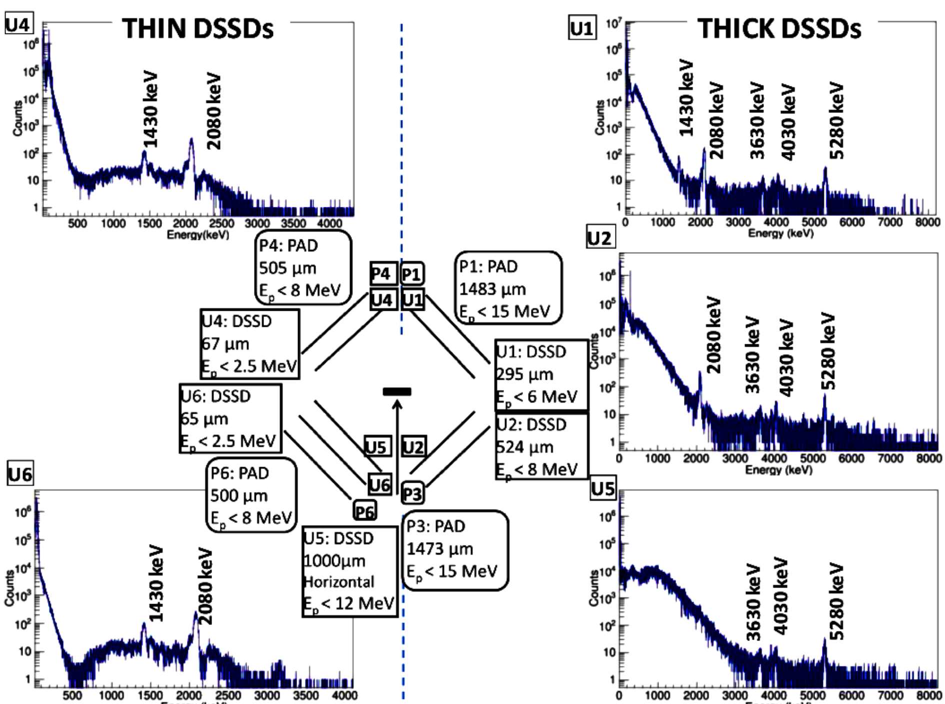

Fig. 3. Array of detectors DSSD (U1–U6) and PAD (P1–P6) used in the experiment with indications of thickness and required punch-through energy for protons. On the side to each telescope, the corresponding proton spectrum is shown. Left: Thin DSSDs used for low-energy protons up to 2.5 MeV. Right: Thick DSSDs used for high-energy protons up to 6–8 MeV.

The β background can be removed using the telescope configuration shown in Fig. 4. An additional method to clean up the spectra is to use cross-coincidences between the events collected in a given DSSD and the betas detected in all the other detectors of the set-up, excluding its own PAD.

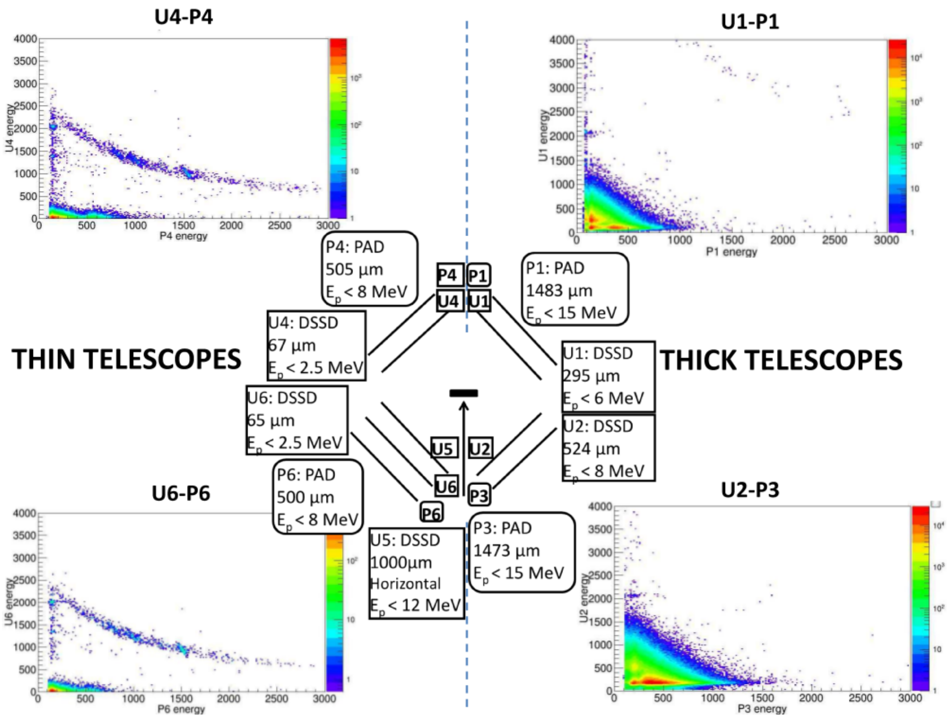

Fig. 4. The same as in Fig. 3, showing for each telescope the corresponding 2-dimensional spectrum ΔE–E. Left: ΔE–E spectra of the thin telescopes showing well-separated proton and beta bands, from where high-energy proton events (punched-through) were obtained. Right: Thick telescopes where one can easily identify and exclude the β particles from the proton spectra.

The energies of the unbound excited states in ^{31}Cl (in the rest frame of ^{31}Cl) are calculated using

$$E_p = \left(E\left(^{31}\mathrm{Cl}\right) - E\left(^{30}\mathrm{S}\right) - S_p\right) \frac{M\left(^{30}\mathrm{S}\right)}{M\left(^{30}\mathrm{S}\right) + m_p}\,, \tag{1}$$

where E_p is the emitted proton energy and $E(^{31}\mathrm{Cl})$, $E(^{30}\mathrm{S})$ the energy of excited levels in ^{31}Cl and ^{30}S, respectively. S_p is the proton separation energy of ^{31}Cl.

The results from the analysis of the data shown in Fig. 3 are given in Table I. These values are, at this stage of the analysis, in good agreement with the previous measurements of Fynbo *et al.* [11].

TABLE I

Proton-emitter energy levels of ^{31}Cl. The observed proton decay from the ^{31}Cl level at 4030.45(45) keV feeds only the first excited state of ^{30}S at 2210.2(1) keV. All the other decays result in the ground state of ^{30}S. These results are preliminary, the analysis is on-going.

Present work			Fynbo *et al.* [11]		
E_p [keV]	$E(^{31}\mathrm{Cl})$ [keV]	$E(^{30}\mathrm{S})$ [eV]	E_p [keV]	$E(^{31}\mathrm{Cl})$ [keV]	$E(^{30}\mathrm{S})$ [keV]
1415.96(15)	1758(4)	0	1416(2)	1754(3)	0
2079.27(6)	2449(5)	0	2084(2)	2444(2)	0
3626.38(88)	4061(5)	0	3634(3)	4046(4)	0
4030.45(45)	6692(5)	2210.2 (1)	4030(3)	6666(3)	2210.6(5)
5283.18(28)	5787(6)	0	5276(5)	5743(5)	0

3.2. The HPGe γ spectrum

Each of the 4 clover detectors contains 16 HPGe crystals. The γ spectrum resulting from the sum of the corresponding 16 spectra is shown in Fig. 5. The energy calibration was carried out using a ^{152}Eu source, and the high-energy lines produced in the decay of ^{16}N and ^{15}C recorded on-line.

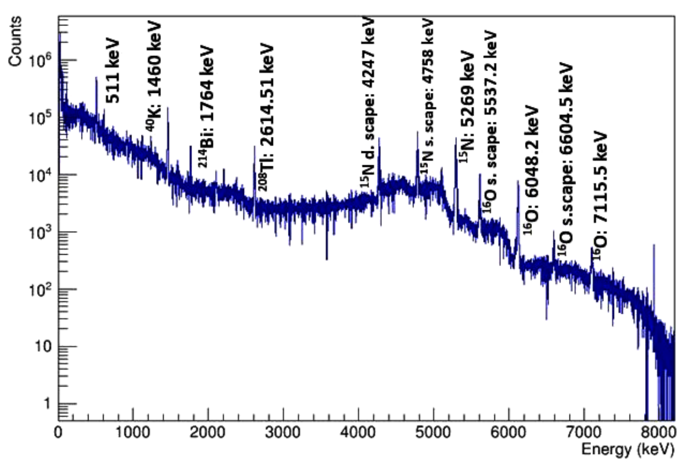

Fig. 5. Full γ spectrum obtained with all HPGe clovers summed.

The most intense γ peaks shown in Fig. 5 were all identified. The peaks observed at energies below 3 MeV are arising from natural background. In the region between 3 MeV and 8 MeV, the γ rays from the decay of ^{16}N and ^{15}C are observed, which is an indication that some on-line contaminants like N_2H and CO molecules were present in the beam. In this spectrum, the γ rays originated in the de-excitation of ^{30}S and ^{29}P are hidden in the background. To observe these transitions, it is necessary to study p–γ coincidences, as discussed in the next section.

3.3. β-delayed 1pγ-decay

The IDS provides the possibility to combine the charged particle set-up with the high-efficiency HPGe clover detectors in order to obtain proton–γ coincidences. A coincidence matrix was defined by correlating the events from any clover and DSSDs. With this method, it was possible to identify the γ rays produced in the de-excitation of ^{30}S and ^{29}P levels populated by one and two proton emission processes. The results are shown in Fig. 6. Here, it is important to clean the spectrum from β background. Furthermore, it is worth noting here that the set-up was not fully optimized for γ efficiency due to mechanical constraints. This problem was solved in a more recent experiment carried out by the MAGISOL Collaboration.

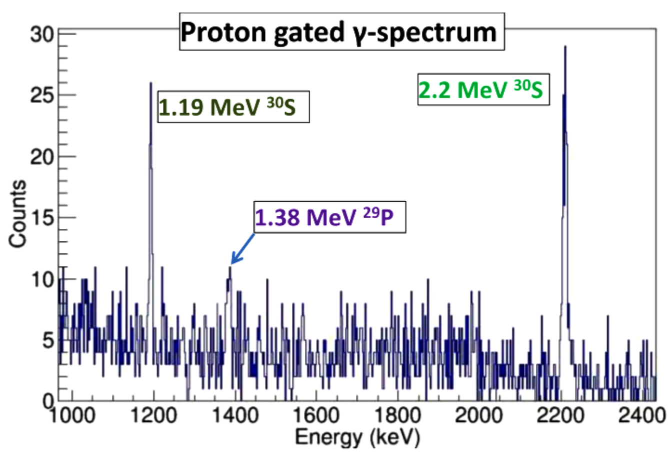

Fig. 6. γ spectrum obtained in coincidence with single-proton events. Values shown are taken from [12].

4. Summary and outlook

For the first time, a multi-particle emission experiment (IS577) was performed successfully at the IDS. The novel set-up used is optimized for multi-particle emission (βp, $\beta 2p$, $\beta 3p$) with high efficiency, well-suited for detecting p–γ coincidences when combined with the HPGe clover array. Up to know, only $1p$–γ coincidences have been analyzed and the first excited levels of ^{30}S and ^{29}P were observed. The on-going analysis will hopefully allow disentangling *e.g.* the proton–proton angular correlations that enables the spin determination of the levels of ^{30}S and ^{31}Cl, the measurement of the γ ray from IAS of ^{31}Cl (12.31 MeV), resonances in ^{30}S and ^{29}P (mainly de-excitation via proton emission or γ ray in levels just above S_p and S_{2p}) and above all, the study of the $\beta 3p\gamma$ channel that leads to γ de-excitation from excited states of ^{28}Si.

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