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To cite this article: Hans Fynbo et al 2017 J. Phys. G: Nucl. Part. Phys. 44 044005

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ISOLDE decay station for decay studies of interest in astrophysics and exotic nuclei

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Received 29 November 2016, revised 27 January 2017
Accepted for publication 3 February 2017
Published 1 March 2017

Abstract

We report on studies of the beta-decays of \(^{31}\)Ar, \(^{20,21}\)Mg, and \(^{16}\)N performed at the ISOLDE decay station (IDS) at CERN. These studies illustrate how beta-decays measured with the IDS can be used to extract information of astrophysical interest, or to study the structure and decay mechanism of exotic nuclei. We discuss the specific implementation of the IDS designed for this type of studies including detector setups and data acquisition.

Keywords: decay studies, exotic nuclei, astrophysics

(Some figures may appear in colour only in the online journal)

1. Introduction

When the existence of an unstable nucleus has been established its decay is one of the first properties that can be measured. Indeed, until the appearance of post accelerators, and facilities based on beam fragmentation reactions, decay properties, mass, and electromagnetic moments were the only observables measurable for many radioactive isotopes. Decay studies have been pursued at the ISOLDE facility at CERN right from the beginning in the 1960s. Some of the history of this endeavour is reviewed in the contribution of Jonson to this issue \([1]\), and in other recent reviews on decay spectroscopy \([2, 3]\).

Because of the richness of decay modes available throughout the chart of nuclides, an all-in-one system would require a large number of well-integrated specialised detectors. Hence, for many years the prevailing approach has been to specially design experiments for selected decay modes. In contrast, reaction experiments have often followed a different approach. Experiments are executed in campaigns using a common setup centred around an array of \(\gamma\)-detectors complemented by various ancillary detectors for charged particles or neutrons \([4–6]\).

In recent years such omni-purpose, permanent setups dedicated for decay spectroscopy are
also being installed at radioactive beam facilities such as the $8\pi$ spectromenterat at the ISAC facility at Canada’s National Laboratory for Particle and Nuclear Physics, TRIUMF, which is now replaced by the GRIFFIN array [7].

The ISOLDE decay station (IDS) at the ISOLDE facility at CERN is a setup of this type dedicated to decay studies. The common infrastructure at the IDS is an array of four high-purity germanium (HPGe) clover detectors and one HPGe Miniball cluster detector. In addition to this, different ancillary detectors suitable for specific types of nuclear decays can be used. The purpose of the present contribution is to present the setup at the IDS designed for studies of exotic decay modes and decay studies motivated by astrophysical problems. Other uses of the IDS include fast timing measurements [8].

While the gamma-ray detectors are sufficient to fully characterise many radioactive decays, particle detectors are indispensable to studies of decays close to the drip lines where particle-emission channels dominate. In such studies, the particle detectors constitute the core of the setup, while the gamma-ray detectors merely provide complimentary information.

The paper is organised as follows. We start with a description of the configuration of the IDS for exotic decays, including the gamma-ray and charged-particle detections systems and the associated data acquisition systems. We then discuss three studies already completed with the setup, and conclude the paper with an outlook.

### 2. The IDS setup for exotic decays

#### 2.1. Gamma detection

The core of the IDS is its gamma detector array. For the studies discussed here it consists of four Canberra Eurgam type clover detectors. The clover detectors (diameter 50 mm, length 70 mm) each contain four HPGe crystals with a mean relative efficiency between 21% and 22%, and a total relative efficiency in add-back mode between 130% and 140%.

![Figure 1. A schematic open cut view of the MAGISOL Si-plugin chamber.](image-url)
2.2. MAGISOL Si-plugin chamber

The MAGISOL Si-plugin chamber contains an array of 5 double-sided silicon strip detectors (DSSD) backed by unsegmented silicon-pad detectors (PAD) in $\Delta E-E$ configuration for $\beta$ and charged particle detection. The detectors have a size of 50 mm by 50 mm and a range of thicknesses between 40 $\mu$m and 1.5 mm. The detectors are directly plugged into a printed circuit board (PCB) that is connected to secondary lateral PCBs, which act as vacuum feedthroughs.

The set-up is fixed onto a separate flange that is held by a movable support so that the full detector set-up can be pulled backwards out of the main chamber for easy access while setting up and to be able to fit calibration sources.

In order to define the beam entering the chamber and to be able to optimise 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 pre-amplifiers, on the outside, are plugged directly into the previously mentioned vacuum-feedthrough PCB, see figure 1.

To complete the set-up, the 4 HPGe clover detectors mentioned above surround the chamber to provide high $\gamma$-ray detection efficiency. A photo of the full set-up is shown in figure 2.
2.3. Ancillary detectors

Further, in order to be able to estimate the amount of activity that is implanted onto the incoming beam collimator (i.e. activity that can be seen by gamma detectors but not by the charged particle detectors), two high efficiency scintillators, LaCl$_3$(Ce) and LaBr$_3$(Ce) respectively can be placed; one facing the collimator from the incoming beam side and the second looking to the implantation point.

2.4. Charged particle detection

Regarding the silicon array detector, the four silicon telescopes are of different thickness in order to optimise the detection of charged particles impacting at different energies. Thin DSSDs are chosen to be insensitive to $\beta$ radiation but thick enough to fully stop low energy charged particles, while more energetic particles penetrate into the second layer of the telescope; this makes it possible to detect low-energy particle-emission branches and perform particle identification. The thick DSSDs will fully stop the particles of higher energy but at the same time have a rather high response to $\beta$ particles that hinder the lower energy identification. The 5th, thick horizontal DSSD, is mainly dedicated to $\beta$ detection. It is positioned just below the collection target, and a fraction of its area is not visible from the collection target. The PAD detectors are used together with the DSSDs as particle telescopes for the protons of higher energy that only lose part of their energy in the DSSD and also in anti-coincidence to identify the $\beta$ particles.

In conclusion, the charged particle detection system comprise a compact set-up with high efficiency for detection of multi-particle emission with a low cut-off energy (100 keV) and with a good energy (20–25 keV) resolution. The total particle detection-efficiency, estimated as the total solid angle covered by the silicon array set-up, is 45% of $4\pi$. The Si-array comprises 1280 pixel detectors of $3 \times 3$ mm$^2$, resulting in an angular resolution of $3^\circ$ that is needed to characterise the different particle-emission channels as for e.g. in the case of $^{31}$Ar, see below.

It should be stated here that the charged particle set-up has evolved between the experiments that are discussed below from lessons learned in these experiments. This evolution mainly involves practical aspects in the handling of the charge particle set-up in relation to the gamma set-up, improvements in the alignment of the implantation point to the focal-point of the gamma detection, and finally to the event correlation between the two separate DAQ-systems that are so far being used (see below). The figures shown in this article focuses on the latest and most optimised setup.

2.5. Data acquisition systems

Beta delayed particle studies have benefited from the development segmented detectors and integrated electronics. This development has inferred an increase in complexity higher and higher complexity, which has made the previous practice of travelling set-ups nearly impossible. For this reason, a more permanent set-up coupled to the HPGe set-up of the IDS has been developed. In the case of the HPGe clover detectors that comprise a relative low number of channels ($\sim 20$) one went for a fully digital DAQ-system: NUTAQ VHS-ADC digitisers developed at Daresbury and supplied to ISOLDE by JYFL Jyvaskyla. However, in the case of the charged particle set-up there is a considerable amount of electronic channels ($\sim 200$) and thus we are using a standard system of pre-amplifier (MPR-Mesytec GmBH) coupled to NIM-amplifiers (STM or MSCF-Mesytec GmBH) that further couple to VME based peak-sensitive ADCs and to TDCs (CAEN V785, V1190 respectively). The VME is
controlled by the GSI developed Multi Branch System MBS. In order to time and event synchronise the two systems several actions were taken making it possible to match events in the off-line analysis based on a global time stamp, and that all triggers where cross recorded in both DAQ-systems. The development of digitised systems is advancing fast and the IDS community have ongoing studies to replace both the NUTAQ and the MBS system by one unified digitised system.

3. Recent studies with IDS setup for exotic decays

Three experiments have been completed using the mentioned charged particle detector set-up coupled to the IDS: a study of the $\beta$-decay of $^{31}\text{Ar}$, a study of the $\beta$-decays of $^{20,21}\text{Mg}$, and a study of the $\beta$-decay of $^{16}\text{N}$. All these studies are examples demonstrating how $\beta$-decays in certain cases can provide information on nuclear resonances that can be used to indirectly determine the reaction rates.

*Figure 3.* The $\beta$-decay of $^{31}\text{Ar}$ is typical of nuclei at or near the drip lines. The high $Q_{\text{EC}}$-value and the low particle separation energies in the daughters allow for many particle emission channels after the $\beta$-decay. Some of the levels slightly above the particle emission thresholds are of astrophysical interest because they are in the Gamow-window of astrophysical reactions. The relative particle- and gamma-decay widths of these states can be used to indirectly determine the reaction rates.
determine or constrain astrophysical reaction rates of these states. In the following we will briefly review the motivation for these experiments, and the results or preliminary results available already.

### 3.1. $^{31}$Ar

$^{31}$Ar is the most neutron deficient isotope of the element argon. Its $\beta$-decay releases a large amount of energy, $Q_{\beta E} = 18.38 (10)$ MeV, and therefore it has a short half life, $T_1 = 15.1 (3)$ ms [18]). Many decay channels are open: $\beta\gamma$, $\beta p$, $\beta p\gamma$, $\beta 2p$, $\beta 2p\gamma$, $\beta 3p$ and perhaps also $\beta 3p\gamma$, as indicated in figure 3. $^{31}$Ar has been studied in previous experiments at GANIL (1987 [9], 1991 [10], 1992 [11]) and at ISOLDE (1988 [12], 1995 [13, 14], 1996/1997 [15, 16], and 2009 [17–19]).

The ISOLDE experiment IS577 performed in 2014 [21] had two main motivations, which came out of the most recent studies at ISOLDE in 2009. The first goal of the new experiment was to use $\beta 2p$- and $\beta p\gamma$-decay and the techniques developed in [16, 17] to study the levels of $^{30}$S, especially those of astrophysical interest just above the proton threshold. The idea behind this method is that the levels in $^{30}$S are populated by proton emission of states in $^{31}$Cl. By gating on those protons and then searching for either protons or gamma-rays in coincidence, the relative widths can be estimated, or a limit placed on the smaller of the two. Also, by studying angular correlations, the information on the spin of the state in $^{30}$S can be obtained. The second goal was to provide a deeper look into the $\beta 3p$-decays of $^{31}$Ar. This decay mode has been already identified, albeit with very few events, not only from the strongly populated isobaric analogue state, but also from higher lying states [18, 19]. Since these states are at high excitation energy, they represent a large Gamow–Teller strength and they are therefore important for understanding the distribution of $\beta$-decay strength over the final states of the daughter $^{31}$Cl. In addition to these physics motivations, the access to improved gamma-detection efficiency with the IDS, and the development of nano-structured CaO targets promising higher yields of argon isotopes [20], added to the potential of a remeasurement of the decay of $^{31}$Ar at ISOLDE with the IDS.

First preliminary results from the experiment have been presented in the conference proceeding [21]. An $^{31}$Ar yield of 1–2 atoms/$\mu$C over the 7 days of experiment was achieved.

**Figure 4.** The proton spectrum from the $\beta$-decay of $^{31}$Ar from a subset of the charged particle detectors of the MAGISOL setup is shown in black. The proton spectrum gated by the 2.21 MeV $\gamma$-ray deexciting the first excited state in the $\beta p$ daughter $^{30}$S is shown in blue. The proton peaks in these spectra originate from states in either the $\beta$-daughter $^{31}$Cl, or the $\beta p$-daugther $^{30}$S.
which was less than expected from the new nano-structured CaO target. Figure 4 shows the total proton spectrum from the experiment from a subset of the charged-particle detectors, and also the proton spectrum gated by the 2.21 MeV γ-ray de-exciting the first excited state in the βp daughter 30S. It is clear that the efficiency of the γ-detectors was non-optimal in the setup designed for this experiment, and it was consequently improved in time for the magnesium run (next subsection).

The charged particle spectrum, however, is of high quality with a significantly better resolution and lower threshold than previously achieved. The main strength of this experiment will be a much improved measurement of the β2p and β3p channels due to the much larger solid angle and segmentation of the charged particle detection system compared to previous measurements. The analysis of these channels is still in progress.

3.2. 20Mg and 21Mg

Neutron deficient beams of magnesium have a shorter history at ISOLDE than that of the element argon. The combination of the laser ion source and a new SiC target allowed for the production of these beams for the first time in the early years of 2000 [22]. The ISOLDE experiment IS507 recently published first results from a study of the β-decay of 21Mg [23, 24]. The focus of that measurement was the charged particle channels, hence the experiment did not contain gamma-detectors. The experiment identified for the first time β-delayed α-particle (βα) emission as well as β-delayed α- and proton (βαp) emission [23, 24].

A measurement of the most neutron deficient isotope in the magnesium isotopic chain, 20Mg, using the IDS setup for exotic decays was completed in 2015. This decay is again typical for nuclei at the drip lines with a large Q-value of more than 10 MeV and both βp and (βαp) channels are open (note that α-emission always is followed by proton emission as 16F is unbound). Decay spectroscopy of 20Mg is challenging because there are close lying levels in the βp daughter 19Ne. It is therefore a case ideally suited for using the IDS to measure the γ-decay of these close lying levels with high precision in coincidence with the detection of
charged particles. The results from this experiment on the decay of $^{20}\text{Mg}$ are now published \cite{25}.

The goal of the experiment was to establish if the 2645 keV level in $^{20}\text{Na}$ is populated in an allowed transition, which would determine its spin and parity as $1^+$. A secondary goal was to search for the $\beta p$ channel in this decay, which would allow to determine the $\alpha$-decay width of the lowest $\alpha$-decaying states in $^{19}\text{Ne}$. Both of these aspects are of direct interest for nuclear astrophysics because they can be used to indirectly determine the reaction rates of the CNO breakout reactions $^{15}\text{O}(\alpha, \gamma)^{20}\text{Ne}$ and $^{15}\text{O}(p, \gamma)^{20}\text{Na}$.

The experiment did not find feeding of the 2645 keV level, and did not identify the $\beta p$ channel; only upper limits could be placed on these decay channels. Instead, the experiment established a much improved decay scheme of $^{20}\text{Mg}$, including 7 new out of a total of 27 identified $\beta p$ channels, and provided an improved half life determination for $^{20}\text{Mg}$ \cite{25}.

The experiment also collected data on the isotope $^{21}\text{Mg}$ for calibration purposes. This adds new information compared to the already published works on that decay \cite{23, 24}, where the setup did not provide information on the population of excited states in the $\beta p$ daughter $^{20}\text{Ne}$. Figure 5 shows the proton spectrum with and without coincident detection of the decay of the 1634 keV first excited state in $^{20}\text{Ne}$. The analysis of this data, still in progress, will provide a better understanding of the $\beta$-decay of $^{20}\text{Mg}$.

3.3. $^{16}\text{N}$

The ISOLDE Experiment IS605 was performed in May 2016 with the main objective of determining the branching ratio for $\beta$-delayed $\alpha$-emission in the decay of $^{16}\text{N}$ with a precision of 10% or better. Precise knowledge of this branching ratio will help constrain the astrophysical $S$-factor of the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ fusion reaction \cite{26}.

Thin DSSDs (40 and 60 $\mu$m) were used to detect the $\alpha$ particles, which have energies between 1.0 and 2.2 MeV. The branching ratio for $\alpha$ decay is only of the order of $10^{-5}$, making the use of thin detectors imperative, as otherwise the $\beta$ background would be overwhelming. As shown in figure 6, a thickness of 60 $\mu$m is just sufficient to cleanly separate the $\alpha$ spectrum. Since the absolute efficiency of each DSSD is precisely known (within a few percent, the efficiency is equal to the solid-angle coverage), the number of $\alpha$ particles emitted in $4\pi$ can be reliably deduced from the number of detected $\alpha$ particles.
The $\beta$ decay of $^{16}$N gives rise to characteristic $\gamma$-ray lines at 2742, 6129 and 7115 keV with well-known intensities, from which the total number of decays can be deduced, given a precise and accurate efficiency calibration of the Ge clovers. To this end, a rather elaborate calibration scheme was developed, based on a combination of off-line ($^{152}$Eu, $^{60}$Co) and on-line ($^{34}$Ar and $^{17}$Ne) measurements. It is hoped that this calibration scheme will allow the efficiency to be determined with a precision of a few percent across the entire energy range.

As in previous experiments, the signals from the Ge clovers were duplicated and fed not only to the NUTAQ acquisition system, but also to the MBS acquisition system, which additionally handles signals from all Si detectors and other auxiliary detectors. The $\gamma$-ray spectra obtained with the two DAQs is shown in figure 7. NUTAQ outperforms MBS in all respects: better resolution, lower thresholds and less dead time. Nevertheless, the duplication of the $\gamma$-ray signals was deemed necessary to ensure the possibility of off-line analysis of particle-gamma coincidences. Also, it may prove advantageous for the normalisation to have particle and gamma data subject to the same dead time. Note that the $\gamma$-ray trigger in MBS was down-scaled by a factor of 64 to reduce dead time to manageable level.

Several improvements had been made to the setup compared to previous experiments. Most notably, the MAGISOL Si-plugin chamber had been re-designed, allowing the Ge clovers to be brought closer to the source, giving us a factor of $\sim 7$ gain in $\gamma$-ray detection efficiency. Also, a protocol to synchronise the two DAQs had been implemented, making it possible to match events in the off-line analysis based on global time stamps.

Furthermore, several steps were taken to ensure correct overall normalisation which was crucial for the experiment: two small auxiliary $\gamma$-ray detectors placed in strategic positions were added to the setup and were used to ensure that the radioactive beam was being fully implanted in the catcher foil. Furthermore, a small SiSB detector placed at the beam dump was used to monitor the integrity of the foil.

![Figure 7](image_url) Addback spectrum measured in one Ge clover during experiment IS605. The three main $\gamma$-ray lines from $^{16}$N are visible at 2742, 6129 and 7115 keV. First- and second-escape peaks are labelled by asterisks. Two separate DAQs (NUTAQ and MBS) were used to process the electronic signals, resulting in the two spectra shown in the figure. The MBS spectrum has reduced statistics because the trigger was down scaled by a factor of 64. Note that the figure only shows a subset (about 25%) of the acquired data.

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4. Conclusions and outlook

A compact particle detection setup consisting of an array of double sided silicon detectors has been designed for the IDS. In the present version it operates its own analogue data acquisition system, which can be synchronised with the digital acquisition system used for the IDS gamma-detectors. For the future, a common digital system would clearly be advantageous and allow for a simpler analysis of the data.

Experiments on the $\beta$-decays of $^{31}$Ar, $^{20,21}$Mg, and $^{16}$N have been completed with this setup. The decays of most isotopes near the drip lines have not been studied with a setup of similar strength, and there is therefore an avenue to explore. A region of particular interest is the most neutron deficient isotopes between magnesium and argon, $^{22}$Al, $^{22,23}$Si, $^{26}$P, and $^{27}$S. However, these isotopes are presently not produced at ISOLDE. The development of some of these beams would be highly desirable, but challenging. The list should also include species slightly above argon: $^{35}$Ca, $^{40}$Sc, and $^{39}$Ti.

Moving down from magnesium on the proton-rich side of the chart of nuclei, decays of $^{17}$Ne and $^{15}$O could also provide interesting new information if studied with a powerful setup like the IDS. A beam of $^{15}$O is however also not presently available at ISOLDE. An intense beam of $^8$B has recently been developed; while the decay of this isotope has been studied on several occasions, feeding of the highest region of excitation energy in the daughter $^8$Be is not well understood, and a study to explore this region is in preparation.

Acknowledgments

The authors want to acknowledge the financial support by the Spanish research grant FPA2015-64969-P. OSK acknowledges support from the Villum Foundation. HOUF acknowledges support from the European Research Council under ERC starting grant LOBENA, No. 307447.

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