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The resonances of ^{30}S and the ^{29}P(p,γ)^{30}S reaction

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The nucleus ^{30}S is situated at the proton drip line and thus plays an important role in the rp- and αp-process via the ^{29}P$(p,\gamma)^{30}$S reaction. The astrophysical relevant resonances are situated just above the proton threshold. We have studied the nucleus through β-delayed proton decays of ^{31}Ar at ISOLDE, CERN.

Knowledge of the resonances just above the proton threshold of ^{30}S is limited. The energies of the two resonances predicted to dominate the ^{29}P$(p,\gamma)^{30}$S reaction have recently been measured. Previously, no experiment has been able to measure the proton and gamma partial widths of these resonances. With our newest experiment made in 2009, which incorporated a segmented Si-particle array and two Miniball gamma detectors, it is possible to measure both protons and gammas from these resonances and thereby estimate the Γ_p/Γ_γ ratio.

The analysis is still under development and only the preliminary results are shown here. Currently, we have only been able to positively identify the gammas from the lowest of these two resonances at 4687(4) keV. Due to a substantial amount of electronic noise and beta background the protons from this resonance have not been identified. Instead, we have been able to put an upper limit on the ratio. A 95 % confidence upper limit of 10.4 % has been found.

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1. Introduction

Detailed knowledge of the energy levels in exotic nuclei, especially the ones just above the proton threshold, is important for understanding astrophysical processes such as explosive hydrogen burning. ^{30}S is situated close to the proton drip line and is produced in the ^{29}P$(p,\gamma)^{30}$S reaction in the rp- and αp-process in type I x-ray bursts [1]. The relatively long life time of ^{30}S makes it a critical waiting point nucleus for these processes.

The ^{29}P$(p,\gamma)^{30}$S reaction is also important for the study of presolar dust grains. The most extensively studied grains are SiC grains because they are relatively abundant. A small fraction of these have been suggested to originate from classical novae [2] and are characterised by low ^{12}C/^{13}C and ^{14}N/^{15}N ratios, high ^{30}Si/^{28}Si ratios and ^{29}Si/^{28}Si ratios close to or lower than terrestrial ratios. The silicon isotopic abundance can provide information on the dominant nuclearsynthetic paths followed by the thermonuclear runaway, which sets in near the base of the accreted layers from a white dwarf onto a main sequence star in a binary system [3]. But to understand the origin of the isotopic ratios observed, the processes that create and destroy the different silicon isotopes have to be well understood. The ^{29}P$(p,\gamma)^{30}$S reaction has a strong influence on the silicon abundances. If this reaction is faster than the β^+-decay of ^{29}P, the amount of ^{30}Si would increase and the amount of ^{29}Si would decrease. Iliadis *et al.* [4] showed that the uncertainties in the ^{29}P$(p,\gamma)^{30}$S reaction rate have great implications on the abundances of ^{29}Si and ^{30}Si. Therefore, it is important to determine the level structure of ^{30}S just over the proton threshold and the proton-gamma branching ratios for these levels.

The astrophysically important states in ^{30}S are the ones just above the proton threshold. The reason for this is that the Gamow window of the ^{29}P$(p,\gamma)^{30}$S reaction for the relevant temperatures spans from 100 keV to 1100 keV. The proton separation energy for ^{30}S is 4393.9(9) keV found from [5] and [6]. So the relevant levels of ^{30}S have excitation energies between ~4.5 MeV and ~5.5 MeV. In this energy range the ^{30}S resonances are all narrow and the reaction rate through one of these is given by [7]

$$N_A \langle \sigma v \rangle_r = N_A \left(\frac{2\pi}{\mu k T} \right)^{3/2} \hbar^2 (\omega\gamma)_r e^{-E_r/kT}. \tag{1.1}$$

The subscript r specifies that it belongs to a certain resonance with energy E_r, and $\langle \sigma v \rangle$ denotes the thermally averaged cross section. μ is the reduced mass and the resonance strength $(\omega\gamma)_r$ is given by

$$(\omega\gamma)_r = \frac{(2J_r+1)}{(2J_a+1)(2J_b+1)} \left(\frac{\Gamma_p \Gamma_\gamma}{\Gamma} \right)_r , \tag{1.2}$$

where J_r is the spin of the resonance, J_a and J_b are the spins of the original particles (in this case the proton and ^{29}P), and Γ_p and Γ_γ are the proton and gamma partial widths respectively of the resonance with total width $\Gamma = \Gamma_p + \Gamma_\gamma$. The total reaction rate is the sum over the relevant resonances r of (1.1).

Iliadis *et al.* [8] predicted that the reaction rate of the ^{29}P$(p,\gamma)^{30}$S reaction was dominated by two resonances in ^{30}S with spins 3^+ and 2^+ with energies of 4733(40) keV and

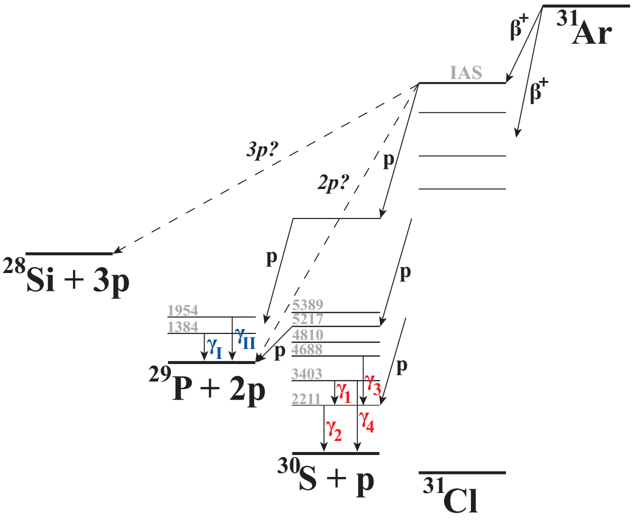


Figure 1: The β-decay of ^{31}Ar. Different proton and gamma decays are drawn as an illustration. The β3p-decay and the simultaneous β2p-decay are still not positively identified.

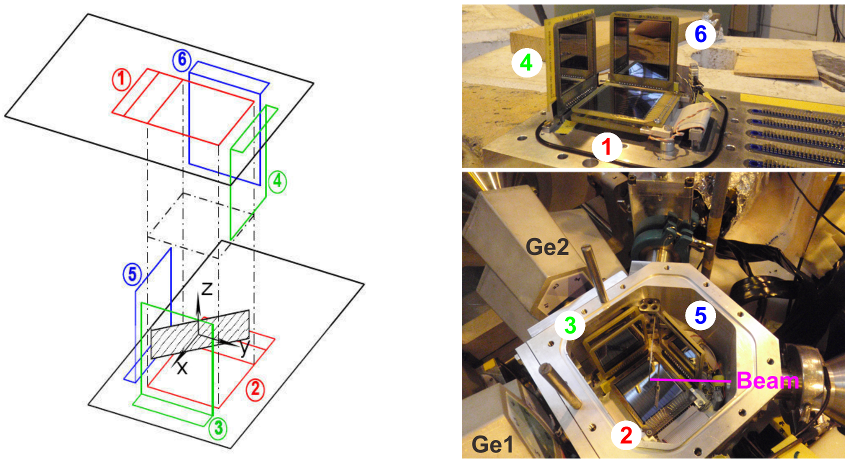
4888(40) keV, respectively, which had not been observed at that time. The first experimental evidence came through studies of ^{32}S$(p,t)^{30}$S by Bardayan *et al.* [9] and Setoodehnia *et al.* [10]. Currently, the most precise experimental values for the energies are 4688.0(4) keV and 4810.4(6) keV, tentatively assigned with spins 3^+ and 2^+ respectively, from the study of ^{28}Si$(^{3}$H$,n\gamma)^{30}$S [11].

Beside the energy and spin of the resonances it is also important to know the proton and gamma partial widths in order to calculate the resonance reaction rate. These have not yet been measured experimentally. In [10] they were calculated by Setoodehnia *et al.* Hopefully, analysis of the experiment presented here will be able to provide a value for the ratio Γ_p/Γ_γ. This is possible because both gamma and proton decays from the resonances can be measured.

2. Experiment

The experiment studied the β-delayed proton emission of ^{31}Ar. The decay sceme can be seen in Figure 1. The resonances just above the proton threshold in ^{30}S are studied via the β-delayed two-proton decay and the β-delayed proton-gamma decay.

The radioactive 60 keV ^{31}Ar beam used in the experiment was produced at ISOLDE, CERN using a CaO target. An average yield of ~1 per second of ^{31}Ar was obtained for a run time of about 7 days. The beam was collected in a 50 μg/cm^2 carbon foil situated in the middle of the detector setup consisting of a Silicon Cube detector [12] from CENGB, containing six Double Sided Silicon Strip Detectors (DSSSDs): One 69 μm, one ~500 μm and four ~300 μm. The setup can be seen in Figure 2. The DSSSDs are segmented into 16 strips in the front and in the back side, each 3 mm wide and 0.1 mm apart. Behind the thin DSSSD and three of the four ~300 μm DSSSDs a 50 mm × 50 mm unsegmented silicon



(a) (b)

Figure 2: The experimental setup used for the experiment. (a) is a schematic drawing of the Silicon Cube detector from [12]. (b) are two pictures of the setup. The cube is opened by taking the top with three of the detectors off. The top picture shows the top with detectors 1, 4 and 6 mounted. The bottom picture shows the open cube with detectors 2, 3 and 5 and the two Ge-detectors situated outside the cube. The purple line represents the beam, which is collected in the foil. Detector 1 is the thin DSSSD and half of the strip of DSSSD 2 was broken. Detectors 4 and 5 are not used in the analysis presented here.

pad detector were placed, which enables particle identification. Only the four DSSSDs in telescope with a pad detector are used in the analysis presented here. For detection of gammas, two cluster detectors, each consisting of three germanium detectors, from MINIBALL [13] at REX-ISOLDE were placed outside the chamber containing the Silicon Cube.

3. Preliminary results

The gamma spectrum is shown in Figure 3. Gamma lines from transitions in both ^{30}S and ^{29}P have been identified. It was found that the peaks marked with blue Roman numbers originate from 2p-events, while the peaks marked with red numbers originate from 1p-events. This means they stem from transitions in ^{29}P and ^{30}S, respectively. The peaks have been studied to ensure that the protons feeding the transitions are significantly different from the background. The peak details are shown in Table 1. The peak marked 5? does not contain significant statistic to be positively identified as a peak, but it is known that the resonance at 4810.4(6) keV decays to the first excited state emitting a 2599.5(5) keV gamma [11].

Peak 3 corresponds to a resonance at 4687(4) keV, which agrees very well with the resonance at 4688.0(4) keV found by Setoodehnia *et al.* [11]. Because of a substantial amount of electronic noise and beta background it is not possible to identify the protons from this resonance in the total proton spectrum. Instead, the protons feeding the level is

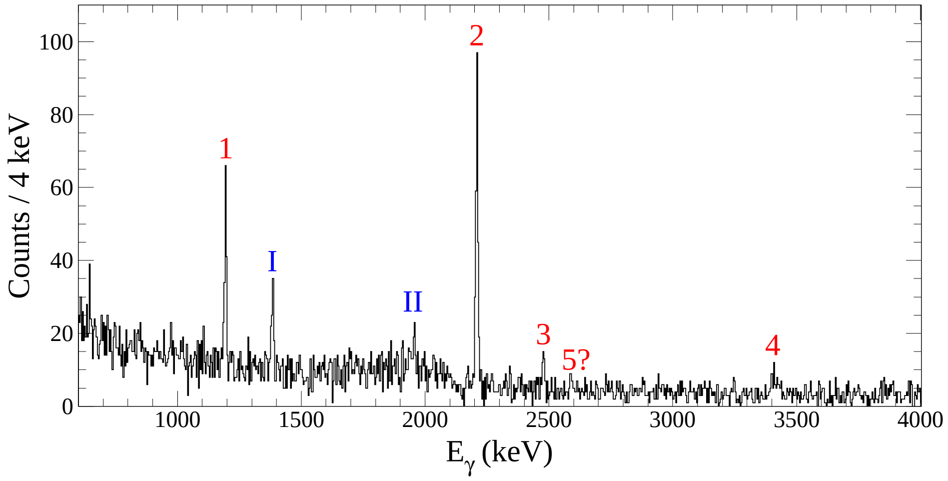


Figure 3: The gamma spectrum gated on protons. To clean the spectrum a time gate from 5 ms to 100 ms is used. Only one gamma in each germanium detector is allowed. The peaks identified are marked. The red numbers correspond to transitions in ^{30}S and the blue Roman numbers to transitions in ^{29}P.

Table 1: The gamma peaks identified in Figure 3. The intensities are relative to the strongest line. FWHM is the full width half maximum of the peaks. The corresponding transitions are shown (g.s. for ground state and 1^{st} ex. for first excited state).

Peak	Area	Energy / keV	FWHM / keV	Intensity / %	Transition
1	120(14)	1193.9(12)	8.9(14)	35(4)	In ^{30}S, to 1^{st} ex.
2	228(17)	2209(3)	10.6(12)	100(7)	In ^{30}S, 1^{st} ex. to g.s.
3	32(8)	2478(3)	11(3)	15(4)	In ^{30}S, to 1^{st} ex.
4	48(20)	3410(10)	35(10)	28(12)	In ^{30}S, to g.s.
5?	17(7)	2591(6)	11(3)	8(4)	In ^{30}S, to 1^{st} ex.
I	62(13)	1383.7(14)	11(2)	20(4)	In ^{29}P, to g.s.
II	30(11)	1955(4)	10(5)	12(4)	In ^{29}P, to g.s.

found by gating on the gammas in peak 3. Gating on these protons reduce the background significantly. It is still not possible to positively identify the proton peak from the resonance, and thus only an upper limit of the Γ_p/Γ_γ can be found. It is found to be

$$\frac{\Gamma_p}{\Gamma_\gamma} = \frac{\#p/\varepsilon_p}{\#\gamma/\varepsilon_\gamma} \leq 10.4\,\% \quad , \quad 95\ \%\ \text{confidence upper limit},$$

where ϵ_p and ϵ_γ are the proton and gamma efficiencies, respectively. Setoodehnia *et al.* calculated the ratio to be $\frac{2.3\times10^{-5}\,\text{eV}}{4.9\times10^{-3}\,\text{eV}} = 0.47\,\%$ for a resonance at 4699(6) keV [10].

4. Outlook

The results presented here are only preliminary results of the ongoing analysis. The energy loss in the collection foil has not been taken into account. This is expected to influence the particles with the lowest energy including the protons from the 4687(4) keV resonance. The upper limit given here will most likely change after this is taken into account.

Another experiment with ^{31}Ar is scheduled to take place at ISOLDE in November 2012. The setup will be optimised for detection of low-energy protons. Gamma detectors will also be used to be able to make the same kind of gates as described here. The goal for the experiment is to be able to identify the proton decay from the resonance at 4687(4) keV and perhaps also from the resonance at 4810.4(6) keV together with their gamma lines. This may prove too optimistic, even with the lowering of electronic noise and better proton efficiency, because the beam time is only one day compared to more than seven days in 2009. But the target group at ISOLDE have prepared a new target and ion source, which should give a much higher yield than what has previously been available [14].

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