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Review

Beta-decay of ^{31}Cl: an indirect probe of the ^{30}P(p, γ)^{31}S reaction. Present status and future perspectives*

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Abstract. β-decay of ^{31}Cl can be used as a selective tool for studying astrophysically relevant states in ^{31}S. In this article we review the present status of the decay data. The implications for the ^{30}P(p, γ)^{31}S reaction rate at novae temperatures, and future experimental ideas are discussed.

1 Introduction

Novae explosions are frequent and bright phenomena resulting from a binary system where a white dwarf accretes hydrogen-rich material from its companion star [1]. Observations from optical, ultraviolet and infrared spectra have given evidence that novae produce enhanced amounts of carbon, nitrogen and oxygen with respect to solar abundances. Heavier so-called ONe novae have shown an enhancement in the abundances of heavier elements. In ONe novae, the ^{30}P(p, γ)^{31}S is a bottle-neck reaction, affecting the production of heavier elements. If the reaction is not fast enough, the beta-decay of ^{30}P ($T_{1/2} = 2.498(4)$ min [2]) takes over and proton capture fails to produce heavier elements.

At typical nova peak temperatures of about 0.2–0.4 GK, the proton capture reaction ^{30}P(p, γ)^{31}S proceeds mostly via resonant capture through narrow and isolated resonances. For such reactions, and in the absence of interference, the reaction rate may be written

$$N_a\langle\sigma\nu\rangle = 1.5399 \cdot 10^{11}\,(\mu T_9)^{-3/2} \times \sum_i (\omega\gamma)_i e^{(-11.605E_i/T_9)}, \tag{1}$$

in units of cm^{3}mol^{-1}s^{-1}, where μ is the reduced mass of the colliding nuclei in atomic mass units, T_9 the temperature in GK, and E_i and $\omega\gamma_i$ are the center-of-mass energy and the resonance strength of the i-th resonance in MeV, respectively [3, 4]. Due to the exponential nature of the energy dependence, it is crucial to determine the resonance energies to a reasonably good precision: Uncertainty of few keV is usually enough. However, sometimes better resolution is needed to distinguish densely packed states. In addition, proper identification of the spins and parities, as well as the proton and γ-widths of the states affects the rate directly via the resonance strength $(\omega\gamma)_i$. Typically for low resonance energies when $\Gamma_p \ll \Gamma_\gamma$, the resonance strength depends only on the proton width, *i.e.* $\omega\gamma \approx \omega\Gamma_p$.

Given the short half-life of ^{30}P no such targets can be manufactured. So far direct experimental studies of the reaction have not been possible due to low intensities of available ^{30}P radioactive ion beams. On the other hand, ^{31}Cl has a high β-decay Q value ($Q_{EC} = 11976(50)$ keV [5]), allowing it to populate states above the proton separation energy in ^{31}S ($S_p = 6130.9(4)$ keV [5]).

Nuclear β-decay is a very selective process: allowed decays populate only states where the spin changes maximum by one unit, and the parity remains unchanged. If the spin changes by more than one unit, or the parity changes, the decays are strongly suppressed (forbidden decays). Thus β-decay of ^{31}Cl ($J^\pi_{g.s.} = \frac{3}{2}^+$) populates levels in ^{31}S that most likely have $J^\pi = \frac{1}{2}^+$, $\frac{3}{2}^+$, or $\frac{5}{2}^+$.

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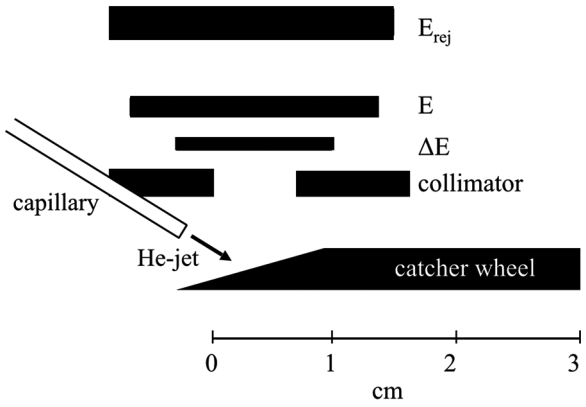

Fig. 1. The experimental setup at Berkeley, adapted from fig. 1 of ref. [8].

In the case of ^{30}P(p,γ)^{31}S, the proton is captured by a ^{30}P nucleus with $J^\pi = 1^+$ and thus the s-wave ($l = 0$) captures will go to states with $J^\pi = \frac{1}{2}^+$ or $\frac{3}{2}^+$ which may be populated in the β-decay of ^{31}Cl. As mentioned earlier, allowed β-decay may also populate $J^\pi = \frac{5}{2}^+$ states, corresponding to d-wave ($l = 2$) capture.

In this article we review the known experimental data of β-decay of ^{31}Cl, concentrating on the states relevant for the ^{30}P(p,γ)^{31}S reaction: *i.e.* we focus on the existing data above $S_p(^{31}\mathrm{S})$. Since the early 1980s, β-decay of ^{31}Cl has been studied with several different techniques. We group here the experiments by the sample production method used. Experimental setups for experiments where samples were produced with different ISOL (Isotope Separation On-Line) techniques are discussed in sect. 2, and with samples produced with in-flight technique in sect. 3. In sect. 4 we summarize the known β-decay data that are relevant for the ^{30}P(p,γ)^{31}S reaction rate evaluation presented elsewhere in this Focus Point.

2 Samples produced with ISOL techniques

2.1 Studies in Oslo

The first studies on the beta-decay of ^{31}Cl were performed at the MC-35 cyclotron of the University of Oslo in 1982 [6,7]. The ^{31}Cl$^+$ ions were produced using a 34 MeV proton beam impinging on a ZnS target and transported from the target region via He-jet technique. The ^{31}Cl beam was implanted on an aluminized mylar tape surrounded by a single 31.1 μm thick surface-barrier detector and a detector telescope consisting of a 10.8 μm, 25 mm^2 ΔE and a 300 μm E, 100 mm^2 E detector. The two most intense beta-delayed proton groups of ^{31}Cl at 989(10) and 1528(20) keV were observed and a half-life of 150^{+25}_{-20} ms determined based on those groups.

2.2 Studies in Berkeley

The next beta-decay studies on ^{31}Cl were performed at the Lawrence Berkeley Laboratory 88 inch Cyclotron [8] with a 45 MeV proton beam on a ZnS target. The reaction products were swept away from the target region using the He-jet technique and implanted on a rotating wheel in front of a ΔE (8.3 μm, 50 mm^2) - E (68 μm, 100 mm^2) - E_{rej} (20 μm, 300 mm^2) setup as illustrated in fig. 1. The E_{rej} detector was used to reject the events due to positrons but also to detect higher-energy protons. An overall resolution for protons of 75 keV was achieved with this setup. Altogether eight proton peaks in the energy range of 845 to 2204 keV were observed [8]. ^{31}Cl was restudied at Lawrence Berkeley in the 1990s using two gas ΔE (CF_4, 30 μg/cm^2) - gas ΔE (CF_4, 30 μg/cm^2) - E (Si 300 μm, 380 mm^2) detectors. However, this latter experiment suffered from contamination by beta-delayed protons of ^{25}Si resulting from the aluminum backing discs of the ZnS target. As a result, only the two strongest proton peaks of [8] were confirmed although the total proton beam charge was 220 mC [9] compared to 90 mC in the previous Berkeley experiment [8] and 15 mC at the Oslo MC-35 cyclotron [7].

2.3 Studies in Jyväskylä

In 2004, the first experiment on ^{31}Cl employing a mass-separator was performed at the IGISOL3 (Ion Guide Isotope Separator On Line) facility [10] at the Accelerator Laboratory of the University of Jyväskylä (JYFL). There, 40 and 45 MeV proton beams impinging on a thin ZnS target at the entrance of the ion guide cell were employed. The reaction

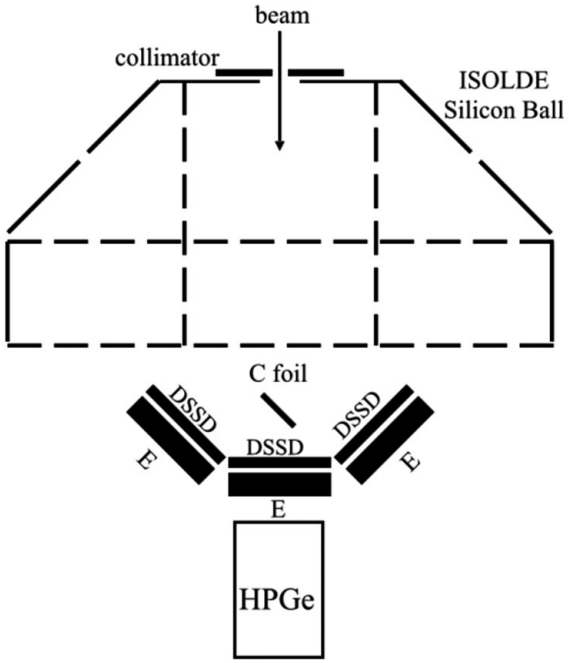

Fig. 2. An illustration of the experimental setup for the beta-decay of ^{31}Cl at IGISOL. Not in scale, adapted from fig. 2 of ref. [11].

products were stopped and thermalized in the helium gas of the ion guide ($p = 200$ mbar) and extracted from the gas cell through use of a differential pumping system and application of an electric field. The ions were accelerated to $40q$ keV and further mass-separated with a 55° dipole magnet. As a result, a pure beam of $A/q = 31$ reaction products was delivered to the spectroscopy setup. This was an advantage since the previous experiments had to collect data also at lower energy below the ^{31}Cl production threshold in order to distinguish the proton peaks belonging to other reaction products, such as ^{32}Cl. The yield of ^{31}Cl at IGISOL was about around 14 ions/s which was about 1000 times less than the yield of ^{31}S [11].

New double-sided silicon strip detectors (DSSSDs), offering much better energy resolution and reduced summing of the events due to pixelated readout structure, became available in the beginning of the millennium [12, 13]. At IGISOL, the $^{31}Cl^{+}$ beam was implanted into a 30 μg/cm^2 thick carbon foil surrounded by three DSSSDs and the ISOLDE Silicon Ball detector [14]. The DSSSDs were about 60 μm thick and had sixteen 50 mm long and 3 mm wide front strips and similar but orthogonal back strips. One of the DSSSDs was a Micron Semiconductor Ltd. (MSL) W1 detector with a dead layer of 600 nm [12] and two others were of a newer design with a dead layer of 100 nm [13]. Each DSSSD was backed with a thick silicon detector in order to detect positrons and higher energy protons. A hemisphere of the ISOLDE Silicon Ball detector [14] consisting of 144 individual 25.5×25.5 mm^2 Si detectors was useful for covering a larger solid angle for detecting beta particles. For the first time in these types of experiment, a HPGe detector (70%) was used to detect beta-delayed gamma-rays from ^{31}Cl. The detector setup of the experiment is shown in fig. 2.

The peaks observed in ref. [8] were confirmed together with 5 new peaks. The experiment suffered from electronic noise at lower energies, as well as strong isobaric background, from ^{31}S, and no proton peaks below 700 keV could be distinguished. Some of the observed proton peaks were uncertain. Total of four γ-lines were attributed to ^{31}Cl decay. One of the lines, at 4045(2) keV, was deduced to originate from the isobaric analogue state (IAS) at 6280(2) keV.

3 Samples produced with an in-flight technique

3.1 Studies in Texas A&M

In a series of experiments at Texas A&M University (TAMU) [15–17], a ^{31}Cl beam was produced by bombarding a 2.5 mg/cm^2 thick liquid-nitrogen–cooled H_2 target at 1.6 atm pressure with a ^{32}S beam at 40 MeV/u. The reaction products from inverse-kinematics reaction ^{1}H(^{32}S, ^{31}Cl)2n were separated with the Momentum Achromat Recoil Spectrometer (MARS) [18]. The production method and the energy used allowed, for the first time, the separation of ^{31}Cl from its isobars. The resulting ^{31}Cl beam had intensity of 3000 pps at 90% purity, the major impurity stopped in the

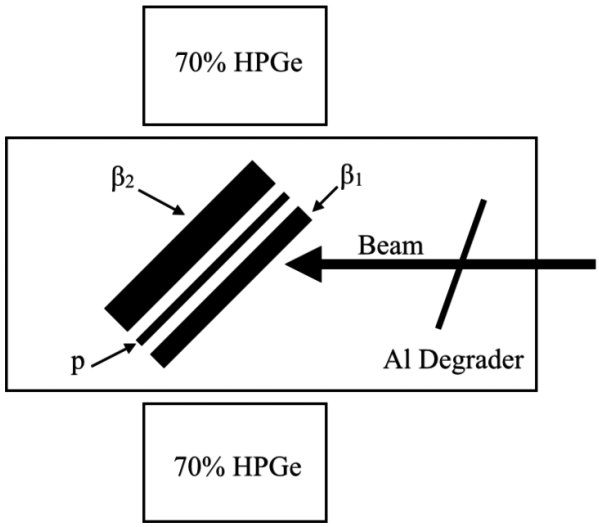

Fig. 3. A schematic presentation of the experimental setup at Texas A&M, not to scale. Label "p" refers to a DSSSD used, "β_1" to Si detector added for the second experiment, and "β_2" for a thick Si-pad detector. In the first experiment, only one HPGe was used. See text for more details.

setup being ^{29}S. During the implantation into the setup the beam momentum spread was restricted to $\Delta p/p = 0.25\%$ and the rate to about 800 pps.

In the first of the experiments, the produced ^{31}Cl ions were implanted into a detector setup consisting of a 65 μm thick MSL W1 type DSSSD with $16 + 16$ $3.1 \times 50\,\mathrm{mm}^2$ strips (labeled "p" in fig. 3), a 1 mm thick Si-pad detector ($50 \times 50\,\mathrm{mm}^2$,"$\beta_2$" in fig. 3), and a 70% HPGe detector facing the front side of the Si detector stack [15, 16]. In the second experiment, the DSSSD was changed to a 45 μm thick MSL BB2 type detector with $24 + 24$ $1 \times 24\,\mathrm{mm}^2$ strips, an additional 300 μm thick Si $50 \times 50\,\mathrm{mm}^2$ detector was added before the DSSSD "β_1" in fig. 3, and another 70% HPGe detector was added on the opposite side [17, 19]. During the second experiment, data were taken also in a configuration consisting of only the two HPGe detectors and the thick Si detector, while the other Si detectors ($\beta 1$, p) were replaced by an 125 μm thick Al plate. This configuration allowed maximum beam to be used for higher statistics of β-γ-γ coincidences. In addition, to measure a more precise half-life, the standard tape transport - gas counter setup for high-precision β-decay half-life measurements was used. See, *e.g.*, ref. [20] and references therein for a detailed description of the half-life setup.

The TAMU experiments [15–17] confirmed the results of the JYFL experiment [11] for the proton spectrum up to about 2 MeV, while suffering from ^{29}S impurities and the fact that the higher-energy protons escaped the implantation detector. In addition to proton data, an extensive set of γ-lines was collected. The results include first direct measurement of the IAS through direct four different decay paths, including coincident cascades through the excited states. The comparison of the datasets is discussed further in sect. 4.

3.2 Studies at the NSCL

Very recently, β-decay of ^{31}Cl has been studied at the National Superconducting Cyclotron Laboratory (NSCL) by using coupled K500 and K1200 cyclotrons and the A1900 separator to produce an about 88% pure beam of ^{31}Cl with intensity of more than 6000 pps. In this experiment, 50 MeV/u ^{31}Cl ions were implanted into a plastic scintillator, surrounded by an array of Yale Clovershare "Clover" type HPGe detectors. At the time of writing this contribution, the resulting $\beta\gamma(\gamma)$-coincidence data are under analysis [21, 22].

4 Summary of the ^{31}Cl β-decay data above $S_p(^{31}S)$

The proton spectra of the experiments in JYFL and in TAMU are compared in fig. 4. It is worth noting that in the JYFL experiment the ^{31}Cl source was implanted into a C foil, whereas the TAMU spectrum has been collected by implanting the ^{31}Cl ions inside the detector. The latter method thus measures not only the proton energy, but also the energy of the recoiling proton daughter and the preceding β-particle. The TAMU spectrum has several peaks from ^{29}S contamination. The JYFL data have large backgrounds from the whole $A = 31$ isobar present in the beam (mainly ^{31}S). The extracted proton energies of both the aforementioned experiments, along with all other known data are given in table 1. All the known experimental proton energies agree within the uncertainties of each experiment.

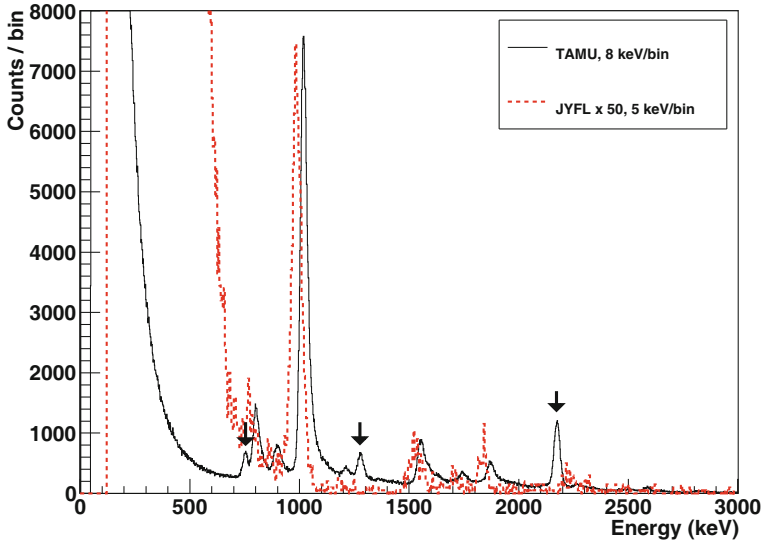

Fig. 4. A comparison between the proton spectra of the experiments in JYFL (red, dashed) and in TAMU (black, solid). The JYFL data has been multiplied by factor of 50 to match the statistics of the 996 keV proton line in TAMU spectrum. The arrows point out ^{29}S contamination in the TAMU data. Note that in the JYFL experiment the ^{31}Cl source was implanted into a C foil, whereas the TAMU spectrum was collected by implanting the ^{31}Cl ions inside the detector, measuring the total decay energy. See text for details.

Table 1. A comparison of known proton energies from ^{31}Cl decay. All energies are given as $E_{\rm lab}$ in keV. The average value is the weighted average of all the works presented in this table. The corresponding level energy is determined by assuming decay to the ground state of ^{30}P and using the calculated average proton energy with $S_p(^{31}\mathrm{S}) = 6130.9(4)$ keV [5].

Refs. [6, 7]	Ref. [8]	Ref. [9]	Ref. [11]	Ref. [17]	Average	$E_{\rm lev}$
			762(14)	780(2)	780(2)	6936(2)
	845(30)		853(18)	877(2)	876(2)	7036(2)
989(15)	986(10)	986(10)	978(15)	993(2)	993(2)	7157(2)
	1173(30)		1175(19)	1185(3)	1185(3)	7355(3)
				1345(17)	1345(17)	7521(17)
1528(20)	1520(15)	1524(10)	1521(20)	1520(3)	1521(3)	7702(3)
				1594(17)	1594(17)	7778(17)
	1695(20)		1688(22)	1706(3)	1706(3)	7894(3)
	1827(20)		1825(23)	1830(3)	1830(3)	8022(3)
				1927(17)	1927(17)	8122(17)
	2113(30)		2075(30)	2070(17)	2079(13)	8279(13)
	2204(30)		2217(30)	2224(3)	2224(3)	8429(3)
			2299(30)	2286(17)	2289(15)	8496(15)
			2454(40)	2489(17)	2484(16)	8697(16)
			2601(40)	2641(17)	2635(16)	8854(16)
			2751(40)	2807(17)	2799(16)	9023(16)

Table 1 gives these proton energies as ^{31}S excitation energies, assuming that the proton decays populate the ground state of ^{30}P. It is worth noting that there is some evidence for some of these decays populating excited states in ^{30}P as shown in ref. [17]. However, so far known levels populated by β-delayed proton emission from ^{31}Cl are too high in energy to yield information about the states inside the Gamow window of $^{30}\mathrm{P}(\mathrm{p},\gamma)^{31}\mathrm{S}$ in typical novae temperatures as illustrated in the partial decay scheme in fig. 5.

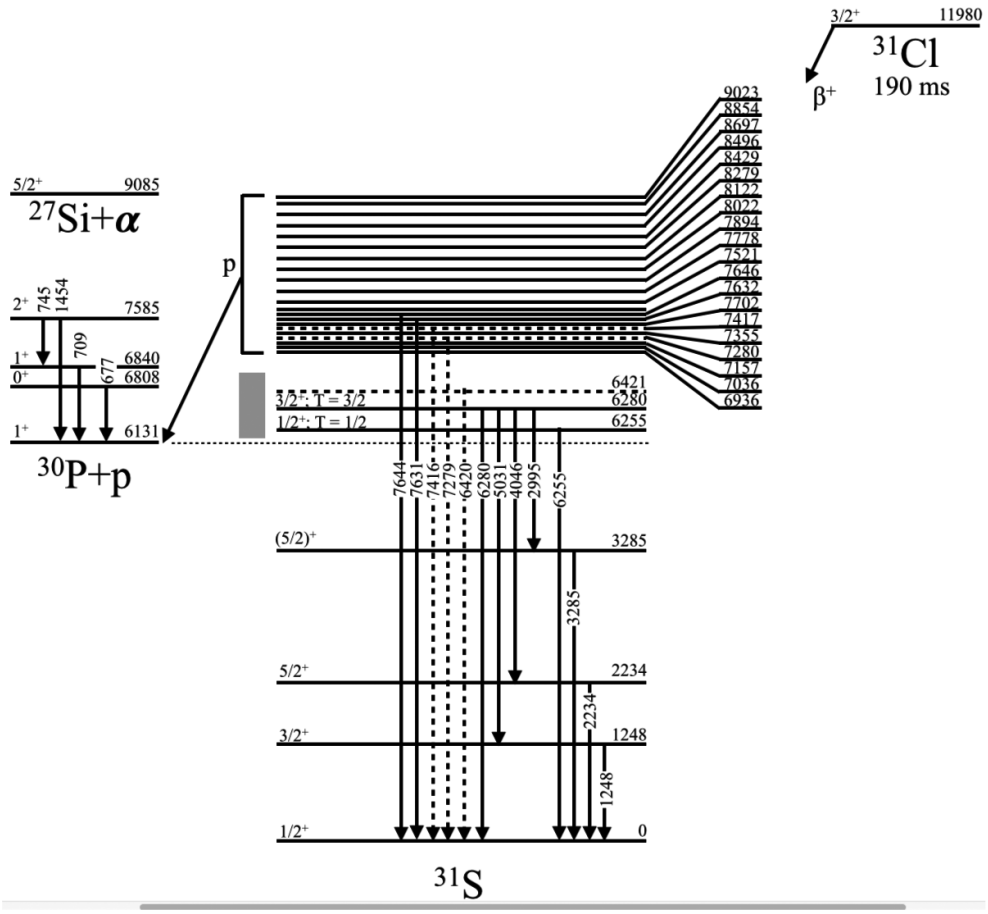

Fig. 5. Partial and simplified decay scheme of ^{31}Cl illustrating levels above $S_p(^{31}\mathrm{S})$. See tables 1 and 2 for more detailed energies. The definitive spin-parities are from ref. [23]. Most of the proton unbound levels have $J^\pi = (1/2, 3/2, 5/2)^+$. The dashed lines and γ-transitions are tentative assignments of ref. [17] without known literature counterpart. The gray band denotes the Gamow window at typical novae temperatures (0.2–0.4 GK).

The presently known β-delayed γ-data have more information to offer about states inside the Gamow window. Table 2 lists the known β-delayed γ-lines beyond the proton threshold, with comparison to other known states that can be populated in β-decay. In the JYFL data, ref. [11], one γ-line was assumed to originate from beyond the proton threshold: the 4045(2) keV was deduced to be transition from the IAS to the 2234 keV second excited state in ^{31}S, and thus a level energy of 6280(2) keV was deduced. However, no coincidence data were collected. The TAMU dataset, refs. [15–17], has a direct transition from the IAS, along with three transitions that are in coincidence with γ-lines from the lower levels. One direct transition corresponding to a previously known level at 6259 keV was measured with improved precision. In addition, two transitions without previously known matching levels at 6420 and 7280 keV were observed and tentatively assigned to corresponding levels. Two high-energy γ-lines matching previously known 7600(30) and 7660(30) keV levels were observed and tentatively assigned to originate from these levels. None of these four transitions could be attributed to originate from any other species in the beam cocktail, nor escape or sum peaks. Their nature needs to be confirmed with an independent measurement. In the TAMU dataset, there is a γ-line at 6389.7(11) keV, but this overlaps with an escape peak of a higher-energy γ-ray.

An increase in the number of counts at 5030 and 6420 keV was also seen in the JYFL data set, although statistics was not enough to assign them as peaks. In addition, peaks at around 7630 and 7640 keV were observed at IGISOL as seen in fig. 6. Since they were located at the very end of the gamma-ray energy spectrum, they were treated as possible overflow peaks and not taken into account in the data analysis. However, also a peak located at the position of the first escape peak at around 7130 keV is seen in the JYFL data set supporting that the peaks at around 7630 keV are real. This is supported also by the fact that there are no known γ-rays at these energies originating from any nuclei at $A = 31$, $A = 62$, or $A = 15, 16$ regions.

Table 2. The γ-transitions from ^{31}Cl decay above $S_p(^{31}\mathrm{S}) = 6130.9(4)$ keV [5]. The level energies are calculated from the observed E_γ by taking into account the energy of the recoiling nucleus. For comparison, known levels by other techniques from the literature. All energies are given in keV.

Ref. [11]	Ref. [17]		Literature	Remarks
E_γ; E_{final}	E_γ; E_{final}	E_{level}	E_{level}; J^π	
	6254.6(5); 0	6255.3(5)	6259(2); $\frac{1}{2}^+$, $T = \frac{1}{2}$	Refs. [24, 25]
	2995.6(2); 3284.8(3)	6280.2(3)	6281.2(14); $\frac{3}{2}^+$, $T = \frac{3}{2}$	Ref. [25]: Average of refs. [11, 25–28]
4045(2); 2235.6(4)	4046.2(2); 2234.3(2)			
	5031.5(3); 1247.6(3)			
	6279.5(3); 0			
	6420.0(6); 0	6420.7(6)		
	7279(1); 0	7280(1)		
	7415.8(9); 0	7416.8(9)		
	7630.8(6); 0	7631.8(6)	7600(30)	Ref. [26]
	7643.6(8); 0	7644.6(8)	7660(30)	Ref. [26], Ref. [25]: 7641(3), $(\frac{5}{2} - \frac{13}{2})^-$

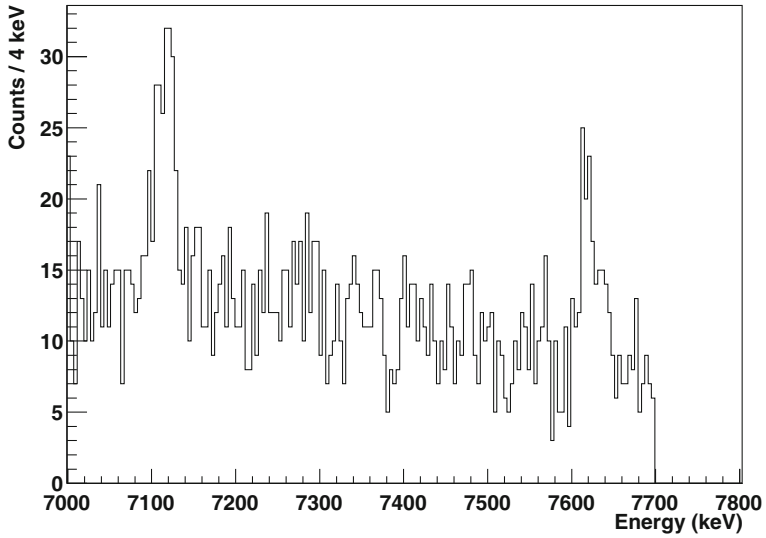

Fig. 6. Previously unpublished high-energy part of the γ-spectrum from the JYFL experiment. The double peak at around 7630 keV and matching line 511 keV below suggest this being a real transition rather than overflow. See text for more details.

5 Conclusions and future perspectives

The main contributions of the present β-decay data to the $^{30}\mathrm{P}(\mathrm{p},\gamma)^{31}\mathrm{S}$ rate at novae temperatures are the precise energies of the resonances at 6255.3(5) and 6280.2(3) keV. The latter of these has been observed in two independent β-decay studies [11, 17]. These energies are in reasonable agreement with the known energies from other known data as seen in table 2. There is a few keV discrepancy to some of the known reaction measurements in refs. [24, 25, 28, 29], but agreement within the uncertainties of ref. [27]. The tentative 6420.7(6) keV state of ref. [17] needs to be confirmed by other study. Some of the dataset of ref. [17] is still under analysis, and the very recent study of refs. [21, 22] may offer some new insights on some of the states above the proton threshold in ^{31}S. It is worth noting that the improved IAS energy yields a more precise prediction for the ^{31}Cl ground-state mass excess through the Isobaric Multiplet Mass Equation (IMME). The determined value of $-7056.8(3.3)$ keV agrees with the known value $-7070(50)$ keV [5] and reduces the uncertainties related to the $^{30}\mathrm{S}(\mathrm{p},\gamma)^{31}$Cl reaction.

It is clear that, so far, in-flight methods provide a cleaner source of ^{31}Cl than ISOL methods. However, if one can acquire high enough production of ^{31}Cl through ISOL methods, then it may be possible to utilize a Penning trap to produce a 100% clean source [30]. In addition, replacing the traditional catcher foil with a Paul trap [31] should allow mitigation against the deleterious features introduced by use of a catcher foil, thus making the dead-layer of used Si detectors the only limitation for the low energy. Such configurations would also allow the nature of the low-energy β-delayed particles to be distinguished, which in principle can be either protons or alphas.

The limitations of silicon detectors make measuring of β-delayed protons of astrophysical interest rather difficult, if not impossible. Even when implanting ions inside a Si detector, which allows the complications due to energy loss in dead layers or catcher material to be ignored, the low-energy region is usually dominated by a large background contribution from the betas originating from decay channels without protons, or even worse, from impurities. In some cases low-energy proton peaks can be extracted by using background subtraction [32]. However, recent advances using Micro-MEsh-GAseous-Structures (MicroMEGAS) based detectors are a promising new tool for measuring low-energy β-delayed particles essentially background free down to 100 keV or even lower [33]. Using such detector, in combination with efficient γ-detection capability, will offer access to the ^{31}Cl β-delayed protons of astrophysical interest.

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