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Decays of $T_Z = -3/2$ nuclei ^{23}Al, ^{31}Cl, and ^{41}Ti

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Abstract This article gives an overview on the decay spectroscopy of $T_Z = -3/2$ nuclei ^{23}Al, ^{31}Cl, and ^{41}Ti performed at the Ion Guide Isotope Separator On-Line (IGISOL) facility. The results of the IGISOL experiments are compared to the experimental results that have been published since. The isobaric multiplet mass equation (IMME) has been studied for the $T = 3/2$ quartets at $A = 23$ and $A = 31$. For ^{41}Ti, a detailed comparison to the Gamow-Teller strengths obtained for the analog transitions via charge-exchange reactions has been done. Further improvements in the experimental instrumentation and methods and possible implementations for studying $T_Z = -3/2$ nuclei at the new IGISOL facility are discussed.

Keywords IGISOL · beta decay · beta-delayed protons

1 Introduction

Nuclei having an isospin component $T_Z = (N - Z)/2 = -3/2$ offer an interesting possibility to study beta-decay strength over broad energy range. Since the main part of the beta-decay strength is concentrated on states above the proton separation energy S_p, beta-delayed proton spectrum is essential in order to study the strength distribution. A large fraction of the beta-decay strength is within the Q_{EC} window allowing a detailed comparison to shell-model calculations or to the strength of analogous transitions studied via charge-exchange reactions, such as in the case of the $T = 3/2$ quartet at $A = 41$ [1].

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The relative β-delayed proton emission window $(1 - S_p/Q_{EC})$ of the $T_Z = -3/2$ nuclei depends strongly on whether they belong to the $A = 4n + 3$ (odd Z) or to the $A = 4n+1$ series (even Z) [2]. Generally for the $T_Z = -3/2$ nuclei with odd Z, such as ^{23}Al and ^{31}Cl, the β-delayed proton emission window is between 0.3 and 0.45, whereas for even-Z nuclei, like ^{41}Ti, it is between 0.8 and 1. This gives a rough indication of the expected β-delayed proton versus γ-ray emission probability. As the β-decay phase space favors the decay to the low-energy states, the γ decay by slow electromagnetic interaction is especially pronounced for the $A = 4n + 3$ series β-decay precursors. Also due to Coulomb and angular momentum barriers, γ decay starts to compete with isospin-forbidden proton decay for low-lying proton unbound states. Therefore, in addition to protons, detecting γ rays with good sensitivity is essential.

According to the Isobaric Multiplet Mass Equation (IMME) [3–5], masses of the members of an isobaric multiplet (T) should lie along a parabola $M(T_Z) = a + bT_Z + cT_Z^2$. In order to study the IMME, masses and excitation energies of the isobaric analog states (IAS) belonging to the T multiplet should be precisely measured. Previously, masses were determined from beta-decay energies, but nowadays Penning trap mass spectrometry offers a more accurate method for measuring the ground state mass excesses directly. Beta-decay studies of $T_Z = -3/2$ nuclei offer information on the excitation energies of the IAS in the $T_Z = -1/2$ nuclei. In addition, isospin mixing in the wavefunctions of the $T = 3/2$ IAS, manifested in isospin-forbidden proton decays of these IAS, can be systematically studied in these nuclei.

The studied $T_Z = -3/2$ nuclei ^{23}Al, ^{31}Cl, and ^{41}Ti lie at the path of the rapid proton capture (rp) process [6,7]. In particular, beta-decay studies of ^{23}Al and ^{31}Cl yield information on the states in the daughter nuclei, ^{23}Mg and ^{31}S, whose properties are relevant for the modeling the nucleosynthesis in ONe novae. Namely, the reactions ^{22}Na(p, γ)^{23}Mg and ^{22}Mg(p, γ)^{23}Al have to be well-known in order to model the production of ^{22}Na in ONe novae [8]. The non-observation of 1275-keV γ-rays from ^{22}Na with COMPTEL telescope [9] has drawn attention to the production mechanisms of ^{22}Na and constrained nova models during the last years. However, there are recent papers on possible observation of these γ-rays based on long-term COMPTEL observations [10,11]. Ref. [10] reports possible detection from a diffused source in the galactic bulge, explaining it to originate most likely from photo-activation of ^{22}Ne by cosmic rays whereas Ref. [11] claims a more localized source from a very slow Nova Cassiopeia 1995. The reaction ^{30}P(p, γ)^{31}S is important since ^{30}P is a mandatory passing point in ONe novae and it will stop further nucleosynthesis unless proton captures on ^{30}P ($T_{1/2} = 2.5$ min) are fast enough [12].

2 Experimental details

2.1 Production of $T_Z = -3/2$ nuclei at IGISOL

At IGISOL [13], the ions of interest with $T_Z = -3/2$ have been produced in light ion fusion evaporation reactions with a proton or ^{3}He beam from the K-130 cyclotron on a thin (few mg/cm^2) target. The recoiling products from the target are thermalized in the gas cell where they undergo charge-exchange reactions and a good fraction of the ions end up at a charge state 1^+. The ions are extracted from the gas cell with the help of differential pumping and a skimmer electrode. During recent years, the skimmer electrode has been replaced by a sextupole ion beam guide SPIG [14]. After the gas cell, the ions are accelerated typically to 40q kV energy and mass-separated by a 55° dipole magnet providing a mass resolving power of $M/\Delta M \approx 500$. The mass-separated beam is implanted on a thin carbon foil for the studies of beta-delayed protons and/or on a movable tape for beta-delayed γ-rays at the experimental station of the IGISOL facility. This on-line mass separation provides much cleaner spectra of the studied nuclides compared to experiments performed with the He-jet technique [15]. Experimental setups and production reactions used for ^{23}Al, ^{31}Cl, and ^{41}Ti are summarized below.

^{23}Al was produced at IGISOL via ^{24}Mg(p,2n)^{23}Al reactions with a $7-10$ μA, 40-MeV proton beam on $^{\rm nat}$Mg target [16]. The observed yields for mass-separated ^{23}Al and ^{23}Mg were ≤ 20 atoms/s and about 4000 atoms/s, respectively. ^{31}Cl was produced with the same type of reaction, ^{32}S(p,2n)^{31}Cl, using a $10-20$ μA, 40 or 45-MeV proton beam on a thin ZnS target [17]. The yields for ^{31}Cl and ^{31}S at 40 MeV were around 14 atoms/s and 20000 atoms/s, respectively [17]. For the production of ^{41}Ti, a $1-7$ eμA, 40-MeV ^{3}He beam on $^{\rm nat}$Ca target was used to produce the ions of interest via ^{40}Ca(^{3}He,2n)^{41}Ti [18]. The production rate of ^{41}Ti was about 1 atom/s with the highest beam intensity [18].

2.2 Detector setups for observing β-delayed γ-rays and protons

Identification of beta-delayed protons from the beta-particle background is a key issue in beta-delayed proton and gamma spectroscopy. Therefore, different $\Delta\mathrm{E}-\mathrm{E}$ detectors have been used, since the energy deposit in a ΔE detector depends on the type of the particle. With the same initial energy, protons leave more energy than beta particles but less than alpha particles. A $\Delta\mathrm{E}_{\rm gas}-\mathrm{E}_{\rm Si}$ detector telescope [19] was used to detect beta-delayed protons of ^{23}Al [16] and ^{41}Ti [18]. The telescope consisted of an E detector which was an Ortec Ultra series silicon detector with an active area of 300 mm^2 and a thickness of 300 μm [19]. A proportional counter mode was applied to the CF_4 gas ΔE detector in order to reach a large enough signal-to-noise ratio. A lower detection limit of 155 keV and an energy resolution of 20 keV was achieved for the telescope [19].

In addition to the $\Delta\mathrm{E}_{\rm gas}-\mathrm{E}_{\rm Si}$ detector telescope for detecting protons, a 1-mm-thick plastic $\Delta\mathrm{E}_\beta$ detector and a HPGe (37.5 % relative efficiency) were used in the initial IGISOL ^{23}Al experiment for detecting beta particles and γ-rays, respectively. The 40 keV ^{23}Al$^+$ beam was implanted on a 40 μg/cm^2-thick carbon foil surrounded by the three detectors. This setup is illustrated in Fig. 1. In the experiment on the beta decay of ^{41}Ti, two different measurement setups were used. For detecting beta-delayed protons, the $\Delta\mathrm{E}_{\rm gas}-\mathrm{E}_{\rm Si}$ detector telescope was used behind a 40 μg/cm^2-thick carbon foil into which the mass-separated beam was implanted. Beta- and proton-delayed γ-rays were observed with a setup consisting of a 0.9-mm-thick plastic scintillator for detecting beta particles, a 50 % HPGe detector for γ-rays, and an ion-implanted silicon detector for both beta detection and proton energy measurements [18]. There, the 40 keV ^{41}Ti$^+$ beam was implanted into aluminized mylar tape.

The mass-separated 25-keV ^{31}Cl$^+$ was implanted into a 30 μg/cm^2-thick carbon foil surrounded by a novel state-of-the-art silicon detector assembly consisting of the ISOLDE Silicon Ball [20], three double-sided silicon strip detectors (DSSSDs) [21,22] backed with three thick silicon detectors, and a 70 % HPGe detector [17]. The DSSSDs were about 60-μm thick, and therefore, beta particles left very little energy in them. This made DSSSDs ideal for detecting beta-delayed protons from ^{31}Cl. The ISOLDE

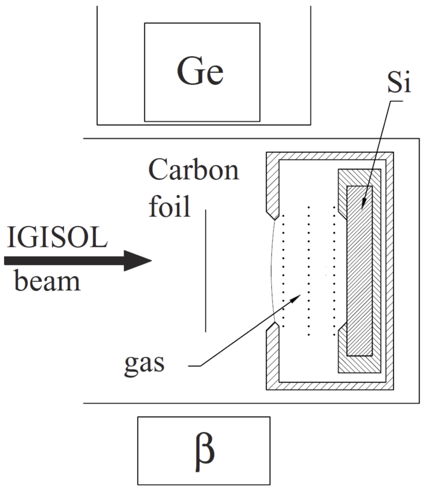

Fig. 1 Schematic presentation of the setup in the IGISOL central beam-line for ^{23}Al β-decay experiment reported in Refs. [16,23]. The 40-keV beam was implanted into 40 μg/cm^2 carbon foil surrounded by 37.5% HPGe detector, 1-mm-thick plastic β-detector and the $\Delta E_{gas} - E_{Si}$ detector telescope.

Silicon Ball and three thick Si detectors were used for detecting betas. The total beta efficiency was measured as 24.9(19) %. Protons below 700 keV could not be observed due to noise and β-tail caused mainly by ^{31}S in the spectrum.

3 Beta-delayed gamma and proton spectroscopy of $\mathbf{T_Z = -3/2}$ nuclei at IGISOL

3.1 ^{23}Al

β-delayed proton emitter ^{23}Al can be used as a tool to probe astrophysically interesting states just above the proton separation threshold in ^{23}Mg. These states are relevant for understanding resonant proton capture ^{22}Na(p,γ)^{23}Mg and the amount of ^{22}Na ejected in ONe novae. Measuring this reaction directly is challenging because the need for radioactive ^{22}Na targets complicates the measurement [24,25]. ^{23}Al was first produced in the early 1970's in Berkeley with the He-jet technique where a single proton group with an energy of 870(30) keV and a half-life of 470(30) ms was discovered [26]. In the mid-90's Tighe *et al.* [27] extended the study to lower energies and found a low-energy proton group with high intensity, which was assigned to originate from the $T = 3/2$ isobaric analog state (IAS) of the ground state of ^{23}Al. This was interpreted to occur due to extremely strong isospin-mixing as proton decay from the IAS does not conserve isospin.

Due to the astrophysical importance, and in order to confirm the results of Tighe *et al.* [27], a project to investigate the decay of ^{23}Al was initiated in Jyväskylä in the late 1990's. An experimental setup capable of detecting γ-rays, electrons and heavier charged particles was installed to the end of the central beam line at IGISOL, see Fig. 1. Experimental details related to the ^{23}Al production are summarized in section 2.1.

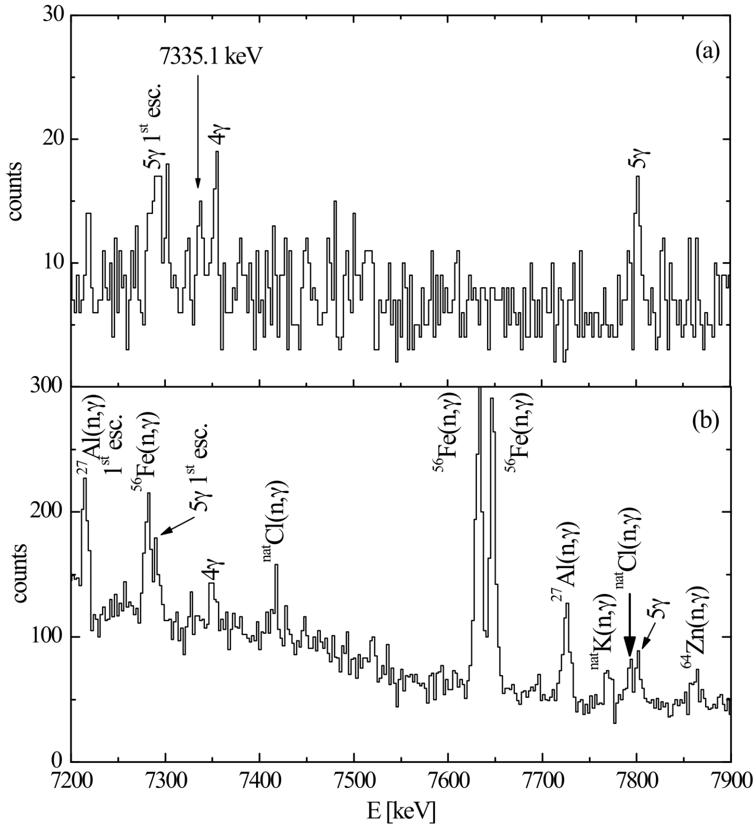

Fig. 2 The high energy part of the γ-spectrum from β-decay of ^{23}Al as reported in Ref. [16].

This was the first ever study of β-decay of ^{23}Al to have a capability for simultaneous observation of both protons and γ-rays.

As the spectroscopy setup was also capable of detecting γ-rays, a γ-decay of the IAS to the ground and first excited state of ^{23}Mg was reported in Ref. [16] for the first time. These observations were confirmed later with much higher statistics by Iacob *et al.* [28]. Figure 2 presents Fig. 2(a) and (b) of Ref. [16], where peak labelled with 5γ is related to the transition from the IAS to the ground state and 4γ from the IAS to the first excited state.

From the decay spectroscopy point of view, it turned out to be that this initial IGISOL experiment [16] did not confirm the low energy part (below 400 keV) of the proton spectrum reported in Ref. [27]. At these energies significantly less intensity was observed at IGISOL [16] compared to Ref. [27]. Iacob *et al.* [28] suggested that this difference was caused by the higher cut-off energy in the $\Delta E_{gas} - E_{Si}$ telescope at IGISOL [16]. However, in a recent experiment at Texas A&M, β-delayed proton

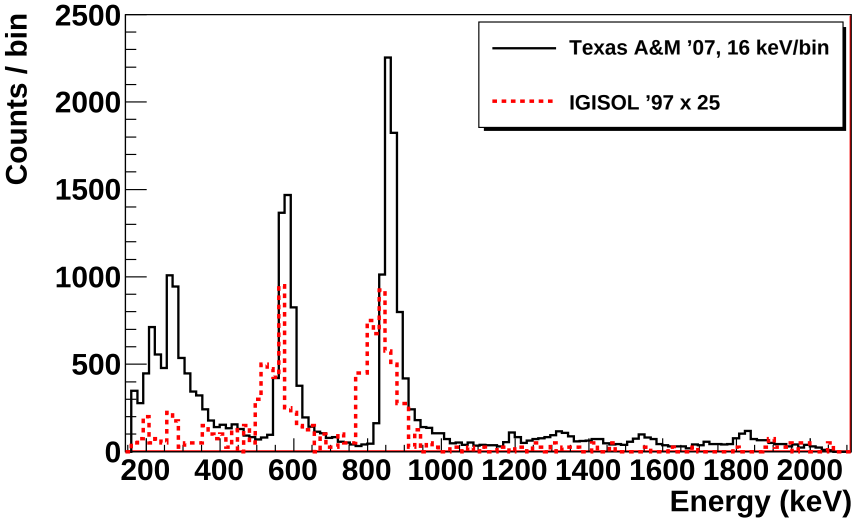

Fig. 3 Comparison of the proton spectra from IGISOL and Texas A&M. The IGISOL spectrum is multiplied ×25 to scale with statistics of the Texas A&M experiment. Note that the IGISOL spectrum has its energy recorded as proton energy in lab, while the Texas A&M spectrum is the recorded total decay energy.

spectrum with high statistics [29, 30] was found out to be closer to the IGISOL spectrum [16] than the Berkeley spectrum [27]. A comparison of these spectra is illustrated in Fig. 3.

^{23}Mg was known to have a level with $J^{\pi} \geq 3/2^{+}$ at 17 keV below the IAS already in Ref. [16]. Using shell-model calculations and the data obtained in Ref. [16] it was concluded that the spin and the parity of the state is not $3/2^{+}$, $5/2^{+}$ or $7/2^{+}$, i.e., allowed beta-decay is not populating it. This conclusion also meant that all observed 200-keV protons were associated to the decay of the IAS. This was, however, a wrong conclusion made due to the low statistics of the experiment. Namely, recent studies [28, 31] have assigned this state to be $(7/2)^{+}$ and to receive a β-feeding of 4.89(25) %. As also correctly predicted by shell-model calculations [16], this $(7/2)^{+}$ state primarily decays to the first excited state of ^{23}Mg at 450.71(15) keV. γ-rays with an energy of 7335.1 keV are associated to this transition [28]. The location of this line is marked into Fig. 2 (a). As shown, a small peak, almost at the level of the surrounding background, is visible, but it basically vanishes into the background when the full statistics is employed (Fig. 2b). Notice also, that due to the higher statistics and better energy resolution the more recent proton experiment (Fig. 3) assigned the lowest proton group to the 7787-keV state instead of the IAS.

Using a setup of four DSSSD - thick Si-pad telescopes, data from β-decay of ^{23}Al was measured at IGISOL during the calibration phases of another experiment in 2008. Improvements in the front-end after the first ^{23}Al experiment at IGISOL [16] increased the yield of ^{23}Al by a factor of around 35. This fact and the high efficiency of the setup enabled collection of sufficient statistics to observe 13 proton groups above the two main groups at 554 and 839 keV in only about 28 hours [32, 33]. One of these groups was observed in the earlier experiment [16]. β-tail in the spectrum caused by the isobars at $A = 23$ extended all the way up to 700 keV, preventing the studies of low-energy proton groups.

Soon after this experiment a high-precision mass measurement of ^{23}Al and ^{23}Mg ground states was done with JYFLTRAP. The resulting masses, reported in Ref. [34], were used to test the IMME at $A = 23$. The quadratic form of the IMME was found to hold well for this $T = 3/2$ quartet [34]. The new mass values also confirmed the Q_{EC} value deduced in Ref. [16].

3.2 ^{31}Cl

Beta-decay of ^{31}Cl has been previously studied with the He-jet technique at the MC-35 cyclotron of the University of Oslo [35] and at the Lawrence Berkeley Laboratory 88-inch Cyclotron [36,37] by using proton beam with an energy of 34 or 45 MeV on ZnS targets, respectively. In these studies, eight proton peaks in the energy range of 845 to 2204 keV and a half-life of 150(25) ms [35] have been observed. However, these He-jet experiments suffer from contaminants with different mass numbers, such as ^{32}Cl [35–37] and ^{25}Si [37]. Therefore, it was important to study the beta decay of ^{31}Cl at IGISOL where on-line mass-separation is used.

At IGISOL, γ-rays with energies of 1249.1(14) keV and 2234.5(8) keV corresponding to the de-excitations of the first two excited states in ^{31}S were measured [17]. In addition, weak γ peaks at 3536(2) and 4045(2) keV were observed. These γ transitions could correspond to the transitions between the $3/2^+$ IAS at 6268(10) keV [38,39] and from the $5/2^+$ state at 5777(5) keV [38,39] to the $5/2^+$ state at 2235.6(4) keV [38,39]. Thus, the deduced excitation energies of the IAS and the $5/2^+$ state are 6280(2) keV and 5772(2) keV, respectively [17]. In the proton spectrum, previously controversial proton peaks were confirmed to belong to ^{31}Cl and a new proton group with an energy of 762(14) keV was found [17]. Proton captures to this state at 6921(15) keV in ^{31}S contribute to the total reaction rate of $^{30}\mathrm{P}(\mathrm{p},\gamma)^{31}\mathrm{S}$ in ONe novae.

Whereas the previous studies of the beta decay of ^{31}Cl have aimed for determination of experimental Gamow-Teller strength distribution and its comparison to the shell-model predictions [36,37], the recent study has also been motivated by nuclear astrophysics. Namely, the reaction rate of $^{30}\mathrm{P}(\mathrm{p},\gamma)^{31}\mathrm{S}$ plays a key role in ONe novae. ^{30}P is a mandatory passing point to ^{32}S via $^{30}\mathrm{P}(\mathrm{p},\gamma)^{31}\mathrm{S}(\mathrm{p},\gamma)^{32}\mathrm{Cl}(\beta^+)^{32}\mathrm{S}$ or via $^{30}\mathrm{P}(\mathrm{p},\gamma)^{31}\mathrm{S}(\beta^+)^{31}\mathrm{P}(\mathrm{p},\gamma)^{32}\mathrm{S}$ [12]. With a half-life of about 2.5 min, ^{30}P stops further nucleosynthesis unless the proton captures are fast enough. In addition, the knowledge of the final abundance pattern is important for example in the identification of the possible nova origin of presolar grains [40,41]. Large excesses in $^{30}\mathrm{Si}/^{28}\mathrm{Si}$ and close-to-solar $^{29}\mathrm{Si}/^{28}\mathrm{Si}$ abundance ratios have been measured in these grains. In fact, the calculations based on several hydrodynamic nova simulations show that if the $^{30}\mathrm{P}(\mathrm{p},\gamma)$ rate is reduced by a factor of 100, an enhancement in ^{30}Si is obtained [12,42].

Since the direct study of this reaction rate is currently limited by the difficulty of producing an intense ^{30}P beam for studies in inverse kinematics, most of the experimental effort has been concentrated on the studies of the excitation energies of the states in ^{31}S either via β^+ decay [17] or different reactions, such as $^{12}\mathrm{C}(^{20}\mathrm{Ne},\mathrm{n})^{31}\mathrm{S}$ [43], $^{32}\mathrm{S}(\mathrm{p},\mathrm{d})^{31}\mathrm{S}$ [44], or $^{31}\mathrm{P}(^{3}\mathrm{He},\mathrm{t})^{31}\mathrm{S}$ [45–47]. Previously, the calculated reaction rates were based on statistical Hauser-Feshbach [48] calculations, which can have uncertainties as high as a factor of 100 up or down. In Ref. [43], a first evaluation of the

^{30}P(p, γ)^{31}S astrophysical reaction rate based on calculated resonant reaction rates of 13 experimentally determined states in ^{31}S was performed.

In the study of ^{32}S(p, d)^{31}S reactions [44], a total of 26 states including five new states in ^{31}S were observed and altogether 66 states were used for calculating a new ^{30}P(p, γ)^{31}S reaction rate. The new rate was found to differ from Hauser-Feshbach estimates by a factor of 10 and be comparable to previous estimates [43] in typical nova peak temperatures. Ma *et al.* [44] observed the states at 5781(5), 7728(4), 7912(5), 8049(6), and 8517(13) keV corresponding to the states at 5772(2), 7705(21), 7878(23), 8019(24), and 8509(30) keV measured via beta-decay at IGISOL [17]. The IAS at 6280(2) keV [17] was not populated in ^{32}S(p, d)^{31}S reactions [44].

The IAS ($T = 3/2$) state at 6280(2) keV [17] was confirmed in Ref. [45] where an excitation energy of 6283(2) keV was measured from the triton spectrum of the ^{31}P(^{3}He, t)^{31}S reaction. In a later publication on ^{31}P(^{3}He, t)^{31}S reactions measured at Yale University's Wright Nuclear Structure Laboratory [46], 17 new levels and 5 new tentative levels were found in ^{31}S. The obtained reaction rate for ^{30}P(p, γ)^{31}S [46] was about a factor of two larger than that from Refs. [43,44] for $0.4 \leq \mathrm{T} \leq 1.9$ GK. Above 1 GK the reaction rate calculated in Ref. [46] is a factor of seven larger than in Ref. [44].

All states observed in the beta decay of ^{31}Cl at IGISOL [17], were confirmed in Ref. [46], except the very weakly populated state at 8669(40) keV [17]. This peak was already marked as a smaller than a 3σ peak [17], and thus, it can be due to random statistical fluctuations. The beta-delayed proton peak observed at 1174(14) keV [17, 36] was assumed to correspond to the proton decay to the ^{30}P ground state, and an excitation energy of 7347(14) keV [17] was deduced for the state in ^{31}S. This was assumed to correspond to a known state at 7311(11) keV in ^{31}S. However, in Jenkins *et al.* [43,49], an excitation energy of 7302.8(7) keV and a spin $11/2^{+}$ was determined for the 7311(11) keV state. Thus, this state cannot be strongly fed in the beta decay of ^{31}Cl having a ground-state spin of $3/2^{+}$. Wrede *et al.* [46] have found that several states in ^{31}S proton decay also to states at 677.01(3) keV (0^{+}) and 708.70(3) keV (1^{+}) [50] in ^{30}P. They have also suggested that the 1174(14)-keV beta-delayed protons [17, 36] would result from a proton decay to the 0^{+} state at 677.01(3) keV in ^{30}P. Then, the corresponding excitation energy would be 8024(14) keV, close to the excitation energy of 8021(16) keV deduced from the 1826(15)-keV proton peak [17]. In future, coincidences of the beta-delayed protons with the γ-rays in ^{30}P should be searched for with better statistics.

The most recent study on ^{31}P(^{3}He, t)^{31}S reactions [47] performed at Maier-Leibnitz-Laboratorium (MLL) in Garching, Germany confirmed the results from previous (^{3}He, t) experiments. However, no evidence for the suggested doublets [46] at 6835 keV or 7030 keV was found. In addition, the angular distributions were analyzed and spin constraints were obtained for almost all critical states [47]. The hydrodynamic nova simulations performed in Ref. [47] show that the remaining uncertainties in the spin values and in the relevant proton spectroscopic factors may still lead to a factor of up to 20 variation in the proton capture rate on ^{30}P and a factor of up to four in the nova yields in the Si-Ar region.

The recent ^{31}P(^{3}He, t)^{31}S studies [45–47] have improved the precision of the IAS in ^{31}S. A weighted mean of 6283.2(8) keV [17,45–47] for the IAS can be utilized in a more precise IMME fit to the A = 31 $T = 3/2$ quartet. At JYFLTRAP, the ground state mass of ^{31}S has been measured very precisely, $-19042.55(24)$ keV [51], and found to deviate from the Atomic Mass Evaluation 2003 (AME03) [52] by more than 1σ. In this paper, we have adopted the mass of ^{31}S from Ref. [51], the mass of ^{31}P from Ref. [53], the latest value for the IAS in ^{31}S, and used otherwise the same, most recent results for the $T = 3/2$ quartet at A = 31, as in Ref. [54], and performed a new IMME fit. The resulting mass excess for ^{31}Cl is $-7048(5)$ keV, which is 10 keV higher than the value obtained in Ref. [54] and about 20 keV higher than in the AME03 [52]. In future, JYFLTRAP aims to measure the mass of ^{31}Cl produced via ^{32}S(p, 2n) reactions.

β-decay of ^{31}Cl has been studied also at Texas A&M in two experiments with a similar setup as in the case of ^{23}Al [29,30]. These experiments confirm the results of the IGISOL experiment [17] for the proton spectrum up to about 2 MeV, even though suffering from ^{29}S impurities and the fact that the higher-energy protons escaped the implantation detector. Final analysis of the proton data from these experiments is an ongoing process. The first experiment yielded a good statistics for $\beta\gamma$-data, see Ref. [55–57] for the preliminary results. In the second experiment, the γ-data were extended further by acquiring $\beta\gamma\gamma$-coincidences to allow building up more complete level scheme [57].

A more precise proton separation energy of ^{31}S, $S_p = 6130.95(39)$ keV, could be determined from the mass excess of ^{31}S measured at JYFLTRAP [51]. This new value deviates from the adopted AME03 value [52] by more than 1σ [51]. Taking into account the new proton separation energy and the new excitation energy for the $T = 3/2$ IAS in ^{31}S [17,45–47], β-delayed protons from the IAS should have laboratory energies of about 147.3(9) keV.

3.3 ^{41}Ti

Beta-decay of ^{41}Ti offers a possibility to study beta-decay strength over a wide energy range and compare the strength and its sum to the shell-model calculations in the crossing region of *sd* and *fp* shells. In addition, isospin mixing in the wave function of the $T = 3/2$ isobaric analog state (IAS), which makes the isospin-forbidden proton decay from the IAS possible, can be investigated.

Delayed proton emission following the beta-decay of ^{41}Ti was observed for the first time at Brookhaven National Laboratory [58,59]. Seventeen beta-delayed proton peaks of ^{41}Ti were observed and a half-life of 88(1) ms was determined [59]. Later, a high-resolution study of the ^{41}Ti decay was performed at Berkeley with the He-jet technique and $\Delta E - E$ counter telescopes [60,61]. A half-life of 80(2) ms and 27 proton peaks belonging to ^{41}Ti beta decay were observed [61]. Most of the peaks agreed with the peaks observed in Ref. [59]. The location of the lowest $T = 3/2$ in ^{41}Sc was determined as 5935(8)keV [60] disagreeing with the old ^{40}Ca(p, p) resonance measurements. Studies at Berkeley continued in the 1980s and six new beta-delayed proton peaks were found in Ref. [62]. ^{41}Ti was also used for calibration purposes in experiments at GSI and GANIL where half-lives of 81(4) ms [63] and 80.1(9) ms [64], respectively, were measured for ^{41}Ti.

In the experiment conducted at IGISOL, no beta- or proton-delayed γ-rays were observed [18]. Therefore, the intensities of the observed 25 proton peaks were directly proportional to the beta-decay transition intensities. For three peaks, beta-proton summing was taken into account in the analysis of peak intensities. The main differences from Ref. [61] were that the intensity of the 986-keV proton peak was about half of the one given in Ref. [61], the proton group just below 1.6 MeV was found to be a double peak, and the 2063-keV proton group was not detected at IGISOL. On the other hand, proton peaks with energies of 754(12), 1586(11), 4298, and 4684(11) keV not observed in Refs. [61,62] were observed at IGISOL [18]. Of these peaks, the 4684(11)-keV protons originate from a new level at an energy of 5886 keV [18].

Extensive shell-model calculations of the ^{41}Ti beta decay were performed with the code OXBASH [18]. The observed experimental decay strength was found to be 0.64 times the theoretical strength corresponding to a quenching factor of $\sqrt{0.64} = 0.80$. Theoretical Fermi strength of the β^+ decay to the IAS is $\mathrm{B(F)^{theor}} = \mathrm{T(T+1) - T_Z(T_Z+1)} = 3$ for $T = 3/2$ and $T_Z = -3/2$. Shell-model calculations give a Gamow-Teller strength of $\mathrm{B(GT)^{theor}} = 0.302$ to the IAS, which yields an estimate of $\mathrm{B(GT)^{exp}} = 0.18$ for the experimental decay strength after correction due to the quenching. The experimentally observed total decay strength to the IAS was $\mathrm{B(F)^{exp}} + \mathrm{B(GT)^{exp}} = 2.87(22)$ [18], thus yielding a value of $\mathrm{B(F)^{exp}} = 2.87(22) - 0.18 \approx 2.69(22)$ for the experimental Fermi strength. This can be explained by the isospin impurity of the IAS. Namely, if there is a state with $J^\pi = \frac{3}{2}^+, T = \frac{1}{2}$ near the IAS ($J^\pi = \frac{3}{2}^+, T = \frac{3}{2}$), the isospins $T = \frac{3}{2}$ and $T = \frac{1}{2}$ of these near-lying states can mix with each other with an amplitude b according to a simple perturbation theory. Then, the perturbed IAS has a structure $a|T = \frac{3}{2}\rangle + b|T = \frac{1}{2}\rangle$ and the other state is $a|T = \frac{1}{2}\rangle - b|T = \frac{3}{2}\rangle$, where $|b| = \sqrt{1 - a^2}$. In order to explain the observed Fermi strength, a fraction $b^2 = 10(8)$ % of the Fermi strength of the IAS ($\mathrm{B(F)^{theor}} = 3$) is shifted to this other state.

After the experiment performed at IGISOL, beta decay of ^{41}Ti has been studied at GSI [65]. The isotopically separated ^{41}Ti beam from FRS was implanted into a silicon detector stack consisting of eight 300 μm thick, 30-mm diameter Si detectors [65]. An array of 14 large-volume Crystal Ball NaI detectors were used to measure emitted γ rays [65]. The energy resolution of around $40 - 100$ keV [65] was worse than at IGISOL, and some of the peaks observed at IGISOL [18] could not be resolved. In Ref. [65], the total number of implanted ^{41}Ti ions could be deduced from the ΔE versus A/q data after correction for the intensity loss due to secondary reactions in the energy degrader at F_4 [65]. In addition, proton-γ coincidence data were collected and five transitions were assigned to populate the 3904-keV state in ^{40}Ca [65]. With the absolute counting of ^{41}Ti ions and proton-γ coincidence data, Liu *et al.* [65] obtain significantly larger B(GT) values at high excitation energies in ^{41}Sc than at IGISOL [18] where the branching ratios were based on the total number of observed protons. The total experimental B(GT) of 3.6(5) determined at IGISOL [18] is also smaller than the value obtained at GSI, 4.83(29) [65].

The GT strength obtained for the transitions in the beta decay of ^{41}Ti ($T_Z = -3/2$) to the states in ^{41}Sc ($T_Z = -1/2$), $\mathrm{B(GT)}_\beta$, can be interestingly compared to the strength $\mathrm{B(GT)_{CE}}$ obtained for analogous transitions from ^{41}K ($T_Z = +3/2$) to ^{41}Ca($T_Z = +1/2$) via $^{41}\mathrm{K}(^3\mathrm{He,t})^{41}\mathrm{Ca}$ charge-exchange reactions at 0° [1]. Assuming isospin symmetry, these transitions should have equal energies and strengths. The 35-keV energy resolution of the observed tritons at the Grand Raiden spectrometer at the Research Center for Nuclear Physics (RCNP) allowed to resolve states of ^{41}Ca up to an excitation energy of $\mathrm{E_x} = 10$ MeV [1]. The beta-decay study of ^{41}Ti conducted at IGISOL had a similar energy resolution of around 30 keV and states up to around 8 MeV in ^{41}Sc were populated, which offered a possibility to compare the observed Gamow-Teller strengths in detail. The determination of the Gamow-Teller strength in the charge-exchange reactions relies on the approximate proportionality of the reaction cross sections measured at the scattering angle 0° and their B(GT) values. In order to normalize this proportionality, a B(GT) value known well from beta-decay studies is

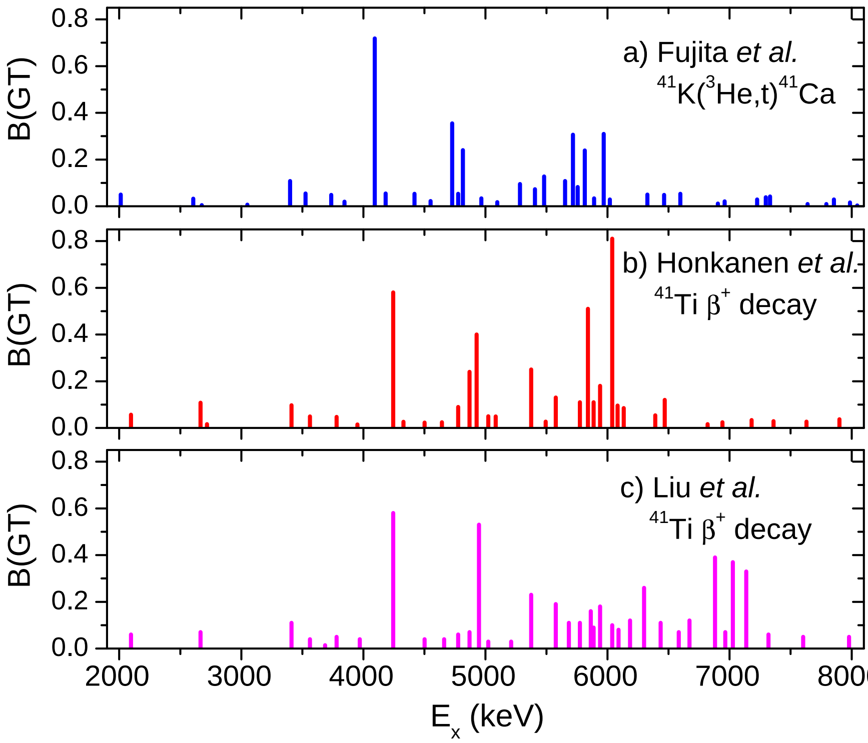

Fig. 4 Experimental B(GT) distributions for $T_Z = \pm 3/2 \rightarrow T_Z = \pm 1/2$ isospin mirror transitions from Refs. [1, 18, 65].

typically used. For the A = 41 system, such well-known beta transition does not exist. Therefore, the total sum of the $\mathrm{B(GT)_{CE}}$ was normalized to the total sum of $\mathrm{B(GT)}_\beta$, which was obtained as an average from Refs. [18, 65]. The transition to the IAS in ^{41}Ca contains both Fermi and GT components, and the $\mathrm{B(GT)_{CE}}$ was estimated to be 0.24(4). If a similar isospin impurity of 10(8) % [18] is assumed as for ^{41}Sc, the $\mathrm{B(GT)_{CE}}$ value would be increased by 0.055(45).

The $\mathrm{B(GT)_{CE}}$ distribution [1] is quite similar to the $\mathrm{B(GT)}_\beta$ distribution obtained at IGISOL [18] (see Fig. 4). Almost one-to-one correspondence of the observed states and GT transition strengths to them is observed up to around 6 MeV. The energy resolution of around $40 - 100$ keV in Ref. [65] did not allow a good comparison to the charge-exchange reactions. In addition, the observed rather strong GT strength to states around 7 MeV in ^{41}Sc [65] was not observed via charge-exchange reactions to ^{41}Ca [1] nor at IGISOL [18]. Most probable J^π values were deduced for each analog pair, which lead to a confirmation of $J^\pi = 1/2^+$ for the states at 3951(14) and 6038(25) keV, $J^\pi = 3/2^+$ for the states at 3562.6(3), 5576(4) and 5939(4) keV, and $J^\pi = 5/2^+$ for the states at 4928(5), 5774(4), 5840(5) and 5886(12) keV suggested as $1/2^+, 3/2^+, 5/2^+$ states in the beta-decay study at IGISOL [18]. The main part of the GT strength was found to the $5/2^+$ states in charge-exchange reactions [1].

Mass of ^{41}Ti has been directly measured at the FRS-ESR facility at GSI [66]. However, the obtained precision for the mass excess, $-15090(360)$ keV, is rather poor compared to Penning trap measurements. In future, the mass of ^{41}Ti could be measured with the purification trap of JYFLTRAP (as was done e.g. for ^{97}Kr at ISOLTRAP [67]) if the half-life is too short for precision trap measurements.

4 Discussion

Various experiments on beta decays of other $T_Z = -3/2$, $A = 4n+1$ nuclei than ^{41}Ti have been performed in the past: ^{9}C [68], ^{13}O [69], ^{17}Ne [70], ^{21}Mg [62], ^{25}Si [71,72], ^{29}S[62], ^{33}Ar [73], ^{37}Ca [74], ^{49}Fe [63], ^{53}Ni [75], and ^{57}Zn [76] (only the most recent references given). In addition to ^{23}Al and ^{31}Cl, $T_Z = -3/2$, $A = 4n+3$ nuclei such as ^{27}P [37], ^{35}K [77,78], ^{43}V, and ^{47}Mn [63] have been studied. At IGISOL, some of these beta decays could be investigated in future. JYFLTRAP mass spectrometer could be applied for example in the direct mass measurement of ^{31}Cl. Future measurements on these nuclei are also motivated by possible one-proton halos in ^{17}Ne, ^{23}Al,^{31}Cl, and ^{35}K, and two-proton halos in ^{9}C and ^{13}O [79].

Straightforward experimental interpretation of the low-energy part of the ^{23}Al β-delayed proton spectrum, around 200 keV, is a challenging task. To distinguish unambiguously protons from the IAS and the neighboring 7787 keV state a detection setup that has a particle identification capability, excellent proton-energy resolution and a thin dead-layer is required. The challenge is similar in the case of β-decay of ^{31}Cl, where the β-delayed protons from the IAS have energy of about 145 keV as discussed in section 3.2.

This is a non-trivial experimental challenge. For example, with the telescope used in the studies of ^{23}Al and ^{41}Ti decays at IGISOL, the lower energy limit was about 160 keV. Even the high-end DSSSDs with ultra-thin dead layers have the detection thresholds around 150-200 keV, mostly due to the electronics noise in the measurement area. In addition, reducing the β-background requires extremely pure source, preferably with capability of removing the activity from the following daughter decays. In the future these requirements could possibly be fulfilled at IGISOL by combing a Penning trap and a micro-calorimeter detector [80] that employs digital electronics.

Novel detector assemblies could provide cleaner spectra and better energy resolution in future. An energy resolution of 1.06 keV, excellent compared to modern silicon detectors with resolutions of around 8.8 keV, has been achieved for 5.3-MeV alpha particles with a cryogenic microcalorimeter detector [81]. A microcalorimeter is based on the conversion of the particle's kinetic energy into thermal excitations in a tin absorber. The temperature change is measured with a superconducting transition edge sensor (TES) at its superconducting transition temperature of 140 mK where a small change in temperature results in a large change in resistance. An advantage of this technique is that it does not suffer from the surface dead layer effect but the disadvantage is the required low temperature. Typically, an adiabatic demagnetization refrigerator at 80 mK is used for a copper mount, and the TES is heated into its resistive transition by electrical bias [81]. This method requires that the sample is cooled and maintained at 80 mK in the same vacuum as the microcalorimeter. Therefore, it is not suitable for on-line experiments where the sample should be implanted and moved in short time periods unless a clever way to maintain the low temperature for TES is invented. Microcalorimeters can also be used for detecting γ-rays: a 47-eV resolution was achieved for a 103-keV γ-peak [82]. Major drawback of this method is that these microcalorimeters are small (≈ 1 mm^2) and slow ($50-100$ counts/s), and a large array of these microcalorimeters would be required for decent efficiency.

After the IGISOL upgrade in 2002-2003 [83] (including e.g. higher pumping efficiency, better radiation shielding to fully gain the high-intensity light ion beams, and improved gas purification control) and after the replacement of the skimmer by SPIG [14], the yields have increased a lot. For example, with a $8-10$ μA, 40-MeV proton beam on $^{\mathrm{nat}}$Mg, yields of 700 atoms/s and 150000 atoms/s were observed for ^{23}Al and ^{23}Mg, respectively [34]. Thus, the production rates of ^{23}Al and ^{23}Mg were about 35 times higher than with the skimmer at the old IGISOL facility. Similar improvement for the production of ^{41}Ti can also be expected. ^{31}Cl was measured already after the IGISOL upgrade using the skimmer. The introduction of SPIG should increase the chlorine yields with a factor of about $4-10$, as reported in Ref. [14] .

The production of ^{31}Cl has been challenging at IGISOL. This is seen for example from the production rates of ^{23}Al and ^{31}Cl produced via similar $(p, 2n)$ reactions at IGISOL: the yield of ^{23}Al has been higher than for ^{31}Cl (see Sect. 2.1). Chlorine is a halogen and it has a high electron affinity of 3.612724(27) eV [84] (compare to 0.43283(5) eV [85] for Al). ^{31}Cl is, unfortunately, in the mass region where major molecular contaminant beams are present in form of different nitrogen and oxide compounds. These molecular beams, e.g. ^{15}N^{16}O, arise mostly from either dirty He-gas or leaks in the gas feeding system. In the past these background beams have been so intense that they have overloaded the Penning trap and thus prevented even purification of the samples for mass measurements. Improvements for the gas-feeding system and He-gas purification for the new IGISOL facility are in the high priority, thus making measurements around $A = 30$ region with the JYFLTRAP a more viable venture. In future, it would be interesting to study the fraction of negative chlorine ions produced at IGISOL and to search for possibilities to produce a beam of these negative ions.

The experiments performed at IGISOL providing mass-separated, thin sources of short-lived nuclei have demonstrated the potential of high-resolution detection technique for β-delayed protons and γ-rays. Taking into account the expected improvement in the yields, these experiments also pave the way for the studies of more exotic nuclei, such as ^{22}Al and ^{40}Ti. ^{22}Al has a very exotic and interesting β-delayed decay spectrum from γ-rays to two-proton and alpha emissions. The decay of ^{40}Ti has significance in determining the detection efficiency of the ICARUS detector for the study of solar neutrinos by utilizing the inverse β-decay of ^{40}Ar. These two nuclei have earlier been studied using the He-Jet technique [86,87], fragment separator at GANIL [75,88, 89] and FRS at GSI [65]. The new IGISOL facility may offer an alternative way for studying these nuclei.

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