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# Study of level structure on $^{26}$Si for the astrophysical interest in $^{26}$Al production

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A radio-isotope of $^{26g}$Al (where g is expressing the ground state) is known as a γ-ray emitter spreading in the Milky Way galaxy. Since the half-life is only $7.2 \times 10^5$ year this is the obvious evidence of ongoing nucleosynthesis in our galaxy. This isotope is also known as an origin of abundance-anomaly of $^{26}$Mg observed in meteorites. Therefore, investigations of production rates for the $^{26g}$Al are quite important for the nucleosynthesis occurring in massive star, classical nova and super nova. Although, there is still some uncertainties in the nuclear structure of $^{26}$Si which is located at the bypass sequence producing the isomeric state $^{26m}$Al (where m is expressing the metastable 1st excited state). For the comprehensive understanding of the nuclear reaction rate to produce the $^{26g}$Al, we have done γ-ray spectroscopy to investigate the level structure for the $^{26}$Si. We confirmed the presence of a recently proposed level located just above the proton threshold. Furthermore, as a result of the gamma-ray angular correlation measurements we could assign the spin of this level as $0^+$.

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## 1. Introduction

Recent observations of 1.809MeV γ-rays by balloon and satellite observatories[1-3] revealed that the γ-ray emitters of $^{26g}$Al are spreading over the Milky Way and rotating with its motion[3]. Since the half-life of the $^{26g}$Al is only $7.2 \times 10^5$ year, it surely proves that the nucleosynthesis is still proceeding in our galaxy. Origin of the $^{26g}$Al could be considered to be massive stars like as Wolf Rayet stars and/or super novae. Classical novae could also have some contribution of the abundance[4]. This isotope is also known as an origin of abundance-anomaly of $^{26}$Mg found in meteorites[5]. The theoretical calculation to reproduce the abundance of the $^{26g}$Al is quite important for the study of nucleosynthesis. However, there are still uncertainties of the reaction rates specially concerning about excited structure of $^{26}$Si which is located at a bypass sequence to produce the isomeric state $^{26m}$Al[6] as shown in Fig. 1. Once the $^{26}$Si decays into the $^{26m}$Al this state directly feeds into the ground state of $^{26}$Mg without the 1.809MeV gamma ray emission. For the comprehensive knowledge of the production of the $^{26g}$Al, we have done γ-ray spectroscopy to investigate the level structure of $^{26}$Si.

Creation of the $^{26g}$Al would be proceeding by a reaction of $^{25}$Al($e^+\nu$)$^{25}$Mg($p$, γ)$^{26g}$Al. Whereas, if the circumstance is high temperature like as super novae or classical novae, another bypass sequence opens to be $^{25}$Al($p$, γ)$^{26}$Si($e^+\nu$)$^{26m}$Al($e^+\nu$)$^{26}$Mg where the reaction flow reaches to the isomeric (metastable) state $0^+$ ($T_{1/2}$ = 6.3 sec) of $^{26m}$Al and feeds directly into the ground state of $^{26}$Mg. Therefore, if the $^{26}$Si is created the 1.809-MeV γ–ray cannot be emitted as shown in Fig. 1.

The reaction flow of $^{25}$Al($p$, γ)$^{26}$Si is considered as admixture of a direct process and resonant captures[6]. Because spins of $^{25}$Al and proton are $5/2^+$ and $1/2^+$, respectively, the predominant flow might proceed through $3^+$ just above the proton threshold in $^{26}$Si[6,7]. There are many efforts to seek the states by using neutron TOF[8], light ion reaction studies[9-14], β-delayed proton emission spectroscopy[16] and γ-ray spectroscopies[16]. Indeed, extensive studies with radioactive ion beams have been reported[17-19]. Furthermore, there are several brief reports proposing a new level around $E_x$ = 5.888-MeV[20,21]. In order to investigate the level structure of the $^{26}$Si we have carried out in-beam γ-ray spectroscopy at University of Tsukuba.

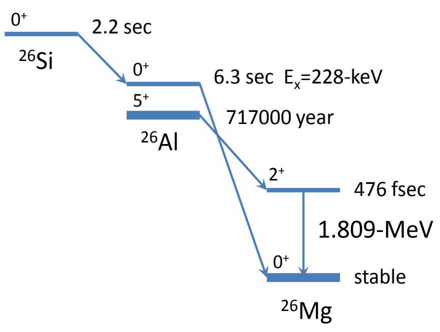


Fig. 1. A sequence through $^{26}$Si feeding into a 6.3 sec isomeric state $^{26m}$Al where the 1.809-MeV γ-ray cannot be emitted. Decay of the ground state $^{26g}$Al is also shown with the 1.809-MeV γ-ray emission.

## 2.Experimental procedure

Present in-beam γ-ray spectroscopy experiments include γ–ray singles, angular distribution, γ-γ and γ-γ-*n* coincidences which are performed using the $^{24}$Mg($^{3}$He,*n*)$^{26}$Si reaction at the University of Tsukuba Tandem Accelerator Complex (UTTAC). A $^{3}$He beam of 10 MeV was irradiated on a natural magnesium target, where the abundance of the $^{24}$Mg is 78.99%. As the nuclear reactions between the magnesium and $^{3}$He, many other reaction channels opened into $^{23}$Mg, $^{24}$Mg, $^{25}$Mg, $^{26}$Mg, $^{25}$Al, $^{26}$Al, and $^{28}$Si. Probability to produce the $^{26}$Si was estimated to be only 1% of total fusion cross section. However the measurements of γ-γ and γ-γ-*n* coincidences can clearly identify transitions of the $^{26}$Si by using high resolution germanium detectors.

For the measurements of γ-rays, because the most important γ-transition is expected around 4-MeV, we used rather large high purity germanium (HPGe) detectors whose efficiencies are 140%, 70% and 50% relative to the efficiency of 3-inch × 3-inch NaI detector. For the neutron detection we used two liquid scintillation detectors located at nearly zero degree with respect to the beam axis. The angular distribution measurement of γ–ray singles has been carried out at the angles of 90 º, 100 º, 110 º, 120 º, 130 º, and 140 º for the 1797.5-keV transition as described in the following sub-section. The angular correlation measurement has been performed with two Ge detectors which were located at either $(\theta_1,\varphi_1,\theta_2,\varphi_2)$=(90 º,0 º,90 º,180 º) or (90 º,0 º,135 º,180 º) . Ratios of the measured intensities defined as $r = I(90^\circ,0^\circ,135^\circ,180^\circ)/I(90^\circ,0^\circ,90^\circ,180^\circ)$ called as DCO ratios were evaluated and compared with theoretical calculations[22].

The energies and efficiencies of the detectors were calibrated using standard radioactive sources of $^{56}$Co and $^{152}$Eu. Furthermore, γ-rays emitted from $^{25}$Mg, $^{26}$Mg, and $^{26}$Al which are the by-products from the natural magnesium + $^{3}$He reactions were also used for the energy calibration. The systematical uncertainty for γ-ray energy is estimated to be 0.5 keV for the energy region between 400 and 3200 keV. This is also estimated to be 0.8 keV around 4000 keV where the estimation includes additional uncertainties derived from the quadrant term applying outside of the calibration points[22].

## 3. Levels structure

In-beam γ-ray spectroscopic studies for $^{26}$Si were reported by Rolfs[23], Bell[24], and recently by Seweryniak[16] with GAMMASPHERE. Furthermore there are several brief reports[20,21] proposing a new level around 5888-keV which would be one of the most important levels for the resonant reaction rate to create $^{26}$Si. We confirmed all of levels observed by Seweryniak[16]. However, levels at 3842- and 4093- keV reported by Rolfs and at 3820-keV by Bell could not be assigned. Those levels were neither reported by Seweryniak[16]. Moreover, we confirmed the 4091.1-keV transition, which Rofls firstly observed and attributed to the 4093-keV level. This corrected placement agrees with the recent brief reports[20,21]. The spin of the 5888.6-keV level was assigned as $0^+$ from the γ-γ angular correlation measurement[22].

### 3.1 1797.5-keV level

The 1797.5-keV level is the 1$^{st}$ excited state of $^{26}$Si that has a spin of $2^+$ and it emits 1797.5-keV transition which is well observed in our neutron coincidence spectrum. This

$\gamma$-ray is only one belonged to $^{26}$Si which can be clearly observed in the singles measurements. Then, $\gamma$-ray angular distribution measurement has been carried out for this 1797.5-keV transition. However, the singles spectrum measured at large angles around 140 º shows serious Doppler broadening shape[22]. Furthermore, the measured result of the $\gamma$-ray angular distribution was strongly distorted and quite different from typical stretched E2 transition of $2 \rightarrow 0$[22]. Unknown strong perturbation might occur inside of the magnesium target to distort the angular distribution. For this reason, rather large value of $\sigma/J = 2$ is adapted for the initial population of magnetic sub-state in the analysis of the $\gamma$-$\gamma$ angular correlation[22].

### 3.2 2786.8-keV level

This level is the second excited state of $^{26}$Si having spin of $2^+$ and feeding into both the 1$^{st}$ and the ground states emitting 989.1- and 2786.9-keV transitions, respectively. The 989.1-keV $\gamma$-ray has been clearly seen in the neutron coincidence spectrum. This $\gamma$-ray has also been observed in the singles spectra, however, the peak is known to make a doublet with 989.9-keV transition of $^{25}$Mg. Then the angular distribution of the singles measurement couldn't have proper information for the spin assignment.

The 989.1-keV transition has the second strongest intensity in all of $\gamma$-rays of $^{26}$Si, so that the gated spectrum by this $\gamma$-ray is clean and informative. This transition is known as M1/E2 mixed transition having the mixing ratio $\delta = -0.21 \pm 0.10$ by Rolfs[23] in their neutron coincident angular distribution measurement. In our analysis of the angular correlation measurements, this value is adapted as the calibration[22].

### 3.3 3335.6-keV level

This level is known as $0^+$ state feeding into the 1$^{st}$ excited state through 1538.1-keV transition. The intensity of this transition is the third strongest in our $\gamma$-ray intensity table which is 32.2% of the strongest 1797.5-keV transition. Seweryniak[16] reported that the intensity of this transition is only 2.6% of the 1797.5-keV transition. This difference could be due to the entrance-angular-momentum-window of fusion reactions. Seweryniak used the $^{12}$C($^{16}$O,2*n*)$^{26}$Si reaction. The maximum angular momenta can be estimated to be 5.0 and 16.2 $\hbar$ for the present study and Seweryniak's, respectively.

### 3.4 3757.9-keV level

This level emits 971.1- and 1960.4-keV transitions and agrees with the reports by Bell[24] and Seweryniak[16]. Measured ratios of angular correlation for the 1960.4-1797.5-keV cascade is consistent to the $3^+$ assignment[22].

### 3.5 4139.1-keV level

This level emits 1351.9- and 2341.6-keV transitions and is consistent to reports done by Rolfs[23], Bell[24] and Seweryniak[16]. They also reported one more transition having an energy of 4441-keV connecting to the ground state.

### 3.6 4186.1-, 4445.4-, and 4795.1-keV level

The 4186.1-keV level emits 1400.5- and 2387.4-keV transitions. This location is consistent to the Seweryniak's report[16]. The 4445.4-keV level is observed by emitting

2647.9-keV transition connecting to the 1st excited state. This level was firstly reported by Bell[24]. Severyniak observed other transition having 1660-keV fed into 2786-keV level which cannot be observed in our results. The 4795.1-keV level is observed to feed into the 1st excited state through 2997.6-keV γ-ray which has firstly been reported by Seweryniak[16].

### 3.7 4808.7- and 4830.6-keV levels

The 4808.7- and 4830.6-keV levels are decaying into the 2nd excited state by emitting 2012.9- and 2043.8-keV γ-rays, respectively. Spin assignments of both levels were only tentatively given by Seweryniak from the discussion of the intensity balance. We have confirmed these spin assignments by our angular correlation results[22] to be $2^+$ and $0^+$, respectively.

### 3.8 5144.0-, 5286.8, and 5517.2-keV level

These levels were firstly reported by Seweryniak[16]. We observed almost the same cascade relations. However, a few transitions in his report[16] cannot be observed in our coincidence matrix.

### 3.9 5672.3-keV level

This level is one of the most important levels for the nucleosynthesis of $^{26}$Si which are just located above the proton threshold. The level was firstly reported by Parpottas with his neutron TOF spectra. He assigned its spin as $1^+$ comparing its cross-section with Hauser-Feshbach calculation. Seweryniak[16] has observed the 3879-keV transition by using GAMMASPHERE detector array combined with a recoil mass analyzer. However, no information of either γ-ray angular distribution or angular correlation has been reported. We observed 3874.8-keV transition which agrees with the previous reports. Our result of the angular correlation can support its $1^+$ spin assignment[22].

### 3.10 5888.6-keV level

As the result of the present study, the newly proposed level[20,21] at 5888.6-keV has been confirmed. This level is emitting 3101.6- and 4091.1-keV γ-rays feeding into the 1st and the ground states, respectively. On the other hand the 4095-keV gamma ray was observed to belong to $^{26}$Si by Bell[24], he allocated it to the different level at 4095-keV which cannot be observed in our result. Then, we verified the previous reports[20,21]. However, there is a discrepancy that de Séréville[21] reported a rather strong γ-transition having an energy of 1750-keV decaying from this level to the 4139-keV level in his neutron coincident γ-ray spectrum.

Spin assignment of this level was performed by angular correlation measurements. We observed that the ratio for the 4091.1 - 1797.5-keV cascade is quit similar to those for 1538.1 – 1797.5-keV cascade which is known as $0 \rightarrow 2 \rightarrow 0$ cascade. A calculated value with consideration of finite solid angle of detectors also agrees with this observation. Then, we confirmed spin of the level is $0^+$.

By comparison with shell model calculation and states of mirror nucleus $^{26}$Mg, there could be three levels just above the proton threshold which are $0^+$, $1^+$ and $3^+$[6]. Parpottas[7] reported a state at 5946-keV as rather faint peak in his neutron TOF spectrum and assigned as $0^+$ from the comparison with Hauser-Feshbach calculation. However, there is no more report to support his observation, except Caggiano's report done by ($^3$He, $^6$He) reaction[8].

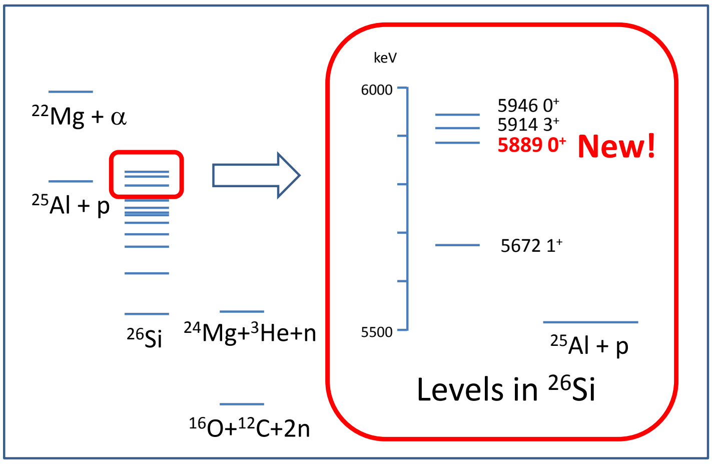


Fig. 2 Levels just above the proton threshold in $^{26}$Si.

## 4. Summary

For the study of nucleosynthesis of $^{26g}$Al, level structure of $^{26}$Si has been investigated via in-beam γ-ray spectroscopy. Existence of the newly proposed level[20,21] at 5888.6 ± 0.9-keV has been confirmed. Spin parity of this level has been newly determined as $0^+$ by the angular correlation measurements[22].

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