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Study of astrophysically important resonant states in ^{26}Si by the ^{28}Si(^{4}He,^{6}He)^{26}Si reaction

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The emission of 1.809 MeV gamma-ray from the first excited state of ^{26}Mg followed by beta-decay of ^{26}Al in its ground state (denoted as $^{26}\mathrm{Al}_{g.s.}$) has been identified by gamma-ray telescopes such the Compton Gamma-Ray Observatory (CGRO) [1]. To resolve controversy over the possible sources of the observational 1.809 MeV gamma-rays, one needs accurate knowledge of the production rate of ^{26}Al. The ^{25}Al(p,γ)^{26}Si reaction which is the competition reaction for production of $^{26}\mathrm{Al}_{g.s.}$ is one of the important subjects to be investigated. In this work, the astrophysically important ^{26}Si states above the proton threshold were studied via the ^{28}Si(^{4}He,^{6}He)^{26}Si reaction. We have preformed an angular distribution measurement using the high resolution QDD spectrograph (PA) at Center for Nuclear Study (CNS), University of Tokyo. The experimental results and data analysis will be presented.

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1. Introduction

^{26}Al is the first cosmic radioactivity ever detected through its characteristic 1.809 MeV γ-ray line. Since the β-decay life time of ^{26}Al ($t_{1/2}$ = 7.17 $\times$ 10^5 yr) is much shorter than the time scale of galactic chemical evolution ($\approx 10^{10}$ year), the observation of large amounts ($\sim 3\ M_\odot$) 1.809 MeV γ-ray in the Galaxy [2] is strong evidence that the process of nucleosynthesis is currently active. One possible source for the production of $^{26}Al_{g.s.}$ is nova explosion [3]. Under the explosive hydrogen burning conditions in nova site, the production proceeds via the reaction sequence

$$^{25}Al(\beta^+\nu)^{25}Mg(p,\gamma)^{26}Al^{g.s.}(\beta^+\nu)^{26}Mg^*(\gamma)^{26}Mg^{g.s.}$$

However, if the proton capture rate on ^{25}Al is faster than β-decay rate of ^{25}Al, above reaction sequence is bypassed by

$$^{25}Al(p,\gamma)^{26}Si(\beta^+\nu)^{26}Al^m(\beta^+\nu)^{26}Mg^{g.s.}$$

reaction sequence. With shell model calculations and mirror nucleus consideration using past data, Illiadis *et al.* [4] suggested that the ^{25}Al$(p,\gamma)^{26}$Si reaction should be dominated by the 3^+ unnatural parity state (E_x=5970(100) keV) under explosive hydrogen burning process in nova. Recent studies of ^{28}Si(*p,t*)^{26}Si [5], ^{24}Mg(^{3}*He,n*γ)^{26}Si [6], and ^{29}Si(^{3}*He*,^{6}*He*)^{26}Si [7] reduced the uncertainties in the ^{26}Si levels above the proton threshold and identified new states as candidates for the unnatural parity states. Also precise mass measurement of ^{26}Si via ^{28}Si(*p,t*)^{26}Si reaction has been performed [8]. However, for such candidates, they could not make any spin assignment directly using the angular distribution measurement. In present work, we decided to study the astrophysically important resonant states in ^{26}Si via the ^{28}Si(^{4}*He*,^{6}*He*)^{26}Si reaction which could excite unnatural parity state directly, in contrast with the (*p,t*) reaction that cannot excite unnatural parity state.

2. Experimental procedure

The ^{28}Si(^{4}*He*,^{6}*He*)^{26}Si reaction was studied using the high resolution QDD(quadrupole-dipole-dipole)-type magnetic spectrograph (PA) at Center for Nuclear Study (CNS), University of Tokyo. Recently PA has been connected to RIKEN accelerator facility which consists of Ring Cyclotron (RRC) and Linear Accelerator (RILAC). The intrinsic momentum resolution of PA is given by Δp/p $\sim$ 0.01%. However, in the test experiment after installation, the momentum resolution was measured to be 0.1% in FWHM (Full Width at Half Maximum). In order to derive the best condition of a magnetic spectrograph, first of all, the beam condition of accelerator and spectrograph at the target position should be matched. The dispersion matching method [9] has been used to realize this. To find the optimized beam transport parameters for dispersion matching, we simulated the beam transportation with the TRANSPORT code[10]. We tested the dispersion matching beam transportation with ^{12}C(^{4}He,^{4}He)^{12}C reaction at 10 degrees of PA angle. As a result, for elastic scattered alphas, we achieved Δp/p $\sim$ 0.017% which is enough to study ^{28}Si(^{4}*He*,^{6}*He*)^{26}Si reaction.

A beam of ^{4}He at 120 MeV was extracted from RIKEN linear accelerator (RILAC) + RIKEN ring cyclotron (RRC). Beam intensity was typically 70 enA at the target position. A self-supporting

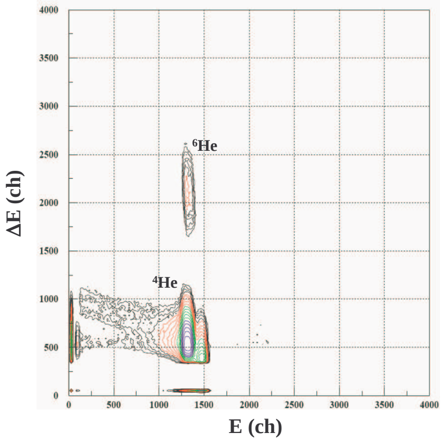

Figure 1: Two-dimensional spectra of ΔE-E, measured at 8°. ΔE and E represent the first energy loss gas counter and thick scintillator, respectively. The contour levels are in logarithmic steps. As shown, ^{6}He could be clearly discriminated from other particles.

natural silicon target (thickness $\sim$ 1 mg/cm^2) was used to populate states in ^{26}Si. To avoid the contamination from elastically scattered ^{4}He which could be the main source of contamination due to its large cross section, the magnetic parameters of the PA were set to bend the elastically scattered ^{4}He beam off from the effective region of the focal plane detection system. Consequently the spectra were free from the contamination of elastically and inelastically scattered ^{4}He.

The focal plane detection system consisted of a hybrid gas counter and plastic scintillators. Four proportional gas counters, which were two position counters (X1 and X2) and two energy loss counters (ΔE1 and ΔE2) were installed in the hybrid drift chamber. We determine the excitation energies of the levels in ^{26}Si from the position information on the focal plane. The position corresponds to the linear momenta of incident particles. The position counters give precise position information by charge division method. The relation between the position and charges from the both ends of counters is expressed as follows:

$$x = \alpha \times \frac{X^{high}}{X^{low} + X^{high}} + \beta. \tag{2.1}$$

where,x stands for the position. $X^{high(low)}$ represents for output signals from the high (low) momentum side of the position counter. α and β are constants. The plastic scintillators consisted of thin (0.5 mm) and thick (10 mm) scintillators as ΔE and E detectors, respectively.

For the particle identification, we used six ΔE-E information : ΔE1-E, ΔE2-E, ΔE-E, (L1+H1, sum of lower and higher momentum side signals for X1)-E, and (L2+H2)-E. Also we used time-of-flight (TOF) information with RF signal from accelerator and vertical position information. The vertical position information on the focal plane could be deduced by the time difference between the fast energy signal from thick plastic scintillator (E) and the slow energy loss signal from gas counters (ΔE1 and ΔE2). Using these information, we could clearly identify ^{6}He (Fig 1).

3. Results

To get the information for the level structure in ^{26}Si, we have measured the angular distribution

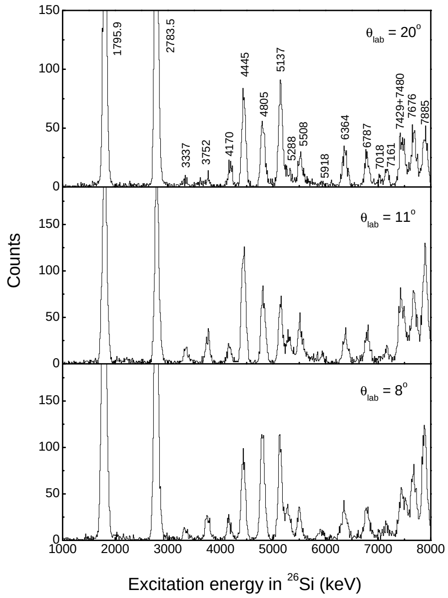

Figure 2: Calibrated ^{26}Si excitation energy spectra are shown. The position information at focal plane was calibrated by the well-known peaks.

at θ_{lab} = 8°, 11°, 15°, and 20°. The overall energy resolution was 100 keV (FWHM). Figure 2 shows the calibrated excitation energy spectra. The well-known states that were populated and observed in the ^{28}Si(^{4}*He*,^{6}*He*)^{26}Si reaction were used to calibrate with a quadratic polynomial function (due to the relation between the energies and linear momenta) of the focal plane detector position representing the linear momentum. Using the calibration function, at each angle, we converted focal plane position into excitation energies in ^{26}Si. Then we determined excitation energies using the weighted average value method. The states used for calibration were the ground state and excited states in ^{26}Si at 0, 1795.9(0.2), 2783.5(0.4), 4445(3), and 4805(2) keV [11]. The uncertainties of excitation energies were determined mainly by uncertainty in determining the ^{6}He peak channels. The excitation energies in^{26}Si (E_x > 5.5 MeV) are given in Table 1. The excitation energies below the E_x = 5.5 MeV agree well with those from previous experimental results [5, 6, 7]. For E_x = 7676(4) keV and 7885(4) keV, our results reduce the uncertainties in the excitation energies. We confirmed 7019(6) keV state which was observed only in (p,t) reaction study [5]. For 3^+ resonant state, the study of *(^{3}He,^{6}He)* reaction [7] suggested spin-parity assignment of 3^+ for the 5945 keV state by Coulomb shift calculation. The study of *(^{3}He,nγ)* reaction [6] suggested 5912 keV as a 3^+ resonant state based on the comparison between the measured differential cross section with Hauser-Feshbach calculations. However, the (p,t) reaction study [5] assigned directly 5916 keV as a 0^+ state by the distorted-wave Born approximation (DWBA) analysis. We observed 5918 keV state in our measurement within the error bar. To clarify this level information clearly, spin-parity assignment by DWBA calculation is in progress. We expect that the results of DWBA analysis will give accurate level information for candidates of 3^+ resonant state. We also observed several candidates for unnatural parity states at 5612 keV, 5825 keV, 6004 keV and 6107(8) keV.

(p,t) [5]		$(^3He,n\gamma)$ [6]		$(^3He,^6He)$ [7]		$(^4He,^6He)^a$
$E_x(keV)$	J^π	$E_x(keV)$	J^π	$E_x(keV)$	J^π	$E_x(keV)$
5515(5)	(4^+)	5515(4)	4^+	5526(8)	4^+	5508(3)
		5670(4)	1^+	5678(8)	1^+	
5916(2)	0^+	5912(4)	3^+			5918(8)
		5946(4)	0^+	5945(8)	3^+	
6300(4)		6312(4)	2^+			6364(4)^b
6380(4)		6388(4)	2^+			6364(4)^b
		6471(4)				
6787(4)	3^-	6788(4)	3^-			6787(4)
7019(10)						7018(6)
7160(5)	2^+	7152(4)	2^+			7161(6)
7425(7)		7425(4)	0^+			7429(7)
7498(4)	2^+	7493(4)	2^+			7480(20)
7687(22)	3^-	7694(4)	3^-			7676(4)
7900(22)	1^-	7899(4)	1^-			7885(4)

^{a} This work.

^{b} Average centroid of doublet peak.

Table 1: The excitation energies (units in keV) in ^{26}Si above 5 MeV from our measurement with the previous results.

Further data analysis will be performed to find out the 3^+ resonant states above proton threshold level.

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