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Experimental study of resonant sates in ^{26}Si and ^{27}P via elastic scattering of ^{25}Al+p and ^{26}Si+p

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The rapid proton capture process (rp process) is a dominant reaction sequence in explosive hydrogen burning that synthesizes heavier elements, especially proton-rich unstable nuclides. Therefore, accurate thermonuclear reaction rates for (p,γ) reactions on the rp process path are essential for an understanding of the nucleosynthesis processes and energy production. We studied proton resonant states in ^{26}Si and ^{27}P via elastic scattering in inverse kinematics at the low-energy RI beam facility CRIB (CNS Radioactive Ion Beam separator), University of Tokyo. By using a thick H_2 gas target, excitation energies range of 6.8 to 8.2 MeV in ^{26}Si and 2.3 to 3.8 MeV in ^{27}P were scanned, respectively. Several resonances above the proton threshold level were observed with high statistics and free from any background contribution in the target. Their resonance parameters were subsequently extracted by an R-matrix analysis; these are important to better constrain the production rates of the $^{25}Al(p,\gamma)^{26}Si$ and $^{26}Si(p,\gamma)^{27}P$ reactions.

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1. Introduction

The ^{25}Al(p,γ)^{26}Si and ^{26}Si(p,γ)^{27}P reactions are relevant to the synthesis of galactic ^{26}Al^{gs} ($t_{1/2}$ = 0.717 million years), which decays to the first excited state in ^{26}Mg, giving rise to a 1.809-MeV γ-ray [1]. In principle, internal transitions from the isomer to the ground state of ^{26}Al are forbidden by their large nuclear spin difference as shown in figure 1. However, if the ^{26}Al^{m} is effectively communicated with the ^{26}Al^{gs} through the thermal population of higher excited levels above the critical temperature of T = 0.4 GK [2-4], then this thermal process whould enhance the production of ^{26}Al^{gs}. The ^{25}Al(p,γ)^{26}Si reaction becomes significantly faster than the β decay of ^{25}Al at higher temperatures [5]. Moreover the ^{26}Si(p,γ)^{27}P reaction competes with the β decay of ^{26}Si to ^{26}Al^{m}. Therefore the destruction of ^{26}Si is an important consideration, and reaction rates of ^{25}Al(p,γ)^{26}Si and ^{26}Si(p,γ)^{27}P should be determined accurately for an estimation of the production of ^{26}Al in explosive hydrogen burning.

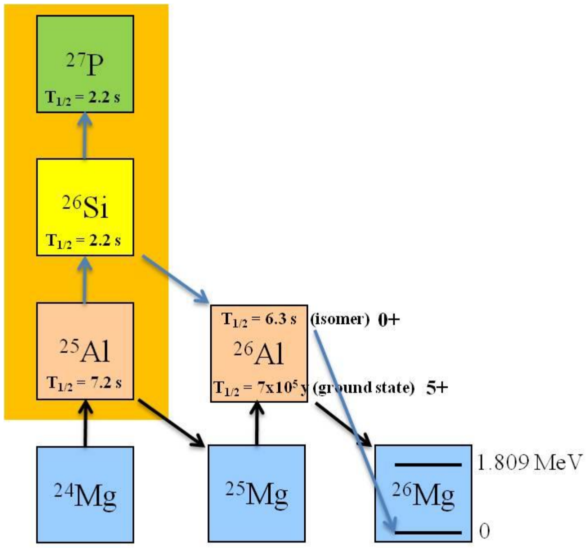

Figure 1: Reaction paths towars the production of the ^{26}Al

Apart from considerations related to ^{26}Al, these reactions may play a role in novae of the hotter variety or type I X-ray bursts. In such scenarios processing occurs mostly via the rp process which control the energy generation and nucleosysnthesis. Model simulations show that these reactions are activated along the rp-process paths in explosive hydrogen burning [6,7].

The thermonuclear reaction rates of stellar capture reactions are determined by the properties of energy levels in the compound nucleus within the Gamow windows corresponding to the stellar temperatures at which these reactions occur. Therefore states in ^{26}Si and ^{27}P need to be well understood in order to determine these proton capture reaction rates. The uncertainty in these rates is mainly due to the lack of nuclear structure information above the proton threshold. States in ^{26}Si have been studied with different reactions, for example: (p,t), (^{3}He,n), (^{3}He,^{6}He), (^{4}He, ^{6}He), and (p,p). Although many states have been discovered, their parameters are still unmeasured at energies corresponding to higher temperatures. Moreover, a comparison with its mirror nucleus ^{26}Mg reveals that missing states still remain. Concerning the structure of ^{27}P, it has been studied with measurements of the (^{3}He,^{8}Li) and (^{7}Li,^{8}He) reactions, and Coulomb dissociation of ^{27}P. Even though five resonant states above the proton threshold were observed, the knowledge of the structure of ^{27}P is still insufficient because of uncertain resonance parameters such as resonance energies and spin-parity assignments. In addition, there is the possibility of finding a number of experimentally unobserved states.

2. Experiment

The measurments of ^{25}Al+p and ^{26}Si+p elastic scattering were performed at the low-energy RI beam facility CRIB [8,9] by impinging ^{25}Al and ^{26}Si radioactive ion beams onto a thick H_2 gas target in inverse kinematics. A ^{24}Mg primary beam with an energy of 7.5 MeV/nucleon bombarded a ^{3}He gas target, where ^{25}Al and ^{26}Si beams were produced by the ^{3}He(^{24}Mg,^{25}Al)d and ^{3}He(^{24}Mg,^{26}Si)n reactions simultaneously, and separated by CRIB using the in-flight method. The secondary beams are contaminated with other isotopes including the ^{24}Mg primary beam. Beams were identified with a Time-Of-Flight (TOF) method and two Parallel Plate Avalanche Counters located upstream from the secondary target. The experimental details and results of ^{26}Si+p were published elsewhere [10]; the present article focuses on the results of ^{25}Al+p.

The radioactive ^{25}Al beam, with a well-defined energy of 71.58±0.54 MeV on target, an intensity of 3.3×10^{4} pps, and a purity of 62%, was delivered to the secondary target position. The beam energy was measured with a silicon detector directly before the measurement of scattered protons. Protons elastically scattered from the ^{1}H(^{25}Al,p)^{25}Al reaction to forward angles in the laboratory frame were detected by using silicon detectors for a ΔE-E telescope. By calculating the elastic scattering kinematics of ^{25}Al+p, the measured proton energy of each event was converted to a center-of-mass energy, $E_{c.m.}$, corrected for the energy loss of particles in the target. The experimental differential cross sections of the proton scattering events were calculated from the number of selected proton events and incident beam ions, the target thickness, and the different solid angles depending on the interaction position in the thick target. Figure 2 is the excitation function at $\theta_{lab} = 0^{\circ}$ in $E_{c.m.}$. Several peak-like structures were clearly observed. Corresponding excitation energies in ^{26}Si were calculated through the relation that $E_x = E_{c.m.} + 5.518$ (MeV) [11].

3. Data anaylsys and results

The differential cross section data has been analyzed using the R-matrix code (SAMMY-8.0.0) [12] to extract resonance parameters such as excitation energy E_x, spin *J*, parity π, and proton partial width Γ_p of resonance states. The spin-parity of the proton is $J^{\pi} = 1/2^{+}$ and that of the ground state of ^{25}Al is $5/2^{+}$, which couple together to give the incident channel spin $S = 1/2 \oplus 5/2 = 2$ or 3. Therefore, allowed spin-parities of the compound nucleus, ^{26}Si, are assigned as $J^{(-1)^{l}}$ where $J = l \oplus S$ and *l* is the relative orbital quantum number of the proton with respect to the nucleus.

Since at low energies below ~1.5 MeV Coulomb scattering is dominant or the widths of the resonances are expected to be too narrow, no clear resonance was observed in the excitation function over this energy region. The lowest resonance peak observed around 1.63 MeV was reproduced well by the R-matrix calculation with a $J^{\pi} = 2^{+}$ assignment. This is in good agreement with previously reported assignment for this resonance level [13-15]. The second small peak around 1.89 MeV was fitted best with a $J^{\pi} = 4^{+}$ assignment. The most recent study by Chen et al. [16] suggested $J^{\pi} = 2^{+}$ assignment, however this is difficult to confirm due to the large error bars. As shown in figure 2(a), the result of fitting our experimental data with a $J^{\pi} = 2^{+}$ assignment was worse than in case of a $J^{\pi} = 4^{+}$, the previously reported assignment [13]. A resonance to attempt to describe a small bump around 2.35 MeV in the middle of the two prominent peaks was included in the R-matrix calculation. Exclusion of this bump resulted in a less satisfactory fit for the tail of the most prominent peak around 2.14 MeV as shown in figure 2(a). An assignment of $J^{\pi} = 1^{-}$ for this state was adopted from previous work [14,15]. However we could not confirm the spin assignment clearly due to the narrow peak for this resonance. The third resonance (around 1.97 MeV), fits best with $J^{\pi} = 2^{+}$, which together with the level energy is in good agreement with the previously reported assignment for this level from transfer reaction studies [13-15] and the previous proton resonant scattering experiment [16].

As shown in figure 2(b), the fourth resonance at 2.14 MeV was fitted with $J^{\pi} = 2^{+}$, 3^{+} or 3^{-} assignments, which were based on previous measurements [13-16]. The best fit was obtained for $J^{\pi} = 2^{+}$or 3^{+}, but $J^{\pi} = 3^{-}$ could not be reproduced and totally deviated from our data. Because the fit results of both $J^{\pi} = 2^{+}$and 3^{+} were consistent with experimental data, we could not determine the final spin assignment clearly for this resonance. Furthermore, in the recent high-resolution study of Matic et al. [13], two states in this region were measured at E_x = 7.661(12) and 7.701(12) MeV, but there was no difference in fitting results between a single and a doublet state with our data.

Lastly, the fifth resonance around 2.46 MeV corresponds to a level at 2.501 (14) MeV from Chen et al. [16], which has observed this state firstly, suggesting an assignment of $J^{\pi} = 3^{+}$. However, there was almost no difference between $J^{\pi} = 2^{+}$ or 3^{+} with our result, as shown in figure 2(c). Figure 2(d) shows best-fit results for the excitation function of ^{25}Al+*p* elastic scattering. The corresponding level energies and spin-parities in comparison with those from previous studies are given in Table 1. The uncertainty in the energy includes both systematic and fitting uncertainty.

Table 1: Level energies, E_x (MeV) and spin-parities in ^{26}Si in the range of 7.1 MeV to 8.3 MeV from the present work and in comparison with those of previous studies.

this work	^{1}H(^{25}Al,p) [16]	(p,t) [13]
7.147(27), 2^{+}	7.162(14), 2^{+}	7.151(5)
7.401(28), 4^{+}	7.402(40), 2^{+}	7.415(23),(4^{+})
7.484(28), 2^{+}	7.484(13), 2^{+}	7.479(12)
7.654(29), (2^{+},3^{+})		7.661(12),(2^{+})
	7.704(13), 3^{+}	7.701(12)

7.866(29), (1^-)		7.874(4)
7.977(30), (2^+,3^+)	8.015(14), 3^+	
		8.222(5),(1^-)
	8.356(12), 3^+	

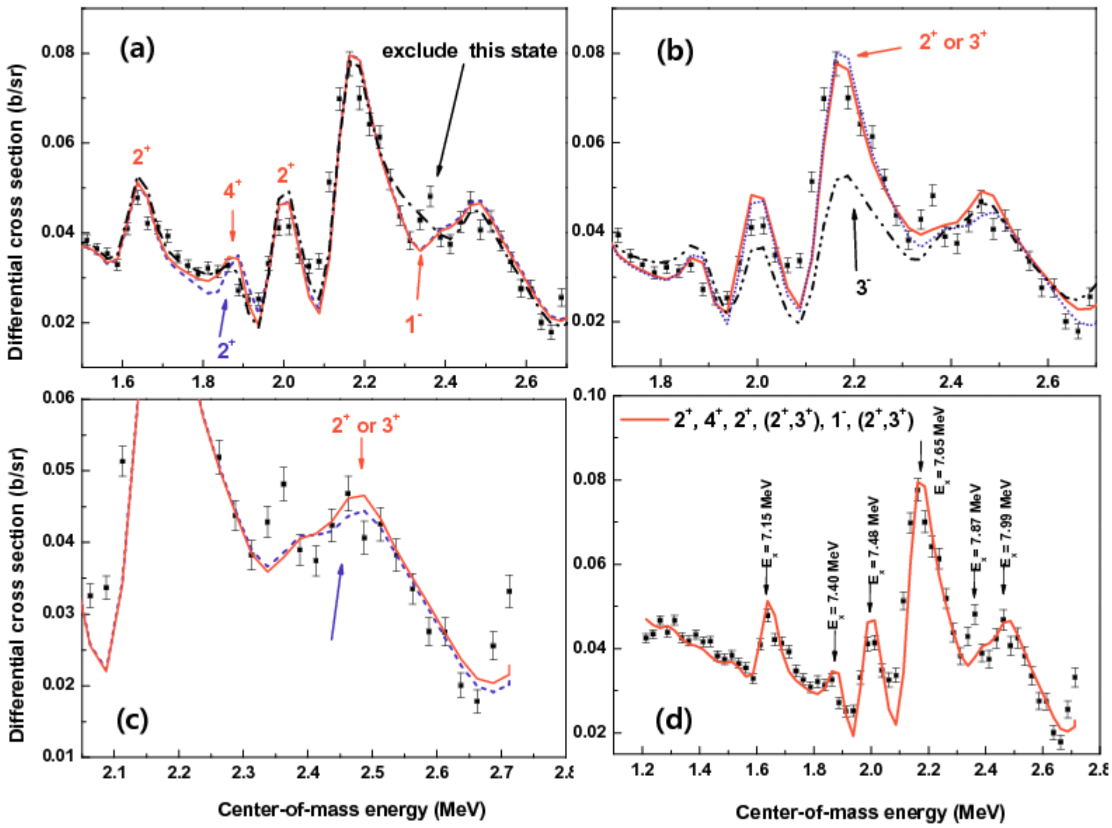

Figure 2: Excitation function for the ^{25}Al+p elastic scattering scross section fitted with an R-matrix calculation. (a) For the second resonance around 1.89 MeV, fitting results are compared between $J^\pi = 2^+$ and 4^+, and the fit for $J^\pi = 4^+$ gives a better result. A small bump around 2.35 MeV having an assignment of $J^\pi = 1^-$ resulted in an improved fit of the tail of the fourth peak. No other assignments can reproduce the tail. (b) The fourth resonance at 2.14 MeV was fitted with $J^\pi = 2^+$, 3^+ or 3^- assignments. Both $J^\pi = 2^+$ and 3^+ were consistent with the experimental data, but for $J^\pi = 3^-$, it totally deviated from the data. (c) High energy part of the excitation function with calculations assuming $J^\pi = 2^+$ or 3^+ for the last resonant peak shows that there is no difference between two assignments. (d) Final result as the best fit for $J^\pi = 2^+$, 4^+, 2^+, (2^+, 3^+), (1^-), and (2^+, 3^+) are shown but without firm spin-parity assignments for the fourth and fifth resonant peaks.

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