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Study of Proton Resonances in ^{22}Mg by Resonant Elastic Scattering of ^{21}Na+p and Its Astrophysical Implication in ^{18}Ne(α, p)^{21}Na Reaction Rate*

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Abstract: Proton resonant states in ^{22}Mg have been investigated by the resonant elastic scattering of ^{21}Na+p. The ^{21}Na beam with a mean energy of 4.00 MeV/u was separated by the CNS radioactive ion beam separator(CRIB) and bombarded a thick$(CH_2)_n$ target. The energy spectra of recoiled protons were measured at scattering angles of $\theta_{cm}\approx 172°$ and 146°, respectively. A new state at 7.06 MeV has been observed clearly and another new one at 7.28 MeV is tentatively identified due to its low statistics. The proton resonant parameters were deduced from an *R*-matrix analysis of the differential cross section data. The astrophysical resonant reaction rate for the ^{18}Ne(α, p)^{21}Na reaction has been estimated, and it is about five times larger than that assumed before.

Key words: nuclear astrophysics; reaction rate; nuclear structure and property

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1 Introduction

Nowadays the nuclear structure study of ^{22}Mg is becoming very interesting for its important role in estimating the astrophysical reaction rates of ^{21}Na(p, γ)^{22}Mg and ^{18}Ne(α, p)^{21}Na reactions in explosive stellar scenarios[1, 2].

Previously the excited states in ^{22}Mg were investigated via many reactions: ^{24}Mg(p,t)^{22}Mg[3-6], ^{24}Mg(^{4}He, ^{6}He)[7] and ^{12}C(^{16}O, ^{6}He) reactions[8], which preferentially populate the natural-parity states in ^{22}Mg; ^{25}Mg(^{3}He, ^{6}He) reaction[9] which populates both the natural-parity and unnatural-parity states; ^{20}Ne (^{3}He, n) reaction[10, 11] as well as ^{20}Ne(^{3}He, nγ) reaction[12, 13]. By knowing the exact location of excitation states in ^{22}Mg, the resonance property of states just above the proton threshold has been studied by the direct ^{21}Na(p, γ)^{22}Mg measurements[14, 15] as well

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Biography: He Jian-jun(1973－), male(Han Nationality), Inner Mongolia, China, Senior Researcher, working on the field of nuclear astrophysics; E-mail: jianjunhe@impcas.ac.cn as by a resonant scattering measurement of ^{21}Na+p[16] with the DRAGON recoil separator at TRIUMF. Based on the firm experimental results[15, 17], the astrophysical implication of ^{21}Na(p, γ)^{22}Mg reaction has been discussed, and the conclusion is no further measurement is needed to determine this resonant reaction rate under nova conditions.

On the other hand, Wiescher et al.[1] have proposed that the ^{18}Ne(α, p)^{21}Na reaction is probably one of the key reactions for the break-out from the hot CNO cycle in X-ray burst. In order to estimate the resonant reaction rate of ^{18}Ne(α, p)^{21}Na, the knowledge about the resonant properties of those states above the α threshold ($Q=8.14$ MeV) in ^{22}Mg is required. As for these states although their excitation energies were determined[7—9, 11], their resonant properties (such as, J^{π}, Γ_{α} and Γ_{p}) have not been determined yet. Actually, in calculating the resonant reaction rate of ^{18}Ne(α, p)^{21}Na using the narrow resonance formalism, knowledge of the proton partial widths (Γ_{p}) is not required. According to the knowledge of the states in ^{22}Ne, $\Gamma_{\alpha}\ll\Gamma_{\mathrm{p}}\approx\Gamma_{\mathrm{tot}}$, and thus the resonance strength $\omega\gamma=(2J+1)\left(\frac{\Gamma_{\alpha}\Gamma_{\mathrm{p}}}{\Gamma_{\mathrm{tot}}}\right)\approx(2J+1)\Gamma_{\alpha}$. Here, J is the spin of resonant state, and the partial width Γ_{α} is given by $\Gamma_{\alpha}=\left(\frac{3\hbar^2}{\mu R^2}\right)P_l C^2 S_{\alpha}$[8, 18]. In previous papers[8, 18], the spectroscopic S_{α} factors were assumed from those of mirror states based on the ^{18}O(^{6}Li, d)^{22}Ne α-transfer studies[19]. Therefore, the spin-parity of resonance and the uncertainty in S_{α} caused by the potential incorrectness of mirror assignments are still unknown.

The paper is organized as follows. In section 2, we introduce the experiment briefly. In section 3, we show the results, including the proton spectra and the R-matrix fitting. Finally, in section 4 we discuss the effect of our results on the resonant reaction rate of ^{18}Ne(α, p)^{21}Na.

2 Experiment

The experiment was performed using the CNS radioactive-ion-beam separator (CRIB)[20, 21]. It will be briefly introduced below for the details can be found in[22]. An 8.11 MeV/u ^{20}Ne^{8+} beam bombarded a water-cooled ^{3}He gas target (0.36 mg/cm^2), where a ^{21}Na beam was produced through ^{3}He(^{20}Ne, ^{22}Mg*)n with subsequent decay to ^{21}Na+p. The ^{21}Na beam, with a mean energy of 4.00 MeV/u (4.1 % in FWHM) and an average intensity of 1.5×10^4 particles/s, was delivered at the secondary target position where it bombarded a 7.9 mg/cm^2 $(\mathrm{CH_2})_n$ foil in which the ^{21}Na particles were stopped. The recoiled light particles were measured using the ΔE-E Si telescopes that subtended $\Delta\theta_{\mathrm{lab}}\simeq10°$ (~35 mSr in solid angle). The energy calibration for the detector system was performed using the secondary proton beams separated by CRIB at several energy points. In addition, a carbon target with a stopping-thickness equivalent to that of the $(\mathrm{CH_2})_n$ target was used in a separate run for evaluating the background contribution.

The center-of-mass energy(E_{cm}) has been deduced using the elastic scattering kinematics of ^{21}Na+p with correction of the energy loss of particles in the target. At scattering angle of $\theta_{\mathrm{cm}}\approx172°$, the typical energy resolution(FWHM of E_{cm}) is approximately 20 keV at $E_{\mathrm{cm}}=0.5$ MeV and 45 keV at $E_{\mathrm{cm}}=3.5$ MeV, and the corresponding energy uncertainty is approximately ±15 and ±20 keV, respectively; at $\theta_{\mathrm{cm}}\approx146°$, the typical energy resolution is approximately 20 keV at $E_{\mathrm{cm}}=0.5$ MeV and 75 keV at $E_{\mathrm{cm}}=3.5$ MeV, and the corresponding energy uncertainty is approximately ±15 and ±30 keV, respectively. The major contributions in resolution and uncertainty of E_{cm} energy to the latter telescope are from two aspects, one is the large kinematical shift, and the other one is that, for this position sensitive detector, only horizontal x strips were used and vertical y strips were unused due to the practical difficulties.

3 Results

Fig. 1(a) and (b) show the center-of-mass differential cross sections for the ^{21}Na+p elastic scattering at angles of $\theta_{\mathrm{cm}} \approx 172°$ and 146°, respectively. The cross-section data have been corrected for the stopping cross sections[23], and the data within the dead layer region (between ΔE and E) were removed from the figure. The excitation energies indicated on the figure are calculated by relation $E_{\mathrm{ex}} = E_{\mathrm{r}} + 5.502$ MeV, where the resonant energies E_{r} are deduced from the R-matrix analysis, and the previously determined ones are shown in parentheses for comparison. The region investigated by the TRIUMF group is also indicated, and two resonant states well observed at $E_{\mathrm{ex}} = 6.61$, 6.81 MeV are corresponding to the previously observed 6.615, 6.795 MeV states, respectively[16].

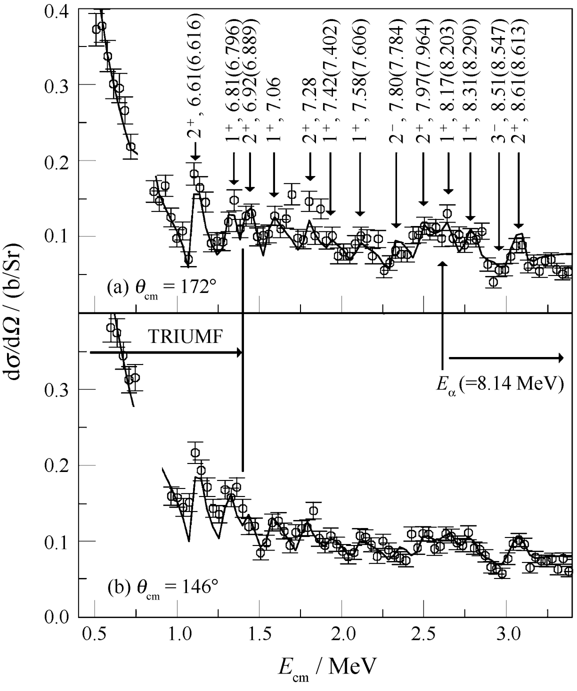

Fig. 1 R-matrix analysis of center-of-mass differential cross sections for the ^{21}Na+p resonant elastic scattering at the angles of (a) $\theta_{\mathrm{cm}} \approx 172°$, and (b) $\theta_{\mathrm{cm}} \approx 146°$. See text for details.

The center-of-mass differential cross sections have been analyzed by an R-matrix[24] code SAMMY-M6-BETA[25], which enables multilevel R-matrix fits to the cross-section data using Bayes's equations. The fits with all possible spin-parity assignments to the observed resonances have been attempted. The preferred fits are shown in Fig. 1, and the χ^2/N values are 2.50 and 2.13, respectively. The energy resolution has been taken into account in the fitting curves. The deduced resonant properties, J^π and Γ_{p} have been determined and listed in Table 1, where the excitation energies are determined by the data at $\theta_{\mathrm{cm}} \approx 172°$ for their better energy resolution and the uncertainties include both systematic and fitted ones; the proton partial widths are obtained by weighted average of those deduced from both data at $\theta_{\mathrm{cm}} \approx 172°$ and 146°. The excitation energies and spin-parities determined before are also listed for comparison. By comparing the level population intensity in the previous experiments[7—9], the probable parity properties (natural or unnatural) are estimated as listed in the 6th column of Table 1. The probable spin-parity and transferred ℓ values are recommended based on the natural-or-unnatural property restrictions (see 8th column in Table 1). For instance, the present R-matrix analysis gives a $J^\pi = (1^-, 2^-, 3^-)$ for the 8.51 MeV state, while based on the previous work[7—9] this state most probably has a natural parity, so it is assigned as $J^\pi = (1^-, 3^-)$ in the present work. By looking at the states in the mirror nucleus ^{22}Ne around this energy region there is no such 1^- (as well as 2^-) spin-parity state, and thus this state probably have a $J^\pi = 3^-$.

A level scheme of ^{22}Mg deduced from the present work is shown in Fig. 2. The previous level scheme of ^{22}Mg as well as that of mirror nucleus ^{22}Ne[26] are shown for comparison. The dashed lines in the present scheme indicate those states which can not be determined very well due to their counting statistics. We conclude that a new state, i. e. , at 7.06 MeV has been observed in the present experiment, and another new one at 7.28 MeV is tentatively identified because of its low statistics. As for all other observed states, the deduced excitation energies are in good agreement with those measured before. Furthermore, several resonances have been seen above the α threshold, which could be very difficult (or even impossible) to observe directly by the ^{18}Ne(α, p)^{21}Na reaction because of the small cross sections.

Table 1　Resonant properties of excited states in ^{22}Mg deduced from the present work. The uncertainties of energy, in units of keV, are included in the parentheses*

$E_{\rm ex}^{\rm present}$/MeV	$E_{\rm ex}^{[7]}$/MeV	$E_{\rm ex}^{[8]}$/MeV	$E_{\rm ex}^{[9]}$/MeV	$E_{\rm ex}^{[11]}$/MeV	Parity$^{\rm a}$	J^{π}(R-matrix)$^{\rm b}$	J^{π}; l(adopted)	$\Gamma_{\rm p}$/keV
6.61(15)$^{\rm c}$	6.606(9)	6.606(11)	6.616(4)		π=N～[4]	$(2^+, 1^+)$	2^+; 0	23(7)
6.81(15)$^{\rm d}$	6.766(12)	6.767(20)	6.771(5)	6.760(90)		$(1^+, 2^+)$	$(1^+, 2^+)$; 0	62(7)
6.92(15)		6.889(10)	6.878(9)		π=N	$(2^+, 1^+, 3^-, 2^-)$	$(2^+, 3^-)$; 0(1)	16(7)
7.06(16)						$(1^+, 3^-, 2)$	$(1^+, 3^-, 2)$; 0(1)	48(7)
7.28(16)						$(2^+, 1^+)$	$(2^+, 1^+)$; 0	17(7)
7.42(17)		7.402(13)	7.373(9)			$(1, 2^+)$	$(1, 2^+)$; 0(1)	10(7)
7.58(17)	7.614(9)		7.606(11)			$(1^+, 2^+)$	$(1^+, 2^+)$; 0	23(7)
7.80(18)		7.784(18)	7.757(11)	7.840(90)	π=uN	$(1^- - 3^-)$	(2^-); 1	27$^{\rm g}$
7.97(19)	7.938(9)	7.964(16)	7.986(16)	7.890(100)	π=N	$(1^+, 2^+)$	(2^+); 0	20$^{\rm g}$
8.17(19)	8.197(10)	8.203(23)	8.229(20)			$(1^+ - 3^+)$	$(1^+ - 3^+)$; 2	34$^{\rm g}$
8.31(20)				8.290(40)		$(1^+ - 3^+)$	$(1^+ - 3^+)$; 2	53$^{\rm g}$
8.51(20)$^{\rm e}$	8.512(10)	8.547(18)		8.550(90)	π=N	$(1^- - 3^-)$	(3^-); 1	40(7)
8.61(21)$^{\rm f}$	(8.644(18))	8.613(20)	8.598(20)			(2^+)	(2^+); 2	27(7)

* a N, uN denote level of natural and unnatural parity, respectively; b Present R-matrix results; c $J^{\pi}=2^+$ determined for the 6.616 MeV state[26]; d $J^{\pi}=(1^-, 2^-)$ determined for the 6.796 MeV state[26]; e $J^{\pi}=2^+$ assumed in Chen et al.[26]; f $J^{\pi}=3^-$ assumed in Chen et al.[26]; g The proton widths of these states are only roughly estimated from the R-matrix fits on the data. See text for details.

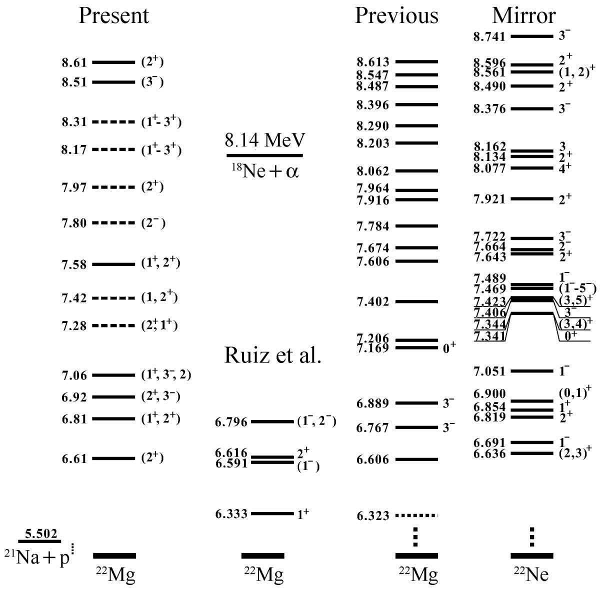

Fig. 2 A level scheme of ^{22}Mg deduced from the present work. The previous ones and that of the mirror nucleus ^{22}Ne are shown for comparison. The dashed lines in the present work indicate those states which can not be determined very well due to their counting statistics.

4　Astrophysical Implication

We have observed four states above the α threshold, i.e., at 8.17, 8.31, 8.51 and 8.61 MeV. The first two states possibly both have $J^{\pi}=(1^+\text{-}3^+)$ with $l=2$, but due to present energy resolution and counting statistics they are not well resolved and only have tentative spin-parity assignments; the latter two probably have 3^- and 2^+, respectively. Based on the work of Görres et al.[18], Chen et al.[8] made a mirror assignment between states in ^{22}Mg and ^{22}Ne, i.e., the 8.547 and 8.613 MeV states in ^{22}Mg were corresponding to the 8.596 and 8.741 MeV states in ^{22}Ne, respectively, and they were assignment with $J^{\pi}=2^+$ and 3^-, respectively[8]. However, their results are contrary to ours. If we simply suppose that the 8.547, 8.613 MeV states in ^{22}Mg are respectively corresponding to the 8.741 and 8.596 MeV states in ^{22}Ne, the previously used spectroscopic S_α factors for 8.547 and 8.613 MeV states should be exchanged, and the corresponding width Γ_α should be corrected with respect to the energy change. This exchange will greatly affect the reaction rate below temperature $T_9 < 0.4$, where the previous dominant contribution from 8.547 MeV state is negligible in the present calculation for its resonant strength is reduced by two orders of magnitude compared to the previous value[8]; while the contribution from 8.613 MeV state becomes dominant with a resonance strength increased by two orders of magnitude compared to the previous one[8]. Generally, the present resonant reaction rate for these two states is larger than that of previous one by a factor of ～30 around $T_9 = 1.0$; while around $T_9 = 0.3$ the present total resonant reaction rate for those 7 states used in Chen et al.'s work are about a factor of 5 larger than that assumed before[8] (see Fig. 3). The detailed R-matrix analysis of the data and reaction rate calculation will be published soon[27].

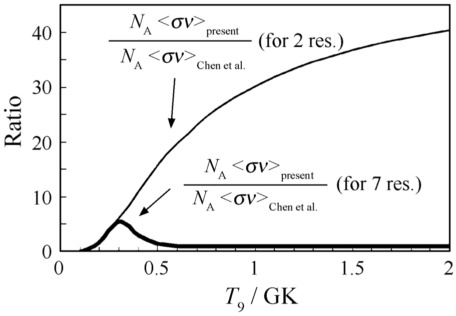

Fig. 3 The ratios between the present resonant reaction rates and those previous ones at certain temperature range. See text for details.

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