Study of Proton Resonance States in 23Mg via 22Na+p Thick-Target Elastic Scattering

Authors: Hu Jun, Han Zhiyu, Li Yunju, Li Zhihong, Lian Gang, Shen Yangping, Yan Shengquan, Zeng Sheng, Guo Bing, Liu Weiping, Bai Zhen, Jia Baolu, Jin Shilun, Ma Junbing, Ma Peng, Ma Shaobo, Xu Shiwei, Yang Yanyun, Zhang Ningtao, Tang Xiaodong, Zhang Liyong, Jun Su, He Jianjun, Sun Lijie, Huang Meirong, Wang Jiansong, Wang Hongwei, Zhang Yuqiang, Jinglong, Wang Youbao, Wang Youbao

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Abstract

22Na(p, γ)23Mg and 19Ne(α, p)22Na are two key reactions in the NeNa-MgAl cycle and the rp-process in nova environments, which are of great significance for understanding nova evolution and nucleosynthesis. Due to the involvement of numerous resonant levels above the proton separation threshold of the odd-A nucleus 23Mg, there remain large discrepancies in the reaction rates of these two reactions. At the RIBLL1 radioactive beam line of the Heavy Ion Research Facility in Lanzhou, the proton resonance states of the compound nucleus 23Mg were measured using the 22Na+p thick-target inverse kinematics elastic scattering method, the excitation function of 22Na(p, p) in the center-of-mass energy range of 1.5–4 MeV was obtained, and distinct proton resonance structures in the compound nucleus 23Mg were discovered, thereby laying a foundation for further R-matrix theoretical analysis.

Full Text

Preamble

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Study of Proton Resonant States in 23Mg via 22Na+p Thick-Target Elastic Scattering

Y.Q. Zhang[1], L. Jing[2], Y.B. Wang[1], J. Hu[2], Z.Y. Han[1], Y.J. Li[1], Z.H. Li[1], G. Lian[1], Y.P. Shen[1], S.Q. Yan[1], S. Zeng[1], B. Guo[1], W.P. Liu[1], XFHDX-HDXGJXFG[2], B.L. Jia[2], S.L. Jin[2], J.B. Ma[2], P. Ma[2], S.B. Ma[2], S.W. Xu[2],

Y.Y. Yang[2], N.T. Zhang[2], X.D. Tang[2], L.Y. Zhang[2], J. Su[3], J.J. He[3], L.J. Sun[4], M.R. Huang[5], J.S. Wang[6], H.W. Wang[7]

[1] China Institute of Atomic Energy, Beijing 102413, China
[2] Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
[3] University of Chinese Academy of Sciences, Beijing 100049, China
[4] Institute of Nuclear and Particle Physics, Shanghai Jiao Tong University, Shanghai 200240, China
[5] College of Mathematics and Physics, Inner Mongolia Minzu University, Tongliao, Inner Mongolia Autonomous Region 028000, China
[6] Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China

Abstract

The 22Na(p, γ)23Mg and 19Ne(α, p)22Na reactions are two key processes in the NeNa-MgAl cycle and the rp-process in nova environments, playing crucial roles in understanding nova evolution and nucleosynthesis. Due to the involvement of numerous resonance levels above the proton separation threshold in the odd-A nucleus 23Mg, significant discrepancies remain in the reaction rates for these processes. At the RIBLL1 radioactive beam line of the Heavy Ion Research Facility in Lanzhou (HIRFL), we measured the proton resonant states of the compound nucleus 23Mg using the thick-target inverse kinematics elastic scattering method with a 22Na beam. The excitation function for 22Na(p, p) was obtained in the center-of-mass energy range of 1.5–4 MeV, revealing clear proton resonance structures in 23Mg that provide a foundation for subsequent R-matrix theoretical analysis.

Keywords: nova nucleosynthesis; astrophysical reaction rates; resonance scattering; thick-target inverse kinematics method

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Introduction

In 1972, Black et al. conducted a detailed study of the composition of the famous Orgueil carbonaceous chondrite meteorite [1], discovering anomalous abundances of the neon isotopes 20Ne and 22Ne. The measured abundance ratio was 1.5, approximately 15% of the terrestrial 20Ne/22Ne ratio—this became known as the Ne abundance anomaly problem. These neon isotopes predate the solar system, having been injected into meteorite material during a stellar explosive event before solar system formation and preserved to the present day. The superabundant 22Ne likely originated from the decay of 22Na [2].

In 1974, Clayton et al. used the Thermonuclear Runaway (TNR) model to predict that nova ejecta would contain substantial amounts of 22Na and 26Al [3].

With a half-life of only 2.6 years compared to 7.17×10^5 years for 26Al, the 1.275 MeV γ-ray emitted during 22Na decay could serve as a sensitive probe of nova explosions, holding significant importance for γ-ray astronomy. In recent years, NASA's Compton Gamma Ray Observatory (CGRO) detected five Ne-type nova events in the solar neighborhood, with observations indicating very small ejected masses of 22Na, with an upper limit of approximately 3.7×10^{-8} M . Iyudin et al. performed a systematic analysis of COMPTEL telescope observations from 1991–1997 [4], producing a galactic map of 1.275 MeV γ-ray flux, though they concluded it more likely originated from low-energy excitations of 22Ne rather than 22Na decay.

Novae occur in binary systems where a white dwarf accretes hydrogen-rich material from its companion star, leading to explosive hydrogen burning that releases enormous energy. In nova environments, 22Na is primarily synthesized through the NeNa-MgAl cycle. Depending on the internal temperature, two distinct synthesis pathways exist: (1) 20Ne(p, γ)21Na(β^+)21Ne(p, γ)22Na, and (2) 20Ne(p, γ)21Na(p, γ)22Mg(β^+)22Na. The main reaction destroying 22Na is 22Na(p, γ)23Mg. José et al. demonstrated through model calculations that the abundance of 22Na in CO nova ejecta is closely related to the reaction rate of 22Na(p, γ)23Mg [5]. Because the entrance channel involves radioactive nuclei, experimental studies of the 22Na(p, γ)23Mg reaction are scarce, resulting in large uncertainties in its astrophysical reaction rate.

In 1989, Görres et al. at the University of Notre Dame performed the first direct measurement of the 22Na(p, γ)23Mg reaction using a 22NaCl titrated target [6]. Due to numerous impurities in the titrated target, the results were relatively coarse, providing only upper limits for the resonance strengths of a few states in 23Mg. Later, Seuthe et al. at the University of Münster used a 22Na ion-implanted target to measure resonance strengths for several levels in the 7.780–8.193 MeV excitation energy region of 23Mg [7]. Similarly, Sallaska et al. at Washington University measured several resonant states in the 7.770–8.163 MeV region and calculated the astrophysical reaction rate for 22Na(p, γ)23Mg [8, 9]. While ion-implanted targets solved the impurity problem, the 1.275 MeV γ-rays from 22Na decay created strong γ-background and excessively high count rates, likely contributing to the significant discrepancies between these experimental results. In addition to direct measurements, studying 23Mg resonant states via transfer reactions represents another common approach [10–12]. Schmidt et al. at Ruhr University Bochum used the 22Na(^{3}He, d)23Mg single-proton transfer reaction [12], obtaining spin-parity assignments for several levels in the 6.236–8.076 MeV excitation region of 23Mg through deuteron angular distribution measurements. Delayed proton emission from 23Al β^+ decay also provides an important pathway for investigating 23Mg resonant levels [13–17]. Friedman et al. at Michigan State University measured the delayed proton spectrum from 23Al β^+ decay [14], observing several resonances in the 7.79–8.45 MeV region of 23Mg and improving the precision of resonance strength measurements for the 22Na(p, γ)23Mg reaction. Furthermore, Jenkins et al. at Argonne National Laboratory used the 12C(12C, n)23Mg fusion-evaporation reaction to

measure γ-ray angular correlations from excited states in 23Mg [18], obtaining J^π values and lifetimes for multiple resonant levels. Theoretically, Comisel et al. studied known levels in 23Na, the mirror nucleus of 23Mg, to provide resonance strengths for some levels in the 7.583–7.643 MeV region of 23Mg [19]. Because transfer reactions and β-decay are highly selective for final states in 23Mg, these indirect measurements can only obtain partial information relevant to the 22Na(p, γ)23Mg reaction. To comprehensively scan all proton resonant levels related to the 22Na(p, γ)23Mg reaction, measuring the excitation function of 22Na(p, p) elastic scattering is the most effective approach. Previously, we studied 22Na+p resonance scattering using the thick-target inverse kinematics method at the CRIB facility of the University of Tokyo [20], discovering three resonant states of 23Mg below E_c.m. < 1.5 MeV. However, the relatively large size of the hydrogen gas target introduced some uncertainties in kinematic reconstruction. To improve upon this, we have remeasured the 22Na+p resonance scattering using a (CH_2)n solid target at the RIBLL1 radioactive beam line of the Heavy Ion Research Facility in Lanzhou (HIRFL).

1 Experimental Setup

The Lanzhou Radioactive Ion Beam Line RIBLL1 is a double-achromatic secondary beam facility comprising four dipole magnets and eighteen quadrupole magnets with a total length of 35 m. The 22Na radioactive beam was produced via the 1H(22Ne, 22Na)n charge-exchange reaction using a 22Ne primary beam provided by the SFC cyclotron at HIRFL at an energy of 7.5 MeV/u with an average intensity of approximately 700 enA. The gas target cell was a cylinder 30 mm in diameter and 80 mm long, sealed at both ends with 2.5 µm thick Havar foils. During the experiment, the H_2 gas pressure was stabilized at (500 $\pm$ 30) mbar, and the gas was cooled to -20 °C using an alcohol refrigerator to increase the effective target thickness. The 22Ne beam bombarded the H_2 gas target, and the resulting 22Na was separated and purified by the RIBLL1 secondary beam line before transport to the experimental end station.

The experimental setup for the 22Na+p resonance scattering measurement is shown in Figure 1 [Figure 1: see original paper]. Two plastic scintillator detectors (C_9H_{10}) were installed in the T1 and T2 target chambers to record time-of-flight (TOF) information. During beam tuning, these worked in conjunction with a stopping silicon detector at the experimental terminal to form a TOF-ΔE system for particle identification. Two X-Y two-dimensional position-sensitive parallel-plate avalanche counters (PPACs) were installed 565 mm apart in the T2 and Tk chambers to determine the incident beam particle position before the reaction target and to measure the incident particle angle. The PPACs also served to determine the beam intensity through coincidence counting. A rail system located 40 mm behind PPAC2 held the (CH_2)n reaction target, a pure carbon background target, and a silicon detector for beam tuning. The (CH_2)n and pure carbon targets had thicknesses of 100 µm and 60.7 µm, respectively, sufficient to completely stop the 22Na radioactive beam and its impurity com-

ponents. Two sets of silicon microstrip detector telescopes were positioned 350 mm behind the reaction target at laboratory angles of 0° and 14° to detect light recoil particles from the target. Each telescope consisted of a double-sided silicon strip detector (DSSD) and a square silicon detector (SSD). The 0° DSSD had 32 strips on each side, a thickness of 63 µm, and an active area of 4900 mm^2, while the 14° DSSD had 16 strips per side, a thickness of 74 µm, and an active area of 2500 mm^2. The DSSDs provided position information for outgoing particles, enabling event-by-event two-body kinematic reconstruction of 22Na(p, p) when combined with PPAC data. The SSD detectors had an active area of 2500 mm^2 and a thickness of 1500 µm. Prior to the experiment, the DSSD and SSD detectors were energy-calibrated using triple α-sources of ^{239}Pu, ^{241}Am, and ^{244}Cm.

The beam tuning results for the 22Na secondary beam are shown in Figure 2 [Figure 2: see original paper]. Figure 2(a) displays the beam distribution on target, while Figure 2(b) shows the correlation between the TOF from TOF2 to PPAC2 (horizontal axis) and the energy signal from the tuning silicon detector (vertical axis). The primary impurity was $22Ne^{10+}$, which had matched magnetic rigidity. During formal data acquisition, the tuning silicon detector was moved away using the rail system, and only TOF information was used for 22Na particle identification. Throughout the experiment, the 22Na secondary beam purity remained at approximately 78% with an average intensity of about 2×10^5 pps. To determine the 22Na beam energy, the magnetic field and tuning silicon detector were calibrated using the $22Ne^{10+}$ primary beam under both empty-target and gas-filled conditions. Based on the magnetic field settings and energy loss calculations, the beam energy at the (CH_2)n reaction target was determined to be (93.3 ± 1.4) MeV, as shown in Figure 2(c), where the red line represents the fitting result and the black line shows the experimental data.

After energy calibration of the silicon detectors, particle identification was performed using ΔE-E coincidences. Figure 3 [Figure 3: see original paper] shows the two-dimensional ΔE-E particle identification spectra measured by the silicon telescopes at 0° and 14°. The DSSD thickness of approximately 70 µm resulted in relatively small energy loss ΔE for protons and other particles in the DSSD. The 1.5 mm thick E-detector, combined with the DSSD, could stop protons with energies up to about 16 MeV. Protons exceeding this energy appear as a downward-curving tail in Figure 3, representing particles that penetrated the SSD detector and fell outside our region of interest; these were excluded from offline analysis. The dominant outgoing particles observed were protons and helium ions, as the 1H(22Na, p)22Na and 1H(22Na, α)19Ne channels have relatively large cross sections in the 22Na+p reaction system.

2 Data Analysis

For thick-target inverse kinematics elastic scattering experiments, the beam energy distribution within the target is continuous, requiring determination of the reaction energy on an event-by-event basis. The two-body kinematic reconstruc-

tion for 1H(22Na, p)22Na elastic scattering is illustrated in Figure 4 [Figure 4: see original paper]. Based on the incident 22Na particle energy and angle, along with the corresponding outgoing proton energy and angle, the reaction point is determined, allowing conversion of the proton energy to center-of-mass energy E_c.m. on a per-event basis. At the reaction point, the center-of-mass energy E_c.m. relates to the proton energy E_p through the simple expression:

$$E_{c.m.} = \frac{M_b + M_p}{4M_b \cos^2 \theta_{lab}} E_p$$

where E_p is the recoil proton energy at the reaction point, M_b and M_p are the masses of 22Na and the proton, respectively, and _{lab} is the laboratory angle. The energy resolution of E_c.m. is determined by the intrinsic resolution of the ΔE-E detectors, the laboratory angular resolution, and energy straggling of particles in the target. The procedure for locating the reaction point proceeds as follows:

First, starting from the point where the 22Na particle enters the reaction target, the remaining energy is calculated point-by-point as it advances along the incident direction. Second, the energy of outgoing protons produced by 1H(22Na, p)22Na elastic scattering at each energy point is calculated. Third, the remaining energy of protons escaping the target along the emission angle is computed. Fourth, the calculated remaining proton energy is compared with the energy detected by the silicon ΔE-E telescope; when the difference is less than 0.1 keV, the true reaction point is considered found, allowing determination of the 22Na injection depth in the target, E_p, and _{out}, from which E_c.m. is calculated. This step is implemented through mathematical interpolation; the 0.1 keV threshold was chosen to balance iteration effectiveness with computational cost while minimizing artificially introduced errors from the interpolation process.

Because a (CH_2)n target was used, carbon within the target could react with 22Na and produce proton background. To obtain the center-of-mass energy spectrum, the carbon background contribution must be subtracted from the measured spectrum. First, the same kinematic reconstruction procedure is applied to proton background events measured with the carbon target to obtain the proton center-of-mass energy spectrum from the carbon target alone. Since the atomic densities of the carbon and (CH_2)n targets differ and the beam time required for each varies, normalization must be performed before background subtraction. The normalization coefficient is calculated as:

$$coe = \frac{I_{CH_2} N_{CH_2}}{I_C N_C}$$

where I_{CH}$_2$ and I_C are the numbers of beam particles incident on the (CH_2)n and carbon targets, respectively, and N_{CH}$_2$ and N_C are the cor-

responding target atomic densities. In thick-target experiments, because the beam energy is continuous throughout the target, the target atomic number must be calculated for the selected energy interval. After normalization, the background can be subtracted to obtain net counts. The resulting background-subtracted center-of-mass energy spectra are shown in Figure 5 [Figure 5: see original paper], with Figure 5(a) corresponding to the laboratory angle of 0° and Figure 5(b) to 14°.

The differential cross section for 1H(22Na, p)22Na in the laboratory frame is calculated using:

$$\left(\frac{d\sigma}{d\Omega}\right)_{lab} = \frac{N_p}{IN_t d\Omega}$$

where I is the number of incident particles, N_p and N_t are the numbers of outgoing protons and target atoms per unit energy interval, respectively, and dΩ is the solid angle. The center-of-mass differential cross section for 1H(22Na, p)22Na is then obtained using:

$$\left(\frac{d\sigma}{d\Omega}\right)_{c.m.} = 4\cos\theta_{lab}\left(\frac{d\sigma}{d\Omega}\right)_{lab}$$

as shown in Figure 6 [Figure 6: see original paper].

Because event-by-event two-body kinematic reconstruction was employed for protons, the dominant contributions to energy resolution come from the detectors' intrinsic resolution and uncertainties in the energy loss calculations. The 22Na beam energy was determined from the magnetic field settings at RIBLL1 with relatively small error, while the energy uncertainty of the silicon detectors for measuring recoil protons was approximately 50 keV. The total estimated uncertainty is about 100 keV, which improves by nearly a factor of four in the center-of-mass frame due to inverse kinematics effects, yielding approximately 25 keV resolution. Considering background subtraction and statistical fluctuations, a bin width of 40 keV was chosen for Figure 6.

In R-matrix theory, the elastic scattering cross section formula is given by [22]:

$$\sigma_{\alpha\alpha} = 4\pi g_J \sin^2\phi_c - g_J \frac{2\Gamma_{\lambda c}\sin^2\phi_c + \Gamma_\lambda(1-\cos 2\phi_c)}{(E_\lambda+\Delta_\lambda-E)^2+\Gamma_\lambda^2/4} + \sum_{c'}\frac{(\Gamma_{\lambda c}\Gamma_{\lambda c'})(E_\lambda+\Delta_\lambda-E)\sin 2\phi_c}{(E_\lambda+\Delta_\lambda-E)^2+\Gamma_\lambda^2/4}$$

where g_J is the spin statistical factor defined as:

$$g_J = \frac{2J+1}{(2I_1+1)(2I_2+1)}$$

Γ and Δ represent the level width and level shift, respectively, defined as:

$$\Gamma_{\lambda c} = 2P_c\gamma_{\lambda c}^2, \quad \Delta_{\lambda c} = -(S_c - B_c)\gamma_{\lambda c}^2$$

γ_λc is the reduced width amplitude defined by:

$$\gamma_{\lambda c} = \sqrt{\frac{\hbar^2}{2M_c a_c}} C_{\lambda,c} u_p(a_c)$$

k_α is the wave number defined as k_$\alpha = \sqrt{}(2\ E)/\hbar$, where is the reduced mass ($= m_1m_2/(m_1 + m_2)$), P_c is the penetration factor, *φc is the hard-sphere phase shift, B_c is the boundary condition parameter, Eλ* is the eigenvalue, I_1 and I_2 are the spin quantum numbers of the incident particle and target nucleus, and J is the compound nucleus spin quantum number. The first term represents potential scattering (hard-sphere scattering), which is independent of spin and parity and forms the "baseline" of the excitation function without prominent resonance peaks. The second and third terms represent the interference and resonance scattering components, respectively, which produce the peak-valley structures in the excitation function.

According to Equation 7, the scattering cross section is inversely proportional to the system energy overall, which is clearly demonstrated in Figure 6. In addition to the smooth potential scattering component, numerous peak-valley structures appear in Figure 6, which can be interpreted as proton resonant states in 23Mg. Multi-level R-matrix fitting can resolve these structures in detail to extract the resonance parameters for the 23Mg proton resonant states.

3 Summary and Outlook

In this work, we measured the excitation function for radioactive 22Na+p resonance scattering using the thick-target inverse kinematics method. By employing a (CH_2)n target to reduce geometric uncertainties, we obtained the 22Na+p elastic scattering excitation function in the center-of-mass energy range of 1.5–4 MeV, revealing clear resonance peak structures. We are currently performing theoretical analysis of the experimental results using R-matrix programs to obtain resonance parameters for 23Mg states, including central energies, spin-parities, and proton widths, which will enable calculation of the astrophysical reaction rates for 22Na(p, γ)23Mg and 19Ne(α, p)22Na in nova environments.

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Note: Figure translations are in progress. See original paper for figures.