Postprint: Nuclear Astrophysics Research Using the HI-13 Tandem Accelerator

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Abstract

The Nuclear Astrophysics Research Group at the China Institute of Atomic Energy has established China's first low-energy radioactive secondary beam line at the HI-13 tandem accelerator National Laboratory for Nuclear Physics, producing 11 types of radioactive nuclear beams ranging from 6He to 22Na. Using these radioactive beams, a series of studies on important nuclear astrophysics reactions have been conducted via inverse kinematics transfer reaction measurements. Additionally, important nuclear structure information relevant to astrophysics has been investigated through thick-target experimental methods and charge-exchange reactions. On the Q3D magnetic spectrometer at the tandem accelerator, angular distributions for numerous single-nucleon and α-cluster transfers have been measured using stable beams. Based on the Asymptotic Normalization Coefficient (ANC) or spectroscopic factor methods, astrophysical S-factors and reaction rates for a series of key astrophysical reactions have been obtained, providing important experimental input for related research on elemental abundances and astrophysical models.

Full Text

Preamble

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Nuclear Astrophysics Research Based on the HI-13 Tandem Accelerator

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Abstract

The nuclear astrophysics research group at the China Institute of Atomic Energy (CIAE) has established China's first low-energy radioactive secondary beam line at the HI-13 tandem accelerator national laboratory. This facility has produced 11 types of radioactive nuclear beams ranging from ^{6}He to ^{22}Na. Using these radioactive beams, the group has conducted a series of studies on important nuclear astrophysics reactions through inverse kinematics transfer reaction measurements. Additionally, research on astrophysics-relevant nuclear structure information has been performed using thick-target experimental methods and charge-exchange reactions. On the Q3D magnetic spectrometer at the tandem accelerator, angular distributions for many single-nucleon and α-cluster transfer reactions have been measured using stable beams. Based on the Asymptotic Normalization Coefficient (ANC) or spectroscopic factor methods, the astrophysical S-factors and reaction rates for a series of key astrophysical reactions have been obtained, providing crucial experimental input for studies of elemental abundances and stellar models.

Keywords: Nuclear astrophysics, Radioactive ion beam line, Q3D magnetic spectrometer, Astrophysical S-factor

Nuclear astrophysics is an interdisciplinary field formed by the combination of nuclear physics and astrophysics, applying nuclear physics knowledge and laws to explain energy generation from nuclear processes in stars and their influence on stellar structure and evolution; the synthesis of various chemical elements in the universe; the formation of white dwarfs, neutron stars, pulsars, and black holes; the origin of cosmic rays and their interaction with interstellar gas; the chemical evolution of galaxies; and neutrino and γ-ray astronomy. In a specific sense, its main objective is to study the processes, timescales, physical environments, astrophysical sites, and abundance distributions of the synthesis of various elements and their isotopes in the universe.

Nuclear processes are not only the primary energy source for stars to counteract gravitational contraction but also the only method for synthesizing all nuclides other than hydrogen in the universe, playing an extremely important role in cosmic and astrophysical evolution from seconds after the Big Bang until the end of stellar lifetimes. To clarify energy production and the nucleosynthesis processes and abundance distributions of various nuclides during stellar evolution, precise and reliable nuclear reaction data from nuclear physics experiments and theory are required. Since stellar evolution and nucleosynthesis involve thousands of nuclides on both sides of the β-stability line, and nuclear reaction cross sections in the astrophysical energy region are extremely low, while the physical environment leads to thermal population of certain low-lying excited states of nuclei and the interplay between nuclear processes and atomic or plasma processes, both nuclear physics experiments and theory face very severe challenges. Therefore, nuclear astrophysics has been a highly valued modern interdisciplinary field internationally for decades and has consistently been one of the frontiers of nuclear physics.

In 1993, the Nuclear Astrophysics Group at the China Institute of Atomic Energy (hereinafter referred to as CIAE) built China's first low-energy radioactive secondary beam line and successfully produced beams [1], initiating research on indirect measurements of radiative capture reactions of radioactive nuclei. Using the Asymptotic Normalization Coefficient (ANC) method, the group obtained astrophysical S-factors for key reactions such as ^{7}Be(p,γ)^{8}B and ^{13}N(p,γ)^{14}O. Additionally, the halo structure of the second excited state of ^{6}Li was studied using the charge-exchange reaction ^{1}H(^{6}He,^{6}Li*)n, and level information for unstable nuclei relevant to nuclear astrophysics such as ^{14}O, ^{18}Ne, and ^{23}Mg was investigated using the thick-target elastic resonance scattering method.

The nuclear astrophysics research group has fully exploited the capabilities of the tandem accelerator and Q3D magnetic spectrometer, upgrading and renovating the detection equipment, electronics, and data acquisition systems to further improve the detection capability of the magnetic spectrometer. A series of single-nucleon transfer reactions such as (^{7}Li,^{6}Li/^{6}He) have been measured, yielding precise nuclear spectroscopic factors or ANCs for nuclei including ^{7}Li, ^{9}Be, ^{14}N, and ^{16}N. The spectroscopic factor method has been extended to studies of near-threshold resonances above threshold. Furthermore, the α-capture indirect measurement method using the (^{11}B,^{7}Li) transfer reaction has been systematically developed to study key nuclear astrophysics reactions such as the stellar neutron source reaction ^{13}C(α,n)^{16}O and the "holy grail" reaction ^{12}C(α,γ)^{16}O, significantly improving the precision of existing experimental data.

Overall, over nearly 30 years of research at the tandem accelerator nuclear physics national laboratory, the CIAE nuclear astrophysics group has completed indirect measurements of numerous key nuclear astrophysics reactions, refined and expanded experimental methods for indirect measurements and related theories, and achieved fruitful research results.

Experimental Studies of Radioactive Nuclear Beams

1.1 Secondary Beam Line

Radioactive nuclides are of great significance for astrophysical evolution. Although many radioactive nuclides have short half-lives, in early universe environments and some high-temperature, high-density astrophysical environments, radioactive nuclides can participate in various nuclear reactions within short timeframes and generate other nuclides. These nuclear reactions affect the abundances of multiple nuclides, including some stable nuclides. Since most radioactive nuclides have short half-lives and cannot be made into reaction targets, but can be used to produce secondary radioactive beams through inverse kinematics nuclear reactions, which can then be used to complete nuclear reaction cross-section measurements.

In 1993, the CIAE nuclear astrophysics group built China's first radioactive secondary beam line [1], named GIRAFFE for its 象形 (pictographic) characteristics, and continuously upgraded it over the subsequent decade. The final overview of the secondary beam line is shown in Figure 1 [Figure 1: see original paper]. The entire device consists of a primary reaction gas target, an electromagnetic separation, focusing, and purification transmission system composed of a dipole magnet and a pair of quadrupole lenses and a velocity selector, and a secondary reaction target chamber.

During more than a decade of operation, the secondary beam line has produced 11 types of radioactive beams. The types of radioactive nuclear beams produced, specific production reactions, and beam performance indicators are listed in Table 1 . Except for the ^{19}Ne and ^{22}Na beams, most radioactive nuclide beams have good quality. The nuclear astrophysics research group has used these radioactive nuclear beams to measure cross sections for many key astrophysical nuclear reactions and obtained many important research results in nuclear astrophysics.

Table 1 Radioactive nuclear beams produced by GIRAFFE

Beams	Producing reaction	Energy±half-width / MeV	Purity / %	Intensity / pps
^{6}He	^{2}H(^{7}Li, ^{6}He)^{3}He	37.3\$±\$0.5		
^{7}Be	^{1}H(^{7}Li, ^{7}Be)n	30.8\$±\$1.3		
^{8}Li	^{2}H(^{7}Li, ^{8}Li)p	40.0\$±\$0.5		
^{10}C	^{1}H(^{10}B, ^{10}C)n	55.9\$±\$3.5		
^{11}C	^{1}H(^{11}B, ^{11}C)n	63.4\$±\$2.7		
^{13}N	^{2}H(^{12}C, ^{13}N)n	57.8\$±\$2.1		
^{15}O	^{2}H(^{14}N, ^{15}O)n	66.0\$±\$3.6		
^{17}F	^{2}H(^{16}O, ^{17}F)n	76.1\$±\$3.7		
^{18}F	^{3}He(^{16}O, ^{18}F)p	75.7\$±\$2.2		
^{19}Ne	^{4}He(^{16}O, ^{19}Ne)p	56.6\$±\$3.4		
^{19}Ne	^{3}He(^{19}F, ^{19}Ne)^{3}H	68.6\$±\$3.8		
^{22}Na	^{4}He(^{19}F, ^{22}Na)n	52.9\$±\$1.9		

By comparing experimental results with DWBA calculations, the nuclear spectroscopic factor or ANC of the target nucleus B can be obtained, as shown in Equation (1):

$$(d\sigma/d\Omega)_{\mathrm{exp}} = (C_d)^2(C_B^{l_fj_f})^2 R_{l_fj_f}(d\sigma/d\Omega)_{l_fj_f}^{\mathrm{DWBA}}$$

where $(d\sigma/d\Omega)_{\mathrm{exp}}$ is the experimentally measured angular distribution; S_d and $S_B^{l_fj_f}$ are the spectroscopic factors of the deuteron and nucleus B, respectively; C_d and $C_B^{l_fj_f}$ are the proton or neutron ANCs of the deuteron and nucleus B, respectively; l_f and j_f are the orbital angular momentum and total angular momentum of the transferred proton or neutron in nucleus B; $(d\sigma/d\Omega)_{l_fj_f}^{\mathrm{DWBA}}$ is the DWBA calculation curve. $R_{l_fj_f}$ can be obtained through DWBA calculations, expressed as:

$$R_{l_fj_f} = \frac{\sigma_{\mathrm{DWBA}}^{l_fj_f}}{(b_d)^2(b_B^{l_fj_f})^2}$$

where $\sigma_{\mathrm{DWBA}}^{l_fj_f}$ is the differential cross section calculated by DWBA theory; b_d and $b_B^{l_fj_f}$ are the ANCs of the bound-state proton or neutron in the deuteron and nucleus B, respectively. Therefore, based on the known proton or neutron ANC or spectroscopic factor of the deuteron, the ANC or spectroscopic factor of the final-state nucleus can be obtained, and then the astrophysical S-factor or reaction rate for the direct capture process of the target reaction A(p/n,γ)B can be calculated according to radiative capture theory.

1.2 Indirect Measurement of Direct Capture

Some nuclear reactions involving radioactive nuclei are extremely important in elemental nucleosynthesis, such as the ^{7}Be(p,γ)^{8}B reaction directly related to the solar neutrino problem [2], the ^{13}N(p,γ)^{14}O reaction that switches on the hot CNO cycle [3], and the ^{8}Li(n,γ)^{9}Li reaction that bridges unstable nuclear gaps in non-standard models of Big Bang nucleosynthesis [4]. Since radioactive nuclei cannot be made into targets, and neutrons cannot be made into targets either, and because cross sections in the astrophysical energy region are extremely low, direct measurements using radioactive beams are very difficult. Therefore, only indirect methods can be used to obtain the astrophysical S-factors and reaction rates for these reactions. On the secondary beam line, this is typically done by measuring the angular distributions of inverse kinematics (d,n) and (d,p) proton or neutron transfer reactions, extracting the spectroscopic factors of the target nucleus based on Distorted Wave Born Approximation (DWBA) analysis, and then calculating the astrophysical S-factors and reaction rates for proton or neutron capture reactions according to radiative capture theory.

Using radioactive nuclear beams produced on the secondary beam line to bombard deuterated polyethylene targets, a ΔE-E detector telescope system composed of a ΔE detector and an annular detector is placed downstream to identify and measure the outgoing ions. When measuring (d,p) reactions, an annular detector can be placed at backward angles to measure the recoil protons. A typical experimental setup is shown in Figure 2 [Figure 2: see original paper].

After measuring the angular distribution of the A(d,n/p)B reaction, the nuclear spectroscopic factor or ANC of target nucleus B can be obtained by comparing experimental results with DWBA calculations, as shown in Equation (1). The ^{7}Be(p,γ)^{8}B reaction is the production reaction for ^{8}B in the Sun and a key reaction for explaining the solar neutrino problem. The contribution of this reaction in the astrophysical energy region mainly comes from the direct capture process, so its zero-energy astrophysical S-factor $S_{17}(0)$ can be directly calculated from the proton ANC or spectroscopic factor of ^{8}B. In 1996, the China Institute of Atomic Energy Nuclear Astrophysics Research Group first applied the ANC method to study this reaction [2]. Using the ^{7}Be beam produced on the secondary beam line to bombard a deuterated polyethylene target, the angular distribution of the ^{7}Be(d,n)^{8}B transfer reaction was measured at a center-of-mass energy of 5.8 MeV, as shown in Figure 3 [Figure 3: see original paper]. The proton ANC of ^{8}B was extracted using DWBA analysis, and the astrophysical S-factor for the ^{7}Be(p,γ)^{8}B reaction was calculated, providing new experimental evidence for the solar neutrino problem and publishing China's first Physics Review Letter article on nuclear physics experiments.

The ^{13}N(p,γ)^{14}O reaction is the conversion reaction from the CNO cycle to the hot CNO cycle. Comparing the two cycles, the β^{+} decay of ^{14}O involved in the hot CNO cycle ($T_1/_2$ = 70.6 s) is much faster than that of ^{13}N in the CNO cycle ($T_1/_2$ = 9.965 min), so the hot CNO cycle produces energy much faster than the CNO cycle. When the CNO cycle converts to the hot CNO cycle, the energy production rate changes rapidly. Therefore, studying the reaction rate of the conversion reaction ^{13}N(p,γ)^{14}O is important for investigating the temperature and density conditions for the mutual conversion between the CNO cycle and hot CNO cycle.

In the astrophysically interesting energy region, the ^{13}N(p,γ)^{14}O reaction is mainly determined by the low-energy tail of the 1^{-} broad resonance (E_R = 527.9 keV) within the Gamow window. Considerable experimental work has been done on this resonance, including direct measurements with ^{13}N beams [5–10] and Coulomb dissociation measurements [11–12]. These studies have well determined the resonance parameters of the 1^{-} broad resonance. The direct capture contribution in the Gamow window is far below the low-energy tail of the 1^{-} resonance capture, but interference between direct capture and resonance capture may have non-negligible effects. Therefore, studying the direct capture contribution is very important for precisely determining the astrophysical S-factor and reaction rate of ^{13}N(p,γ)^{14}O. In 2006, the nuclear astrophysics group measured the angular distribution of the ^{13}N(d,n)^{14}O reaction on the secondary beam line, extracted the proton ANC of ^{14}O, and combined it with R-matrix calculations to provide the astrophysical S-factor and reaction rate for the ^{13}N(p,γ)^{14}O reaction [3], as shown in Figure 4 [Figure 4: see original paper]. Due to consideration of the direct process contribution, the total S-factor obtained in this work is about 40% larger than the result in reference [13] and consistent with the result given in reference [14]. The calculated reaction rate data is about two times larger than the result adopted by the NACRE database in the temperature range $T_9 < 0.1$ (where T_9 is temperature in units of 10^9 K).

Similar to the ^{13}N(p,γ)^{14}O reaction, the key reaction ^{11}C(p,γ)^{12}N for the second and third branches of the rapid αp (rap) process has contributions from both direct capture and resonance capture in the astrophysically interesting temperature range. Likewise, the nuclear astrophysics group measured the angular distribution of the ^{11}C(d,n)^{12}N reaction on the secondary beam line through inverse kinematics, extracted the proton ANC of ^{12}N, and calculated the astrophysical S-factor and reaction rate for the direct capture of the ^{11}C(p,γ)^{12}N reaction [15].

There are no stable nuclei at mass number A = 8. ^{8}Li plays an important role in non-standard models of primordial nucleosynthesis in the Big Bang and in the r-process of Type II supernova explosions. The ^{8}Li(p,γ)^{9}Be and ^{8}Li(n,γ)^{9}Li reactions are important for bridging the stable nuclear gap at A = 8. Both reactions were indirectly measured on the secondary beam line using the ^{8}Li beam. The reaction angular distributions of ^{8}Li(d,n)^{9}Be and ^{8}Li(d,p)^{9}Li were obtained through inverse kinematics. Based on DWBA analysis, the proton spectroscopic factor of ^{9}Be and the neutron spectroscopic factor of ^{9}Li were extracted, and for the first time internationally, the direct capture cross sections and astrophysical reaction rates for ^{8}Li(p,γ)^{9}Be and ^{8}Li(n,γ)^{9}Li were obtained [4,16]. The reaction angular distribution of ^{8}Li(d,p)^{9}Li and the astrophysical reaction rate of ^{8}Li(n,γ)^{9}Li are shown in Figure 5 [Figure 5: see original paper], demonstrating that direct capture dominates when $T_9 < 1$.

1.3 Nuclear Astrophysics Research Using the Mirror Nucleus Method

The ANC method based on charge symmetry of mirror nuclei is not exactly the same as the conventional ANC method. Mirror nuclei are two nuclei with equal mass numbers, where exchanging the proton and neutron numbers of one nucleus yields the other. Since nuclear forces are approximately charge-independent, the structures of corresponding energy levels in a pair of mirror nuclei are similar. Assuming that nuclei B and D are mirror nuclei, we can indirectly obtain information about the target nucleus D by studying the more easily measurable nucleus B. Taking the study of the C(p,γ)D reaction as an example, the conventional ANC method requires measuring a proton transfer reaction, such as the C(d,n)D reaction, then extracting the proton ANC of nucleus D through DWBA analysis, and subsequently obtaining the astrophysical S-factor and reaction rate for the direct capture of the C(p,γ)D reaction. In the ANC method combining charge symmetry of mirror nuclei, what is measured is the neutron transfer reaction of the mirror nucleus, such as the A(d,p)B reaction. The neutron ANC of nucleus B is extracted through DWBA analysis, then the proton ANC or proton width of nucleus D is derived using charge symmetry of mirror nuclei, and finally the astrophysical S-factor and reaction rate for the

C(p,γ)D reaction can be obtained.

The nuclear astrophysics group used the ANC method combining charge symmetry of mirror nuclei to study four important reactions in the hydrogen-burning stage of stellar evolution: ^{8}B(p,γ)^{9}C, ^{11}C(p,γ)^{12}N, ^{13}N(p,γ)^{14}O, and ^{26}Si(p,γ)^{27}P [17–18]. The ^{8}B(p,γ)^{9}C reaction is one of the important reactions in the fourth branch of the pp reaction chain and the first branch of the rapid αp process. Based on the angular distribution measured for the ^{8}Li(d,p)^{9}Li reaction on the secondary beam line, the integrated cross section for this reaction channel and the neutron ANC of the ^{9}Li ground state were extracted through DWBA analysis. Then, according to charge symmetry of mirror nuclei, the proton ANC of the ^{9}C ground state was given, and the astrophysical S-factor and reaction rate for the direct capture of the ^{8}B(p,γ)^{9}C reaction were derived. Additionally, the reaction rate for resonance capture from the first excited state of ^{9}C was calculated using existing resonance parameters. The results show that direct capture dominates in the astrophysically interesting temperature range.

By analyzing the angular distributions of the neutron transfer reaction ^{11}B(d,p)^{12}B populating the ground state, first excited state, and second excited state of ^{12}B, the neutron ANCs for these three states were extracted. Then, using charge symmetry of mirror nuclei, the proton ANC of the ^{12}N ground state and the proton widths of the 2^{+} and 2^{-} resonance states were obtained. Consequently, the astrophysical S-factor and reaction rate for the ^{11}C(p,γ)^{12}N reaction were derived, with the total S-factor and reaction rate including contributions from direct capture, two resonance captures, and interference between direct capture and the 2^{-} resonance capture. The results show that direct capture dominates when $T_9 < 0.35$, while the 2^{+} resonance capture dominates when $T_9 > 0.35$.

By analyzing the angular distribution of the neutron transfer reaction ^{13}C(d,p)^{14}C populating the ground state, the neutron ANC of the ^{14}C ground state was extracted. Then, according to charge symmetry of mirror nuclei, the proton ANC of the ^{14}O ground state was obtained. Combined with R-matrix calculations, the astrophysical S-factor and reaction rate for the ^{13}N(p,γ)^{14}O reaction were calculated, and the results are consistent with those from indirect measurements using the ^{13}N(d,n)^{14}O reaction.

The ^{26}Si(p,γ)^{27}P reaction may affect the equilibrium abundances of the ground state and isomeric state of the important γ-ray astronomy nuclide ^{26}Al. Similarly, using the mirror nucleus method, the angular distributions of the neutron transfer reaction ^{26}Mg(d,p)^{27}Mg populating the ground state, first excited state, and second excited state were analyzed, and the neutron ANCs for these three states were extracted. Then, the proton ANC of the ^{27}P ground state and the proton widths of the $3/2^{+}$ and $5/2^{+}$ resonance states were obtained, and the astrophysical S-factor and reaction rate for the ^{26}Si(p,γ)^{27}P reaction were derived. For the first time experimentally, the direct capture contribution to the ^{26}Si(p,γ)^{27}P reaction was given. The results show that direct capture dominates in the ^{26}Si(p,γ)^{27}P reaction when $T_9 < 0.1$.

This method makes fuller use of the existing radioactive secondary beams on the GIRAFFE secondary beam line at the HI-13 tandem accelerator, broadening the scope of experimental research and indirectly obtaining cross sections for proton radiative capture reactions that still lack experimental data or reducing their uncertainties.

1.4 Related Nuclear Structure Studies

The nuclear astrophysics group has also conducted some nuclear structure studies using radioactive beams produced on the secondary beam line, mainly exploring halo nuclei and investigating level properties using the thick-target elastic resonance scattering method.

As early as 2002, using a 25 MeV ^{6}He beam, the angular distribution of the inverse kinematics reaction ^{1}H(^{6}He,^{6}Li)n populating the 3.563 MeV excited state was measured [21–22], as shown in Figure 6 [Figure 6: see original paper]. The experimental results show that the angular distribution of this reaction has a considerable cross section near 90° in the center-of-mass system. Only DWBA calculations using ^{6}Li and ^{6}He with halo structure can reproduce the experimental data well, proving that both ^{6}He and ^{6}Li$_{3\cdot563}$ *have halo structures, with* ^{6}*He being a two-neutron halo nucleus and* ^{6}*Li*$_{3\cdot563}$ being a proton-neutron halo. This was the first discovery of the halo structure of the 3.563 MeV 0^+ state of ^{6}Li, verifying theoretical predictions that certain excited states of stable nuclei can have halo structures like neutron drip-line nuclei, while providing a new method for radioactive nuclear beam experimental research.

The elastic resonance scattering method is mainly used to study resonance capture processes in reactions. By measuring the excitation function of elastic resonance scattering reactions, the resonance energy, spin-parity, and level width of the compound nucleus can be obtained, and then combined with R-matrix calculations to obtain the astrophysical reaction rate for resonance capture reactions. Thick-target elastic resonance scattering experiments stop most or even all of the beam energy in the reaction target. The beam continuously loses energy while being stopped and continuously reacts with target nuclei, allowing the excitation function to be obtained from a single beam energy. The nuclear astrophysics group conducted thick-target elastic resonance scattering experiments using ^{13}N and ^{17}F radioactive beams [23–25].

The excitation function obtained from the ^{13}N + p experiment is shown in Figure 7 [Figure 7: see original paper]. This experiment observed for the first time a new 0^- level at 5.7 MeV excitation energy in ^{14}O and determined the spin of the 6.8 MeV level, while obtaining resonance parameters for the levels listed in the figure, providing an independent cross-check for existing experimental data.

The excitation function obtained from the ^{17}F + p elastic resonance scattering experiment is shown in Figure 8 [Figure 8: see original paper]. Combined with R-matrix analysis, the spins, parities, and proton widths of the two levels at 4.52 MeV and 5.11 MeV above the proton threshold in ^{18}Ne were obtained. These two levels correspond to the 0.60 MeV and 1.19 MeV resonances in ^{17}F(p,γ)^{18}Ne. Based on the experimentally obtained resonance parameters, the astrophysical reaction rate for ^{17}F(p,γ)^{18}Ne was calculated, with the 0.60 MeV resonance dominating when $T_9 > 0.5$.

Studies of Stable Nuclear Radiative Capture Reactions

2.1 Q3D Magnetic Spectrometer

The Q3D magnetic spectrometer is a large magnetic spectrometer designed by Scanditronix of Sweden and imported by the Beijing Tandem Accelerator Nuclear Physics National Laboratory. The Q3D was designed by Professor Enge of MIT based on multi-gap magnetic spectrometers and split-pole magnetic spectrometers [26]. The advantages of the Q3D magnetic spectrometer include high energy resolution, large dispersion, high momentum acceptance, and strong kinematic correction capability. As shown in Figure 9 [Figure 9: see original paper], the Q3D magnetic spectrometer system consists of a rotatable target chamber, a quadrupole magnet, three dipole magnets, and a detector chamber.

Theoretically, the Q3D magnetic spectrometer has a momentum resolution of about 10^{-4} and an energy resolution of 2\$×10^{-4}\$. However, in practice, due to the beam quality provided by the accelerator, such as beam spot size, energy straggling caused by different reaction positions in the target, and angular dispersion of reaction products after passing through the target, all cause broadening of the outgoing ions' positions on the focal plane, thereby reducing the energy resolution of the Q3D. Additionally, the Q3D magnetic spectrometer can rotate continuously between 22° and 155° with an angular readout error of \$±\$0.02°, making it very suitable for precise measurement of reaction angular distributions.

The original focal plane detector for the Q3D magnetic spectrometer was a single-wire ionization chamber with an effective detection length of about 1 m. However, gas ionization chambers are only suitable for measuring light ions such as hydrogen and helium. Heavier ions lose too much energy in the ionization chamber window and are not suitable for measurement with gas ionization chambers, so the focal plane detector needs to be upgraded.

Since 2009, the nuclear astrophysics group has attempted to use silicon detectors that can provide two-dimensional position or quasi-two-dimensional position sensitivity for measurements. Finally, the X4 quasi-two-dimensional position-sensitive silicon detector jointly developed with MICRON was adopted. The X4 detector has an effective detection area of 75 mm × 40 mm, divided into 8 strips in the vertical direction, with signals extracted from both ends in the horizontal direction. The position information of measured ions is calculated based on the difference between the signals from the two ends, achieving a position resolution of 0.4 mm (Full Width Half Maximum, FWHM). We installed 6 X4 detectors at 55 mm intervals on a moving platform with micron-level precision to form a detector array, as shown in Figure 10 [Figure 10: see original paper]. Through two successive measurements with a position difference of 65 mm covering the focal plane, an 800 mm range on the Q3D magnetic spectrometer focal plane can be covered. This enables measurement of heavier ions on the Q3D magnetic spectrometer. Over more than a decade, various beams including d, ^{6}Li, ^{7}Li, ^{9}Be, ^{11}B, ^{12}C, ^{13}C, ^{16}O, and ^{23}Na have been used to conduct experimental studies on elastic scattering, single-nucleon transfer, α-cluster transfer, and other different types of reactions.

2.2 Single-Nucleon Transfer Reactions

Given that the Q3D magnetic spectrometer has excellent energy and angular resolution, ion identification can be easily achieved through the energy and position information of the focal plane detector, while enabling fine measurements of angular distributions near zero degrees, which is very conducive to extracting nuclear spectroscopic factors or ANCs. The nuclear astrophysics group precisely determined the proton spectroscopic factor of ^{7}Li through measurement of the ^{6}He(d,n)^{7}Li reaction on the secondary beam line [27]. The DWBA-calculated angular distributions for the (^{7}Li,^{6}He) reaction can reproduce the experimental measurements well. Moreover, the ^{6}He ions emitted from the (^{7}Li,^{6}He) reaction have high magnetic rigidity and are less susceptible to interference. Therefore, the (^{7}Li,^{6}He) reaction is often selected as a tool reaction on the Q3D magnetic spectrometer to extract proton spectroscopic factors of target nuclei.

We first measured the angular distributions of the transfer reactions ^{12}C(^{7}Li,^{6}He)^{13}N and ^{13}C(^{7}Li,^{6}He)^{14}N on the Q3D magnetic spectrometer [28–29], while simultaneously measuring the elastic scattering angular distributions of the entrance channels to extract optical potential parameters. Typical angular distribution measurement results are shown in Figure 11 [Figure 11: see original paper]. Finally, relatively precise proton spectroscopic factors for ^{13}N and ^{14}N were obtained through combined DWBA analysis, which are basically consistent with most existing international results within error ranges, thereby verifying the reliability of our experimental results. Based on the obtained spectroscopic factor results, fits were made to higher-energy direct measurement data for the key CNO cycle reactions ^{12}C(p,γ)^{13}N and ^{13}C(p,γ)^{14}N, yielding the zero-energy astrophysical S-factors and reaction rates for these two proton capture reactions and correcting existing resonance parameters.

The experimental results for the proton spectroscopic factor of ^{9}Be have historically shown large discrepancies. Based on the ^{14}N proton spectroscopic factor obtained above, we designed and measured the angular distribution of the ^{13}C(^{9}Be,^{8}Li)^{14}N reaction [30], using the ^{14}N proton spectroscopic factor to obtain the ^{9}Be proton spectroscopic factor. The obtained angular distribution and theoretical calculation results are shown in Figure 12 [Figure 12: see original paper], which are clearly more precise and reliable than the measurement results obtained using the ^{8}Li beam on the secondary beam line [31]. The final ^{9}Be proton spectroscopic factor is consistent with the average value of all previous international results, thereby eliminating existing discrepancies.

On the Q3D magnetic spectrometer, the (^{7}Li,^{6}He) reaction has also been used to conduct indirect measurements of resonance strengths for (p,γ) resonance capture. First, the angular distribution of the ^{25}Mg(^{7}Li,^{6}He)^{26}Al reaction populating the corresponding 58 keV above-threshold state was measured [32]. Additionally, using the X4 detector array for the first time, the angular distributions populating the ground state and the first 10 excited states of this transfer reaction were obtained through successive measurements covering the focal plane. The obtained energy spectrum is shown in Figure 13 [Figure 13: see original paper]. DWBA calculations reproduced all angular distributions well, allowing extraction of the proton spectroscopic factor for ^{26}Al*$_{6\cdot356}$. The proton width of the 58 keV resonance state was calculated according to $\Gamma_p = C^2S_p\Gamma_{sp}$, where C^2 is the CG coefficient, S_p is the spectroscopic factor, and Γ_{sp} is the calculated single-particle width. The resonance strength is given by:

$$\omega\gamma_i = \frac{\Gamma_p\Gamma_\gamma}{\Gamma_{\text{tot}}}\frac{(2J_i+1)}{(2j_p+1)(2j_t+1)}$$

where J_i, j_p, and j_t are the spins of the resonance state, incident particle, and target nucleus, respectively. Since the ratio of γ width to total width $\Gamma_\gamma/\Gamma_{tot}$ 1 for the 58 keV resonance (E_x = 6.364 MeV, $J^\pi = 3^+$) in the ^{25}Mg(p,γ)^{26}Al reaction [32], the resonance strength was calculated based on the measured spectroscopic factor results. This study eliminated the previous two-fold discrepancy in international spectroscopic factor results. The final astrophysical reaction rate for ^{25}Mg(p,γ)^{26}Al is about 15% larger than NACRE in the temperature range where this resonance plays a role, with the reaction rate uncertainty reduced by about half.

To study the ^{15}N(n,γ)^{16}N reaction, the angular distributions of the ^{15}N(^{7}Li,^{6}Li)^{16}N reaction populating four sub-threshold states were measured on the Q3D magnetic spectrometer. Similarly, to eliminate uncertainties from optical potentials, elastic scattering angular distributions of ^{6},^{7}Li interacting with ^{14},^{15}N were measured respectively. The final transfer reaction angular distributions and theoretical calculation results are shown in Figure 14 [Figure 14: see original paper]. The calculations also reproduced the experimental data well, allowing extraction of the neutron spectroscopic factors for the four sub-threshold states of ^{16}N and calculation of the astrophysical reaction rate for the ^{15}N(n,γ)^{16}N reaction [33]. Additionally, the proton widths of four resonance states for the ^{15}O(p,γ)^{16}F reaction were determined using the mirror nucleus method [34].

In addition to the two single-nucleon transfer reactions (^{7}Li,^{6}He) and (^{7}Li,^{6}Li), (d,p) and (^{13}C,^{12}C) reactions were also used to determine spectroscopic factors for Zr and Sn isotopes [35–36]. Furthermore, elastic transfer reactions such as ^{6}Li(^{7}Li,^{6}Li)^{7}Li and ^{12}C(^{11}B,^{12}C)^{11}B were measured. The advantage of elastic transfer reactions is that no spectroscopic factors or ANCs of other nuclei need to be introduced in DWBA analysis, naturally avoiding errors from other spectroscopic factors or ANCs. Using these two reactions, the neutron spectroscopic factor of ^{7}Li and proton spectroscopic factor of ^{12}C were extracted, which can be further used to calculate the astrophysical reaction rates for ^{6}Li(n,γ)^{7}Li [37] and ^{11}B(p,γ)^{12}C [38].

Alpha Cluster Transfer Reactions

Alpha cluster capture reactions are an important class of reactions in astrophysical nucleosynthesis processes, including key reactions such as the helium-burning process reaction ^{12}C(α,γ)^{16}O, the rapid αp process reaction ^{7}Be(α,γ)^{11}C, and a series of neutron source reactions in neutron capture processes such as ^{13}C(α,n)^{16}O and ^{22}Ne(α,n)^{25}Mg. The astrophysical S-factors, reaction cross sections, and reaction rates of these reactions are key inputs for nuclear astrophysics network model calculations, and their accurate experimental measurement greatly influences our understanding of stellar evolution and the nucleosynthesis of medium and heavy elements.

The ANC method based on transfer reactions uses α-cluster transfer reactions to populate the levels that make important contributions in α-cluster capture reactions. Combined with DWBA, the α-cluster widths of above-threshold states and the reduced widths and ANCs of sub-threshold states are obtained and input into Breit-Wigner formulas or R-matrix calculations to derive the capture reaction cross sections and reaction rates. Commonly used α-cluster transfer reaction systems include (^{6}Li,d), (^{7}Li,t), and (^{11}B,^{7}Li). Since the α separation energy of ^{11}B is higher than that of ^{6}Li and ^{7}Li, the (^{11}B,^{7}Li) transfer system has smaller contributions from breakup channels and compound nuclear processes during transfer, with the direct process dominating, which is more conducive to simplifying the theoretical analysis of experimental data and yields smaller systematic errors in the extracted level information. The nuclear astrophysics team has completed studies of reactions such as ^{13}C(α,n)^{16}O, ^{12}C(α,γ)^{16}O, and ^{7}Li(^{6}Li,d)^{11}B on the Q3D magnetic spectrometer using the (^{11}B,^{7}Li) transfer system.

^{13}C(α,n)^{16}O is the main neutron source reaction for the s-process, and precise measurement of its astrophysical S-factor has always been a key research topic. Three previous works internationally gave astrophysical S-factors that differed by 5–25 times [39–41], as shown in Figure 15 [Figure 15: see original paper] [42]. To understand these huge discrepancies, we completed a new α-cluster transfer reaction experiment in 2011 using the (^{11}B,^{7}Li) transfer system for the first time. The results demonstrated that experimental results do not change with different transfer systems or energy variations, refuting the viewpoint of researchers at the Italian National Institute of Nuclear Physics (INFN) that these discrepancies originated from indirect measurement methods [43], and ultimately understanding and clarifying the 5–25 fold discrepancy between S-factor data [42]. This work was the first nuclear physics experimental research result from China published in *The Astrophysical Journal*.

The ^{11}B ground state spectroscopic amplitude is a key input for DWBA calculations when using the (^{11}B,^{7}Li) system. However, previously there were only theoretical predictions from two theoretical calculations [44–45], lacking reliable experimental data. We used the ^{7}Li(^{6}Li,d)^{11}B reaction to experimentally determine the ground state spectroscopic amplitude of ^{11}B for the first time. The new results show that using shell model spectroscopic amplitudes in the past would have overestimated the astrophysical S-factors for the ^{12}C(α,γ)^{16}O and ^{13}C(α,n)^{16}O reactions by 23% and 34%, respectively, which would affect understanding of stellar helium burning and the origin of elements in the universe. This result demonstrates the importance of using experimental data for the ^{11}B spectroscopic amplitude and provides basic data for the application of the (^{11}B,^{7}Li) transfer system to astrophysical nuclear reactions [46].

The ^{12}C(α,γ)^{16}O reaction is a key reaction in the helium-burning process. Competing with the 3α process, it determines the abundance ratio of carbon and oxygen elements in the universe, which has important implications for the origin of life, evolution of massive stars, and element synthesis. Its precise measurement is recognized as one of the most critical scientific problems in nuclear astrophysics [47] and is hailed as the "holy grail" of nuclear astrophysics. Stellar evolution model calculations require the precision of this reaction cross section to be better than 10%. However, the uncertainties in cross sections (S-factors) obtained by various measurement methods are far from meeting the model requirements. Due to uncertainties in the ^{16}O bound state potential, the asymptotic ANC results for the ^{16}O ground state show a 240-fold discrepancy [48–51], making it impossible to accurately determine the E2 cross section of the ^{12}C(α,γ)^{16}O reaction. Through our independently established (^{11}B,^{7}Li) transfer reaction method with less breakup effect interference, and through precise angular distribution measurements and effective constraints on the ^{16}O bound state potential, we obtained a high-precision ^{16}O ground state ANC of (337 ± 45) $\mathrm{fm}^{-1}/^{2}$, clarifying the 240-fold discrepancy in international data [52]. Using the new ANC, the SE2(300) factor for the ^{12}C(α,γ)^{16}O reaction is (70 ± 7) keV • b, which is 55% higher than the latest internationally recommended value [15]. Moreover, the S-factor constrained by direct measurement data alone has an uncertainty of 56%, which was improved to 10% after including the new ^{16}O ground state ANC data [52], as shown in Figure 16 [Figure 16: see original paper].

According to stellar structure and evolution theory, there is a mass gap for stellar-mass black holes. Within this gap, high-energy γ-rays in the stellar core are effectively converted into electron-positron pairs. The reduction in γ-rays weakens the thermal pressure generated inside the core, causing the star to collapse rapidly and subsequently produce a supernova explosion that completely disrupts the star. Based on the research by the CIAE nuclear astrophysics team on the ^{12}C(α,γ)^{16}O reaction, the increased astrophysical reaction rate for

^{12}C(α,γ)^{16}O can enhance the abundance of ^{16}O after core helium burning in massive stars. Enhanced oxygen burning favors the production of more electron-positron pairs, lowering the position of the black hole mass gap. The CIAE nuclear astrophysics team collaborated with domestic and international colleagues to study the impact of the ^{12}C(α,γ)^{16}O reaction on black holes. The results lowered the upper limit of the black hole mass gap from 139 to 132 solar masses and the lower limit from 59 to 52 solar masses, as shown in Figure 17 [Figure 17: see original paper] [54]. This result provides a reliable theoretical explanation for the mass distribution of numerous stellar-mass black holes discovered by LIGO-Virgo [54].

Results and Discussion

This paper summarizes the nuclear astrophysics research conducted by the CIAE nuclear astrophysics team based on the tandem accelerator. Most experiments on the secondary beam line used the ANC method or spectroscopic factor method, studying the direct capture processes of important astrophysical reactions such as ^{7}Be(p,γ)^{8}B, ^{11}C(p,γ)^{12}N, ^{13}N(p,γ)^{14}O, and ^{8}Li(n,γ)^{9}Li through inverse kinematics measurements of transfer reactions to obtain their astrophysical S-factors or reaction rates. Additionally, spectroscopic factor results from reactions such as ^{6}He(d,n)^{7}Li provided an experimental foundation for establishing tool reactions like (^{7}Li,^{6}He). Based on these studies, the ANC method combining charge symmetry of mirror nuclei was developed, broadening the scope of experimental research. The thick-target elastic resonance scattering experimental method was established, and the resonance levels of ^{14}O and ^{18}Ne were studied through ^{13}N + p and ^{17}F + p thick-target experiments. The neutron-proton halo structure of the second excited state of ^{6}Li was also demonstrated through the ^{1}H(^{6}He,^{6}Li)n charge-exchange reaction. It is hoped that after the completion of the superconducting post-accelerator upgrade of the tandem accelerator, the energy and quality of radioactive nuclear beams on the secondary beam line can be further improved and more types of beams added, enabling studies of more nuclear reactions involving unstable nuclei of interest to nuclear astrophysics.

We have continuously upgraded the detection equipment, data acquisition, and automatic control of the Q3D magnetic spectrometer, fully exploiting the spectrometer's resolution capabilities. Similarly, based on the spectroscopic factor or ANC method, single-nucleon capture reactions such as ^{12}C(p,γ)^{13}N, ^{13}C(p,γ)^{14}N, ^{15}N(n,γ)^{16}N, ^{15}O(p,γ)^{16}F, ^{8}Li(p,γ)^{9}Be, ^{6}Li(n,γ)^{7}Li, and ^{11}B(p,γ)^{12}C have been studied by measuring transfer reactions such as (^{7}Li,^{6}He), (^{7}Li,^{6}Li), and (^{9}Be,^{8}Li). The spectroscopic factor method has been extended to indirect measurements of near-threshold resonances above threshold, obtaining the proton width and resonance strength of the 58 keV resonance in the ^{25}Mg(p,γ)^{26}Al reaction, expanding the research field of indirect methods. Additionally, using the (^{11}B,^{7}Li) transfer system on the Q3D magnetic spectrometer, studies of reactions such as ^{13}C(α,n)^{16}O, ^{12}C(α,γ)^{16}O, and ^{7}Li(^{6}Li,d)^{11}B have been completed, establishing an experimental method for extracting α spectroscopic factors.

Since the other two Q3D magnetic spectrometers internationally have been retired, the Q3D magnetic spectrometer at the tandem laboratory, after continuous upgrades and renovations, continues to operate stably, attracting considerable international attention and collaboration interest. The nuclear astrophysics group plans to continue studying the direct capture processes and near-threshold resonances of proton capture reactions related to the CNO cycle and NeNaMgAl cycle, such as ^{14}N(p,γ)^{15}O, ^{15}N(p,γ)^{16}O, ^{16}O(p,γ)^{17}F, ^{17}O(p,γ)^{18}F, ^{18}O(p,γ)^{19}F, ^{19}F(p,γ)^{20}Ne, ^{20}Ne(p,γ)^{21}Na, ^{26}Mg(p,γ)^{27}Al, and ^{27}Al(p,γ)^{28}Si, through transfer reaction measurements. The group also plans to study important astrophysical reactions such as ^{9}Be(α,n)^{12}C, ^{17}O(α,n)^{20}Ne, ^{22}Ne(α,n)^{25}Mg, and ^{16}O(α,γ)^{20}Ne through measurements of α-cluster transfer reactions.

For 30 years since its establishment, the CIAE nuclear astrophysics team has achieved fruitful research results based on the two major experimental platforms of the tandem accelerator national laboratory's secondary beam line and Q3D magnetic spectrometer. Over these 30 years, the team has continuously broken through and innovated, exploring new research directions. Relying on years of accumulated experimental experience at the tandem laboratory, a united and capable research team has been built. Combined with CIAE's advantages in accelerator and detector development, a new base for nuclear astrophysics experiments has been established at the Jinping Underground Laboratory, always dedicated to exploring the mysteries of nuclear astrophysics.

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Author Contributions

LI Jiayinghao and LI Yunju jointly completed article writing, figure selection, and literature organization. All authors checked and revised the article.

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