Progress in Experimental Studies of the Proton-Drip-Line Nucleus ^{9}C

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Date: 2023-07-12T00:00:00+00:00

Abstract

The possible cluster structure of the proton drip-line nucleus ^{9}C is of great significance for understanding exotic nuclear structures and nucleon interactions; furthermore, ^{9}C also holds a very important position in nuclear astrophysics research, thereby attracting tremendous attention. Researchers have conducted extensive experimental investigations on ^{9}C, covering decay properties, level structures, magnetic dipole moments, nuclear astrophysics S factors, reaction cross-sections, and other aspects, achieving numerous results; however, the understanding of ^{9}C remains insufficient. With the construction and operation of next-generation high-intensity heavy-ion accelerator facilities, combined with novel experimental methods and higher-efficiency detection apparatus, higher-precision experimental data are expected to be obtained, deepening the comprehension of the exotic structure and reaction mechanisms of ^{9}C.

Full Text

Preamble

Vol. 37 No. 1

Jul. 2023

Nuclear Physics Review, Vol. 37, No. 1, Jul. 2023
Article ID: 1007-4627(2023)01-0040-16

Experimental Study on Proton Drip-line Nucleus 9C

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Abstract

The possible cluster structure of the proton drip-line nucleus 9C is of great significance for understanding exotic nuclear structures and nucleon interactions. Additionally, 9C holds a crucial position in nuclear astrophysics research. Consequently, 9C has attracted tremendous attention. Researchers have conducted extensive experimental investigations of 9C, covering decay properties, level structure, magnetic dipole moments, nuclear astrophysics S-factors, reaction cross sections, and other aspects, yielding numerous achievements. However, our understanding of 9C remains incomplete. With the construction and operation of next-generation high-intensity heavy-ion accelerator facilities, combined with novel experimental methods and higher-efficiency detection equipment, we anticipate obtaining higher-precision experimental data that will deepen our understanding of the exotic structure and reaction mechanisms of 9C.

Keywords: proton drip-line nucleus; 9C; exotic structure; reaction mechanism; nuclear reaction experiment

1. Introduction

Over the past several decades, with the establishment and upgrading of radioactive beam facilities worldwide, experimental and theoretical studies of radioactive beams have gradually become a frontier field in nuclear physics, yielding a series of achievements [1]. Radioactive nuclei, particularly drip-line nuclei, exhibit many exotic properties distinct from stable nuclei, such as enhanced reaction cross sections, anomalous neutron-to-proton ratios, and valence-nucleon halo structures. Systematic studies of the exotic structures and reaction mechanisms of radioactive nuclei not only create new opportunities for improving and developing traditional nuclear theoretical models but also hold great significance for related fields such as nuclear astrophysics [2-4].

As the most proton-rich carbon isotope, 9C is not only a proton drip-line nucleus but also possesses the largest Z/N ratio (=2) among all bound nuclei discovered to date (identical to 3He), which has attracted researchers' attention since early on. 9C has a half-life of approximately 126.5 ms [5], a single-proton separation energy of S__p = 1.300 MeV, a two-proton separation energy of S__{2p} = 1.436 MeV [6], a matter distribution radius of 2.43 fm, and a charge distribution radius of 3.35 fm [7]. Its low separation thresholds and large radius have led to 9C being widely recognized as a candidate for proton halo structure. On one hand, theoretical studies suggest that 9C may possess exotic cluster structures such as 8B+p, 7Be+p+p, 3He+3He+3He, and 4He+3He+p+p (Figure 1 [Figure 1: see original paper]), which are crucial for understanding properties such as its electric quadrupole and magnetic dipole moments and can deepen our understanding of nuclear cluster structures and nucleon interactions [8-9]. On the other hand, in nuclear astrophysics, in low-metallicity, very massive stars, the proton capture reaction on 8B, 8B(p,γ)9C, ignites explosive hydrogen burning (Hot pp chain): 8B(p,γ)9C(α,p)12N(p,γ)13O(β+)13N(p,γ)14O. This process is considered one of the possible pathways for CNO element synthesis, making the determination of the 8B(p,γ)9C reaction rate critically important [10]. Thus, the proton drip-line nucleus 9C holds exceptionally high research value.

Researchers have conducted numerous studies on the exotic structure and reaction mechanisms of 9C from various perspectives, including decay properties, level structure, magnetic dipole moments, nuclear astrophysics S-factors, and reaction cross sections. This review, combined with work carried out at the Institute of Modern Physics, Chinese Academy of Sciences (IMP-CAS), introduces the experimental research progress on 9C from major laboratories worldwide.

2. Decay Properties

Nuclear decay refers to the spontaneous transformation of an atomic nucleus through the emission of radiation and energy. The decay half-life can be regarded as an intrinsic property of the nucleus, depending only on the type of radioactive nuclide and not changing with environmental conditions such as temperature or gravity. Nuclear decay is one of the important pathways to understanding nuclear properties. Experimental studies of 9C decay began early, initially focusing on the decay properties of 9C itself. In recent years, researchers have begun investigating isospin symmetry by comparing the decays of 9C and its mirror nucleus 9Li.

In 1956, while processing nuclear emulsions containing nuclear fragments produced by high-energy proton irradiation, Swami et al. believed they might have observed the decay of 9C, which may represent the first experimental observation of 9C [11]. Nuclear emulsion is a special photographic emulsion developed from ordinary photographic emulsion, primarily composed of a mixture of silver bromide microcrystals and gelatin. As a track detector, nuclear emulsion offers the advantage of permanently preserving high-energy particle tracks with unique spatial resolution, allowing particle identification and energy determination from the tracks, making it suitable for studying extremely short-lived particles. Its disadvantages include the need for development and fixing processes, inability to obtain immediate results, and poor energy resolution. Swami et al.' s results are shown in Figure 2 [Figure 2: see original paper]. After 9C (track F) was produced, it decayed into four charged particles, leaving four tracks in the nuclear emulsion. Upon identification, these were found to be a 7.6 MeV proton (track 1), two α particles with energies of 2.7 MeV (track 2) and 2.1 MeV (track 3), and a 3.1 MeV positron (track 4). Through analysis, they proposed that 9C decayed via $\beta+$ delayed single-proton emission, after which the unstable 8Be* decayed into two α particles. The complete decay process was 9C $\rightarrow$ 4He + 4He + p + + $\beta+$ + Q. Using the energies and angles of the decay products, they calculated that the mass of 9C should lie between 8408.6 MeV and 8409.6 MeV, very close to later measured values (~8412.4 MeV) [6]. However, since they observed only a single event, they could not conduct more in-depth studies or reach definitive conclusions.

In 1965, Hardy et al. produced 9C through the reactions 12C(p,d2n)9C, 10B(p,2n)9C, and 11B(p,3n)9C, using silicon surface-barrier detectors to measure protons emitted from 9C decay on the reaction target [12]. The experiment detected two proton peaks in the center-of-mass system at 12.25 $\pm$ 0.20 MeV and 9.25 $\pm$ 0.25 MeV, with nearly equal intensities. Hardy et al. analyzed that these two proton peaks corresponded to protons emitted from 9B produced after 9C emitted $\beta+$ particles, with 9B decaying to the ground state and first excited state of 8Be. Through multiple independent measurements of the two decay proton peaks, they obtained a consistent 9C half-life of 127 $\pm$ 3 ms. In 1971, Hardy et al. remeasured the 9C half-life using the 10B(p,2n)9C reaction at 43 MeV, obtaining 126.5 $\pm$ 1 ms [13]. In the same year, Mosher et al. studied 9C decay using the 7Be(3He,n)9C reaction and obtained a half-life of 126.5 $\pm$ 2 ms by measuring $\beta+$ delayed protons [5]. In 1972, Esterl et al. remeasured the $\beta+$ delayed proton spectrum of 9C via the 10B(p,2n)9C reaction. In addition to the previously observed peaks at 9.28 MeV and 12.30 MeV, they observed two new peaks at 3.45 $\pm$ 0.25 MeV and 6.10 $\pm$ 0.10 MeV, which they suggested might correspond to two unknown levels in 9B. They also obtained a half-life consistent with previous studies: 126.5 $\pm$ 1 ms [14].

In 1988, Mikolas et al. at NSCL (National Superconducting Cyclotron Laboratory) used a 35 AMeV 12C4+ beam bombarding a 91 mg/cm^2 Ni target to produce 9C secondary beams and studied 9C decay properties using the implantation-decay method [15]. Chen et al. first applied the implantation-decay method in studies of 9C' s mirror nucleus 9Li [16]. Compared to previous methods that detected decay products of parent nuclei on reaction targets, the implantation-decay method allows precise measurement of all decay products since the parent nucleus is implanted into the detector. By analyzing decay products, Mikolas et al. observed for the first time 9C decay to the ground state ($3/2^-$) and two lower excited states (2.36 MeV, $5/2^-$ and 2.9 MeV, $1/2^-$) of 9B, obtaining relatively precise branching ratios of 60 $\pm$ 10%, 17 $\pm$ 6%, and 11 $\pm$ 5%, respectively. Comparing with previous theoretical calculations and experimental results for the mirror nucleus 9Li, they found a clear asymmetry in the decay strengths (B_{GT}) from the $3/2^-$ ground state to the $5/2^-$ states of 9B and 9Be. The decay strength of 9Li to the $5/2^-$ state of 9Be was more than twice that of 9C to the $5/2^-$ state of 9B—ten times larger than the difference predicted by theory. Mikolas et al. speculated that this might be due to problems in the data analysis of 9Li decay and called for a re-measurement of 9Li β^- decay with higher precision. This phenomenon attracted great attention from researchers, as such a large strength asymmetry had never been observed in other mirror nuclear systems.

In 1990, Nyman et al. at CERN-ISOLDE remeasured the 9Li decay product spectrum and claimed to confirm the existence of asymmetry in the decays of the mirror nuclei 9C and 9Li [18]. However, in 2000, Gete et al. at TRIUMF-TISOL measured the 9C decay product spectrum using the implantation-decay method and, through R-matrix analysis, recalculated the branching ratios and

B_{GT} strengths for each decay channel without observing this asymmetry [19-20]. They suggested that previous studies might have had flaws in their data analysis, since in this excitation energy region B_{GT} is very sensitive to branching ratios, and small differences in branching ratios could lead to large fluctuations in B_{GT}. Subsequently, to exclude effects from data analysis methods and other factors, Bergmann et al. at CERN-ISOLDE conducted decay experiments on both 9C and 9Li using nearly identical experimental setups and analysis methods. They found that 9Li β^- decay primarily populates the $5/2^-$ state of 9Be at 11.8 MeV, with an extracted B_{GT} strength of 5.3 $\pm$ 0.9, about 4.4 $\pm$ 1.0 times the strength of 9C β^+ decay to the $5/2^-$ state of 9B (1.20 $\pm$ 0.15), as shown in Figure 3 [Figure 3: see original paper], again demonstrating the existence of asymmetry in this pair of mirror nuclei [17,21-22].

From using nuclear emulsion to detect particle tracks to using silicon detectors with the implantation-decay method for precise measurement of decay product spectra, our understanding of 9C decay properties has gradually deepened. However, whether asymmetry exists in the decay processes of 9C and 9Li remains controversial and requires more theoretical and experimental research. Notably, this type of asymmetry in mirror nuclear decays has been discovered in increasingly more mirror nuclear systems, such as 26P and 26Na [23], 73Br and 73Sr [24], etc. Recently, domestic research teams conducting decay experiments at IMP-CAS, combining silicon detectors and high-purity germanium detector arrays with the implantation-decay method, discovered that 20Mg and 20O [25], 22Si and 22O [26], and 27S and 27Na [27] also exhibit this mirror nuclear decay asymmetry, proposing a new method for identifying halo nuclei through mirror nuclear decay studies. Thus, with continuous improvements in detection equipment and research methods, decay studies are expected to reveal more information about the structure and properties of 9C, helping to understand the nature and role of isospin-nonconserving forces and deepening our knowledge of isospin symmetry breaking mechanisms.

3. Level Structure

The energy level characteristics of a nucleus reflect the interactions between nucleons and the motion patterns of the nucleon system. In the light nuclear region, where the number of nucleons is small and the system is relatively simple, studies of light nuclear energy levels are particularly helpful for exploring and understanding nuclear many-body dynamics. Using different reactions, researchers have observed some excited states of 9C and compared them with theoretical models, though our knowledge of 9C' s level structure remains limited.

Due to 9C' s short half-life, direct measurement of its mass was difficult in early experiments. Typically, the Q-value of reactions such as A(B,X)9C_g.s. was measured to indirectly calculate the ground-state mass excess of 9C. With careful experimental design combined with magnetic spectrometers and high-precision detection equipment, this indirect method can also yield very precise results. In 1964, Cerny et al. first identified the ground-state level of 9C through the 12C(3He,6He)9C reaction. By comparison with its mirror nucleus 9Li, they determined its spin-parity to be $3/2^-$ and, using the Q-value of this reaction, gave the ground-state mass excess of 9C as 28.95 ± 0.15 MeV, thereby establishing that 9C does not spontaneously emit protons [28]. Subsequent measurements of 9C' s ground-state level using the 12C(3He,6He)9C and 7Be(3He,n)9C reactions eventually determined the ground-state mass excess of 9C to be 28.9110 ± 0.0021 MeV [5-6,29-34].

Initially, excited-state levels of 9C were also calculated indirectly using Q-values. In 1974, Benenson et al. used the 12C(3He,6He)9C* reaction to first identify the first excited state of 9C at 2.219 ± 0.010 MeV with a width of 100 ± 20 keV. Comparison with the mirror nucleus 9Li led to the conclusion that the spin-parity of 9C' s first excited state is $1/2^-$ [35]. In 1984, Bressani et al. at CERN-SC studied the 6Li(3He,π^-)9C reaction using 910 MeV 3He bombarding a Li target, measuring the momentum distribution of π^- particles. After analysis, they concluded that the peak at 723 MeV/c corresponded to 9C' s ground state and 2.2 MeV first excited state, while peaks at 714 MeV/c and 705 MeV/c corresponded to two excited states at 9 MeV and 15 MeV, respectively [36]. In 1991, Golovko et al. also used the 12C(3He,6He) reaction, identifying 9C' s ground state and 2.2 MeV first excited state by measuring σ(E(6He)). They claimed to have discovered a new excited state at E* = 3.30 ± 0.05 MeV, but this finding was not confirmed in subsequent studies. Later researchers analyzed that this state might actually be the excited state at 3.6 MeV due to measurement errors [37].

In recent years, with advances in modern experimental technology and the gradual commissioning of radioactive beam facilities worldwide, direct measurement of exotic nuclei excitation states using radioactive beams has become possible. Experiments using radioactive beams can access higher excitation levels of exotic nuclei through simple direct nuclear reactions, and combined with high-performance detection equipment, can more reliably identify and measure different excited states. In 2007, Rogachev et al. at the University of Notre Dame' s TwinSol radioactive beam facility observed a 9C excited state at 3.6 ± 0.2 MeV with a width of 1400 ± 500 keV using 29 MeV 8B + p resonance scattering, and assigned a spin-parity of $5/2^-$ to this state through R-matrix analysis [38]. In 2017, Brown et al. at NSCL conducted inelastic scattering experiments with 68 AMeV 9C secondary beams on a 1 mm thick 9Be target. Through coincidence measurements of 8B + p, they obtained the invariant mass spectrum of 9C and reconstructed 9C' s first and second excited states at 2.218 ± 0.011 MeV and 3.549 ± 0.020 MeV, with widths of 52 ± 11 keV and 673 ± 50 keV, respectively, consistent with previous results [39]. Additionally, they measured 7Be + 2p coincidence events and reconstructed two resonant states of 9C at 4.40 ± 0.04 MeV and 5.75 ± 0.04 MeV, with widths of 2750 ± 110 keV and 601 ± 50 keV, respectively, as shown in Figure 4 [Figure 4: see original paper] [39]. In 2019, Hooker et al. at the Texas A&M University cyclotron laboratory studied 9C excited states using 8B + p resonance scattering at MARS. In addition to observing the $1/2^-$ state at 2.2 MeV and the $5/2^-$ state at 3.6 MeV, they observed an excited state at 4.3 ± 0.3 MeV with a width of $4000^{+2000}{}_{1400}$ keV. Through R-matrix analysis, they assigned a spin-parity of $5/2^+$ to this state, marking the first observation of a positive-parity state in A=9, T=3/2 nuclei and the first observation of an excited state in the sd (2s) shell in such nuclei. Furthermore, Hooker et al. noted that experimental data suggested the possible existence of a $7/2^-$ state at 6.4 MeV [40].

The experimental results for 9C energy levels (energy E and width Γ) observed to date and their comparison with theoretical calculations are shown in Table 1 . Although theoretical calculations agree reasonably well with experiments, meaningful comparison requires consideration of continuum states due to the large level widths. This is also why AMD (Antisymmetrized Molecular Dynamics) model calculations overestimate the 2s shell energy of 9C by nearly a factor of two [40-41]. Future experiments could study higher excitation levels of 9C through new methods such as transfer reactions [42] and breakup reactions [43], with upgraded experimental equipment to improve measurement precision. Theoretically, researchers are attempting to further develop *ab initio* methods to enable calculations of 9C' s level structure. Comparing *ab initio* predictions with experimental results will better help explain experimental findings and understand 9C' s level structure.

4. Magnetic Dipole Moment

Since atomic nuclei have spin and constitute charged systems, they possess magnetic moments. Nuclear magnetic moments are related to nuclear structure and properties and serve as sensitive probes of nuclear ground-state wave functions, allowing nuclear structure studies from magnetic dipole moment measurements. This is particularly true in mirror nuclear systems, where the similar structures of mirror nuclei enable their magnetic dipole moments to provide more information about nuclear structure and non-nucleonic degrees of freedom.

In 1996, Matsuta et al. at RIKEN-RIPS produced 9C secondary beams through fragmentation of 70 AMeV 12C on a 205 mg/cm^2 12C target. Beams at _{lab} = 5° ± 1° were purified and collected with a polarization of about P = -3.4%. After slowing down through a degrader, they were implanted into a 50 m thick Pt foil cooled to 30 K and placed in a strong magnetic field H_0 = 4 kOe to maintain polarization for nuclear magnetic resonance [44]. Using standard β-NMR techniques, Matsuta et al. measured the asymmetry of β+ particles emitted from 9C decay, obtaining a magnetic dipole moment of (9C) = -1.3914 ± 0.0005 _N. Comparison with theoretical predictions revealed large deviations from simple systematics [45] and shell model calculations, while cluster model [46] and AMD model calculations agreed well with the experimental value. Combining with the magnetic dipole moment of 9C' s mirror nucleus 9Li [47-48], (9Li) = 3.4391 ± 0.0006 _N, and using the relation:

(T_z = -3/2) + (T_z = +3/2) = J + ((p) + (n) - 1/2) σ , where (p) + (n) - 1/2 = 0.380 _N, Matsuta et al. obtained an isoscalar spin expectation value σ = 1.44 for the 9Li-9C mirror pair, much larger than the single-particle spin expectation value σ = 1. The cluster model gave excellent predictions for both (9C) and σ , leading Matsuta et al. to conclude that 9C very likely has a cluster structure.

To verify the anomalous magnetic dipole moment of 9C, Huhta et al. in 1998 used a different projectile-target combination at NSCL, employing an 80 AMeV 20Ne beam on a 107 mg/cm^2 93Nb target to produce 9C secondary beams [49] to improve polarization [50]. Using standard β-NMR techniques, they obtained (9C) = -1.396 $\pm$ 0.003 _N for the 9C ground state. This result was very close to Matsuta et al.' s value ((9C) = -1.3914 $\pm$ 0.0005 _N), again confirming the anomalous magnetic dipole moment of 9C. Comparison with theoretical calculations including shell model, extreme single-particle model, cluster model, and AMD model [51-53], as shown in Table 2 , led Huhta et al. to conclude that in proton drip-line nuclei like 9C, the anomalous magnetic dipole moment values are caused by isospin mixing due to Coulomb interactions. Although theoretical calculations considering this effect agreed better with experimental values, they still underestimated the isoscalar spin expectation value for 9Li-9C. They suggested that future shell model calculations incorporating more realistic wave functions for Coulomb interactions would help understand the anomalous magnetic dipole moment of the 9C ground state [49].

In 2009, Furutachi et al. used AMD and MAMD (Multiple-width Gaussian basis AMD) models to study the halo structure and core excitation of 9C. In addition to successfully describing 9C' s binding energy and radius, they calculated its magnetic dipole and electric quadrupole moments, which differed little from previous experimental results. Furutachi et al. concluded that 9C' s cluster structure is important for describing its magnetic dipole and electric quadrupole moments [54]. In 2011, Artemenkov et al. produced relativistic-energy 9C secondary beams using a 1.2 AGeV 12C beam on a polyethylene target and studied breakup reactions of 9C at relativistic energies using nuclear emulsion for the first time [55-57]. Artemenkov et al. detected 15 events of 9C $\rightarrow$ 8B + p, 16 events of 9C $\rightarrow$ 7Be + 2p, indicating that 9C may have both 8B + p and 7Be + 2p halo structures. Additionally, they detected 16 events of 9C $\rightarrow$ 3^{3}He, which they interpreted as evidence for a 3^{3}He cluster structure in the 9C ground state. This cluster structure could affect 9C' s magnetic dipole moment and might explain the anomalous magnetic dipole moment calculated by shell models [58].

To date, there is no consensus explanation for the experimentally observed anomalous magnetic dipole moment of 9C. Theoretical researchers are attempting to introduce more realistic interactions and develop more reasonable models to describe this phenomenon. A common hypothesis is that possible halo structures and core cluster structures in 9C affect its magnetic dipole moment, awaiting further verification.

5. Nuclear Astrophysics S-Factor

In nuclear astrophysics, radiative capture reactions such as proton capture (p,γ) play important roles in fundamental astrophysical evolution processes (e.g., hydrogen burning) and thus hold significant research importance. However, since astrophysical evolution processes primarily involve thermonuclear reactions at energies far below the Coulomb barrier, reaction cross sections are typically very small, making direct measurement of radiative capture cross sections in this energy region extremely difficult experimentally, especially for reactions involving short-lived nuclides like 8B(p,γ)9C (8B half-life 770 ms). Therefore, experiments mainly employ indirect measurement methods such as Coulomb Dissociation (CD) [59], Asymptotic Normalization Coefficients (ANC) [60], and the Trojan-Horse Method (THM) [61] to avoid difficulties in direct measurements.

Since nuclear reaction cross sections decrease approximately exponentially with energy, obscuring detailed variations, researchers introduced the S-factor, which varies relatively slowly with energy, to clearly reveal trends in the low-energy region. The relationship between reaction cross section σ(E_c.m.) and S(E_c.m.) is defined as S(E_c.m.) = σ(E_c.m.)E_c.m.exp(2π), where is the Sommerfeld parameter = $e^2 Z_1 Z_2/(4\pi\ _0\hbar\ )$. For 9C, in astrophysical thermonuclear reaction energy regions, particularly in low-metallicity, very massive stars with extremely high environmental temperatures and densities, the proton capture reaction 8B(p,γ)9C can compete with or even exceed the β+ decay of 8B, igniting explosive hydrogen burning and representing a possible pathway for CNO element synthesis. Consequently, the nuclear astrophysics S_{18} factor for this process has received great attention from researchers [10].

In 1998, Motobayashi et al. first attempted to extract the S_{18} factor using results from the Coulomb breakup reaction 9C + 208Pb $\rightarrow$ 8B + p + 208Pb [62]. Unlike the radiative capture reaction A(x,γ)B, in Coulomb breakup reactions, B bombards a high-Z target nucleus, gets excited to an unbound state via Coulomb excitation, and then decays to A + x. This process is equivalent to B absorbing a virtual photon and can be considered the inverse reaction B(γ,x)A. Therefore, the cross section of Coulomb breakup reactions is related to that of radiative capture reactions [63-65]. Compared to radiative capture reactions, Coulomb breakup reactions have much higher reaction rates due to the large number of virtual photons and larger phase space, and higher energies allow the use of thicker targets, making them very suitable for radioactive nuclear beam experiments [66-67]. From the measured Coulomb breakup cross section σ{coul}, *one can calculate the radiative capture cross section* σ{capt} and then the corresponding astrophysical S-factor [63]. Motobayashi et al.' s preliminary analysis yielded an S_{18} factor consistent with predictions by Descouvemont [68] but three to four times lower than predictions by Wiescher et al. [10], though no actual numerical value was given. In 2003, Motobayashi et al. again reported indirect measurement of the astrophysical S_{18} factor using Coulomb breakup of 65 AMeV 9C on a 208Pb target, obtaining $S_{18} = 77 \pm 15$ eV · b in the center-of-mass energy range 0.2-0.6 MeV, consistent with Descouvemont' s predicted value (85 eV • b) [69-71].

In 2001, Beaumel et al. at RIKEN-RIPS measured the cross section of the proton transfer reaction d(8B,9C)n at 14.4 MeV/u on a 5.7 mg/cm^2 CD_2 target. Using Distorted Wave Born Approximation (DWBA) analysis, they obtained the Asymptotic Normalization Coefficient (ANC) with an average value of about 1.18 $\pm$ 0.34 fm^{-1}, from which they calculated the astrophysical S_{18} factor for the radiative capture reaction 8B(p,γ)9C [72]. This method assumes that proton transfer reactions occur peripherally, corresponding to the peripheral nature of radiative capture reactions in the astrophysical thermonuclear energy region. By measuring transfer reactions with much larger cross sections than radiative capture reactions in the astrophysical energy region, one can indirectly calculate astrophysical S-factors, effectively reducing experimental difficulty. This method has been used to calculate S-factors for 7Be(p,γ)8B [73-76], 16O(p,γ)17F [77], and 12C(n,γ)13C* [78], with results in good agreement with direct measurements, proving the method' s reliability. Beaumel et al. calculated the astrophysical S_{18} factor for 8B(p,γ)9C in the center-of-mass energy range 1-100 keV to be S_{18} = 45 $\pm$ 13 eV • b, the first formally published experimental value for S_{18}. Compared with previous theoretical predictions, this was about half the microscopic cluster model calculation (85 eV • b) [69], though the microscopic cluster model' s calculated S_{17} factor for 7Be(p,γ)8B (27-30 eV • b) [69] was also nearly double the experimental value (19^{+4} $_2$ eV • b) [79]. Wiescher et al. [10] used a single-particle model to predict an average S_{18} factor of about 210 eV • b for energies below 0.8 MeV, far higher than the experimental value. Beaumel et al. attributed this to Wiescher et al. using a spectroscopic factor (2.5) much larger than experimental values and shell model calculations.

In 2002, Trache et al. found that single-nucleon knockout reactions could also serve as an experimental tool for extracting ANCs, particularly suitable for studies of rare isotopes produced by projectile fragmentation [80]. In low-energy single-nucleon knockout reactions of weakly bound nuclei, the core typically survives to the end of the reaction, naturally placing the knocked-out nucleon' s wave function outside the core—meaning the reaction occurs peripherally—very similar to peripheral transfer reactions of low-energy light particles, making it ideal for ANC extraction. Using this approach, Trache et al. successfully calculated the $S_{17}(0)$ factor for 7Be(p,γ)8B as 17.4 $\pm$ 1.5 eV • b from 8B breakup data combined with the Glauber model, consistent with direct measurement results [80]. Therefore, Trache et al. used previously measured single-proton knockout cross sections of 285 AMeV 9C on various mass targets by Blank et al. [81], combined with Glauber model calculations, to extract an effective ANC value C^2_{eff} = 1.22 $\pm$ 0.13 fm^{-1}, as shown in Figure 6 [Figure 6: see original paper], from which they calculated the astrophysical S_{18} factor for 8B(p,γ)9C as $S_{18}(0)$ = 46 $\pm$ 6 eV • b [82-85], consistent with Beaumel et al.' s result from transfer reactions but with smaller uncertainties. Trache et al. also studied the energy dependence of the S_{18} factor in the proton center-of-mass energy range E_c.m. = 0-0.8 MeV, finding very low energy dependence, with variation of less than 15% across the entire energy range. Later, Enders at NSCL measured the single-proton knockout cross section of 78.3 AMeV 9C on a C target, σ ${}_1$p(9C$→$8B) = 54 ± 4 mb, and using the shell model and eikonal reaction theory [86], obtained a reduced spectroscopic factor R_s = 0.82 ± 0.06 and an ANC value $C^2{}_1$ = 1.27 ± 0.10 fm^{-1}. Using a potential model [87], they calculated the astrophysical S_{18} factor as $S_{18}(0)$ = 49 ± 4 eV·b, consistent with previous results [88].

In 2005, Guo et al. at the China Institute of Atomic Energy used the Beijing GIRAFFE facility [89-90] with a 44 MeV 7Li primary beam bombarding a 1.6 atm d_2 gas target to produce 39 MeV 8Li secondary beams via the transfer reaction 2H(7Li,8Li)1H. These then bombarded a 1.5 mg/cm^2 (CD_2)n reaction target, and the angular distribution of 9Li produced via the transfer reaction 2H(8Li,9Li)1H was measured [91]. After DWBA analysis, they extracted the ANC for 9Li → 8Li + n as 1.33 ± 0.33 fm^{-1}. Using charge symmetry, they calculated the ANC for 9C → 8B + p as 1.44 ± 0.29 fm^{-1}, from which they obtained the astrophysical S_{18} factor as $S_{18}(0)$ = 44 ± 11 eV·b. Comparison with previous theoretical predictions and experimental results, as shown in Figure 7 [Figure 7: see original paper], where the average of five experimental results (48 ± 3 eV·b) is indicated by a blue dashed line, shows good agreement with Guo et al.' s result. Additionally, based on the astrophysical S_{18} factor, Guo et al. calculated the reaction rate for 8B(p,γ)9C radiative capture as:

N_A σv = 3.7313×10^{10} $^{-1}/^{2}$ $T^{-3}/^{2}$ σE exp(-11.605E/T_9) dE,

where is the reduced mass in amu, T_9 is temperature in 10^9 K, σ is the reaction cross section in barns, and E is the center-of-mass energy in MeV. Comparing this reaction rate with that calculated using the Breit-Wigner equation for single-level resonant radiative capture (E_x = 2.218 MeV), as shown in Figure 8 [Figure 8: see original paper], reveals that direct radiative capture dominates in the astrophysical thermonuclear reaction temperature region, and the reaction rate can compete with the β^+ decay of 8B [91].

In 2012, Fukui et al. reanalyzed experimental results from 65 AMeV 9C Coulomb breakup on 208Pb [70-71] and 285 AMeV 9C single-proton knockout on C and Al targets [81] using the Continuum Discretized Coupled Channel (CDCC) method combined with Eikonal Reaction Theory (ERT). The extracted ANC values (C^2*{p8B}) were 1.78 fm^{-1} and 1.69 fm^{-1}, respectively, showing consistency and demonstrating the reliability of using three-body coupled-channel analysis to extract ANC values [92]. Combining these results, Fukui et al. obtained a final result of (*C^2{p8B}) = 1.7 ± 0.3 fm^{-1}, corresponding to an S-factor of $S_{18}(0)$ = 66 ± 10 eV·b. Fukui et al. noted that while this analysis method yielded good results, the description of the high-energy region of the p-8B breakup spectrum was inadequate. Further development of the three-body coupled-channel analysis method by introducing the p + p + 7Be configuration of 9C would help deepen understanding of 9C breakup reactions and improve the precision of $S_{18}(0)$ [92-93].

In 2015, Fukui et al. again used the CDCC method to reanalyze the 14.4 MeV/u proton transfer reaction d(8B,9C)n [72], extracting an ANC value of (C^2_{p8B}) = 0.59 ± 0.15 fm^{-1}, corresponding to an S-factor of $S_{18}(0)$ = 22 ± 6 eV · b, smaller than all previous results [94]. Fukui et al. analyzed that this was because in the d(8B,9C)n reaction, breakup excited states of both d and 9C contribute to the transfer reaction cross section, making the measured transfer cross section larger and resulting in a smaller $S_{18}(0)$ factor. They suggested that in future work, introducing breakup channels for 8B, the p + p + 7Be configuration of 9C, and Pauli blocking effects on transfer reactions would yield more reasonable results [94-95].

Due to 8B' s short lifetime and poor beam quality, the S_{18} factor can currently only be extracted experimentally through indirect methods. The ANC method is most widely used, but since it has strong dependence on nuclear reaction theoretical models, and theoretical models often require approximations to simplify calculations that significantly affect final results, continuous improvement of theoretical models is needed to obtain better results. With continuous upgrading of radioactive beam facilities and improving beam quality for 9C and 8B, future prospects include measuring higher-statistics 9C Coulomb breakup reactions or even directly measuring the radiative capture reaction 8B(p,γ)9C to obtain more precise astrophysical S_{18} factors.

6.1. Total Reaction Cross Section

Total nuclear reaction cross sections are of special importance in studies of exotic nuclear structures and reaction mechanisms, as a typical physical phenomenon of nuclei with halo structures is their significantly enhanced total reaction cross sections compared to stable nuclei. Moreover, information about nuclear deformation and density distributions that reflect nuclear characteristics can be extracted from total reaction cross sections, making them useful for studying nuclear properties.

In 1996, Ozawa et al. at Lawrence Berkeley National Laboratory produced 730 AMeV 9C secondary beams by bombarding a Be target with 12C and measured the total reaction cross sections on an 8.9 g/cm^2 Be target, 10.2 g/cm^2 and 20 g/cm^2 C targets, and a 13.5 g/cm^2 Al target [96]. Using Glauber model analysis and assuming a harmonic-oscillator (HO) type density distribution, Ozawa et al. calculated the root-mean-square radius of 9C' s matter density distribution as 2.42 ± 0.03 fm, larger than those of its isotopes 10C, 11C, 12C, 13C and the isobars 9Li and 9Be, though the differences were not particularly significant. Ozawa et al. concluded that while this suggested 9C might have a halo structure, more experimental data, particularly in the medium-low energy region, were needed for verification.

In 1997, Blank et al. at GSI-FRS produced 285 AMeV 9C through projectile fragmentation of 12C on a Be target and measured the total reaction cross sections on targets of various masses (C, Al, Sn, and Pb). Analysis using the

Glauber model showed that, similar to 7Be, the total reaction cross sections of 9C could be well described using standard density distributions within error bars [81]. This suggested that due to the Coulomb barrier, 9C might not have a pronounced halo structure like neutron-rich weakly bound nuclei, though Blank et al.' s data had large uncertainties requiring further verification.

In 2001, Wang Quanjin et al. at IMP-CAS used the Heavy Ion Research Facility in Lanzhou (HIRFL) to provide a 75 MeV/u 12C beam bombarding a Be target to induce projectile fragmentation, then selected and purified 54.2 MeV/u 8B and 61.1 MeV/u 9C secondary beams through the Radioactive Ion Beam Line in Lanzhou (RIBLL) and measured their reaction cross sections on a Si target. To analyze the results, they used the Glauber model to calculate total reaction cross sections for both normal nuclear density distributions and extended spatial density distributions, obtaining σ_R-E excitation function curves. They found that calculations using extended spatial density distributions agreed better with experimental data, which were about 32% larger than those calculated using normal nuclear density distributions. Wang Quanjin et al. concluded that these results indicated 9C might have a proton halo structure [97-98].

In 2006, Warner et al. at NSCL measured total reaction cross sections of 9C on a Si target at 27.7-41 AMeV. They found that 9C's total reaction cross section was significantly larger than those of 10B, 10C, and 11C, as shown in Figure 9 [Figure 9: see original paper]. The extracted matter distribution radius of 9C (2.75 $\pm$ 0.34 fm) was almost identical to that of another much heavier proton-rich drip-line nucleus 17Ne (2.82 $\pm$ 0.15 fm) and about 12% larger than the high-energy result from Ozawa et al. [96], again suggesting that 9C might have a proton halo structure. However, due to large data uncertainties, no definitive conclusion could be drawn, and Warner et al. called for higher-precision measurements to clarify this hypothesis [99].

6.2. Knockout Reactions

Knockout reactions generally refer to direct nuclear reaction processes where fast-moving projectiles collide with lighter target nuclei at relatively high energies, knocking nucleons out of the projectile. Broadly speaking, knockout reactions are also a type of breakup reaction [100]. Thanks to the high reaction energy, knockout reactions can use relatively thick reaction targets to obtain higher statistics, and simpler assumptions such as the eikonal approximation can be used in reaction dynamics analysis. Therefore, knockout reactions have been widely applied in studies of rare isotopes produced by projectile fragmentation, yielding extensive information about single-particle structures of nuclei far from stability and deepening our understanding of nuclear structure evolution in unstable nuclear regions.

In 1997, Blank et al. at GSI-FRS first measured total cross sections for single- and double-proton knockout of 285 AMeV 9C on targets of various masses (C, Al, Sn, and Pb) and analyzed them using the Glauber model. They found that the double-proton knockout cross section was much larger than the single-proton knockout cross section on all targets, being about 2-3 times larger, indicating that 9C might have both 8B + p and 7Be + 2p cluster configurations [81]. Later, Enders et al. [88] and Warner et al. [101] at NSCL measured single- and double-proton knockout cross sections of 9C at 78.3 AMeV and 20-70 AMeV on C and Si targets, respectively, finding that 9C' s double-proton knockout cross section was significantly higher than its single-proton knockout cross section, further supporting Blank et al.' s conclusion and suggesting that 9C might have a 7Be + 2p two-proton halo structure.

In 2009, Bazin et al. at NSCL conducted the 9Be(9C,8B+X)Y experiment with 97.9 MeV/u 9C on a 188 mg/cm^2 9Be target. Through coincidence measurements of high-energy protons and residual nuclei from single-proton knockout reactions, they studied in detail for the first time the relative importance of diffraction and stripping mechanisms in knockout reactions [102]. The diffraction mechanism refers to processes where most of the projectile' s initial kinetic energy is distributed to the proton and residual nucleus from breakup, while the target nucleus remains in its ground state. This process is sometimes called elastic breakup (EBU). The stripping mechanism refers to processes where a significant portion of the projectile' s initial kinetic energy is transferred to the target nucleus, exciting it, also known as non-elastic breakup (NEB), as shown in Figure 11 [Figure 11: see original paper]. Bazin et al. analyzed experimental data using the eikonal model and Continuum Discretized Coupled Channel (CDCC) model, finding excellent agreement between theoretical calculations and experimental data. The reaction dynamics of the two mechanisms are significantly different, and in 9C single-proton knockout reactions, the diffraction mechanism accounts for only about $25 \pm 2\%$, indicating that knockout reactions are effective tools for studying single-particle structures of rare isotopes.

6.3. Elastic Scattering

Since Rutherford inferred the existence of the atomic nucleus from elastic scattering of α particles on gold foil at energies below the Coulomb barrier, people have studied atomic nuclei using elastic scattering for over a century. In the past, most elastic scattering experimental data concentrated on stable nuclei and were generally considered simple to measure but uninteresting to analyze. However, with the application of radioactive beam facilities, it has gradually been discovered that elastic scattering results are very sensitive to the structure of the projectile nucleus if target nuclei are carefully selected and measurements are precise. Therefore, elastic scattering has also become an effective tool for studying exotic structures and reaction mechanisms of radioactive nuclei [104-106].

In 2013, Matsuda et al. used a 430 AMeV 12C primary beam bombarding a 50 mm thick 9Be target to produce 277-300 AMeV 9C secondary beams and measured elastic scattering on a 5 mm cryogenic solid hydrogen target [7]. By coincidentally measuring 9C and recoil protons, Matsuda et al. effectively identified elastic scattering events, obtained the angular distribution of 9C elastic scattering, and analyzed it using the MH (Murdock and Horowitz), RH (Relativistic Hartree), and MAMD models, ultimately obtaining a matter density distribution root-mean-square radius of $2.43^{+0}.^{55}{}_{0\cdot 28}$ fm for 9C, consistent with previous results obtained from total reaction cross sections [96,99].

In 2014, Rafi et al. argued that the proton density distribution radius (3.345 fm) and neutron density distribution radius (1.647 fm) calculated by Matsuda et al. were unreasonable. They reanalyzed Matsuda et al.' s experimental data using the BHF (Brueckner-Hartree-Fock) method, as shown in Figure 12 [Figure 12: see original paper]. Assuming a relativistic mean-field (RMF) density distribution form for 9C, they calculated what they considered reasonable proton density distribution radius (2.684 fm), neutron density distribution radius (2.164 fm), and matter density distribution radius (2.522 fm). Rafi et al. suggested that precise measurement of elastic scattering angular distributions over a larger angular range would help further determine 9C' s density distribution radius [107].

In 2018, our research group at RIBLL first measured the elastic scattering angular distribution of 9C on a heavy target natPb near three times the Coulomb barrier energy [108]. The experiment was conducted at the Heavy Ion Research Facility in Lanzhou. A 12C6+ beam from HIRFL bombarded a 9Be target to produce 9C and other secondary beams, which after selection, purification, and transport through RIBLL, bombarded a natPb target to undergo elastic scattering reactions with a beam intensity of about 500 pps (particles per second). The natPb target was a self-supporting foil with thickness 4.2 mg/cm^2, composed of 208Pb (52.3%), 207Pb (22.6%), 206Pb (23.6%), and 204Pb (1.48%). The 9C energy at the target center was about 227 MeV, corresponding to approximately three times the Coulomb barrier. Two position-sensitive PPAC (Parallel-Plate Avalanche Counter) detectors were used before the target to measure the incident beam trajectory, and two ΔE-E silicon detector telescope systems after the target detected scattered particles, each consisting of a double-sided silicon strip detector and a large-area square silicon detector, covering an angular range of 7°-30° for simultaneous particle and position identification of scattering events. Through event-by-event analysis and Monte Carlo simulation, the elastic scattering angular distribution of 9C on natPb was obtained, as shown in Figure 13 [Figure 13: see original paper]. Clear Fresnel diffraction structure can be seen, and the Coulomb rainbow is not significantly suppressed, completely different from neutron-rich weakly bound nuclei like 11Be, where the Coulomb rainbow in elastic scattering angular distributions almost disappears due to strong coupling from breakup reaction channels [3,109-110]. Analysis using the CDCC model led our group to conclude that this is because the Coulomb barrier and centrifugal barrier in 9C weaken the coupling effect of breakup channels on elastic scattering channels. When the Coulomb and centrifugal barriers were artificially removed in calculations, the calculated elastic scattering angular distribution of 9C also showed Coulomb rainbow suppression similar to neutron-rich weakly bound nuclei, confirming this hypothesis [108].

6.4. Breakup Reactions

For weakly bound nuclei like 9C, due to their low valence nucleon separation energies, valence nucleons can easily be excited to the continuum during projectile-target collisions, triggering breakup reactions. Experimental and theoretical studies have shown that breakup processes of weakly bound nuclei are highly sensitive to internal nuclear structure, particularly to the single-particle states of valence nucleons. Based on this, our group used the CDCC model to calculate elastic scattering and breakup reaction angular distributions for two different 9C configurations: 8B + p and 7Be + 2p [108], as shown in Figures 13 and 14. The results show that at three times the Coulomb barrier energy, elastic scattering angular distributions of 9C on heavy targets are not very sensitive to 9C' s structure, with both configurations describing experimental data reasonably well. In contrast, breakup reaction angular distributions are very sensitive to 9C' s internal structure. As seen in Figure 14, at about 14°, the breakup reaction cross section for the 7Be + 2p configuration is about 2.5 times that for the 8B + p configuration, which happens to be the angle of the Coulomb rainbow in elastic scattering angular distribution. This suggests that breakup reactions may be ideal probes for studying possible cluster or halo structures in weakly bound nuclei like 9C, compared to elastic scattering [108,111-112].

To further study 9C' s exotic structure and reaction mechanisms using breakup reactions, our group recently conducted experiments on elastic scattering and breakup reactions of 9C on a 208Pb target. Using a 59.7 MeV/u 12C6+ primary beam from HIRFL at the Radioactive Ion Beam Line in Lanzhou (RIBLL) bombarding a 2528 m 9Be target, 9C secondary beams were produced. Combining Time-of-Flight (ToF) detectors and silicon detectors, a ToF-ΔE two-dimensional particle identification spectrum was obtained, as shown in Figure 15 [Figure 15: see original paper], allowing excellent identification of beam particles. The 9C beam intensity was about 300 pps with a purity of about 2.8%. Gating on 9C for event-by-event analysis ensures that breakup reaction products like 8B and 7Be detected after the target do not include scattered impurity particles from the incident secondary beam. The 9C beam bombarded a 208Pb target in the experimental chamber, and silicon detector arrays measured elastic scattering and breakup reaction angular distributions of 9C on the heavy 208Pb target. The 208Pb target was a self-supporting foil made by evaporation with thickness 8.26 mg/cm^2. The 9C energy at the target center was about 304 MeV. Two 16$×$16 double-sided silicon strip detectors before the target measured the incident beam trajectory, and two ΔE-E silicon detector telescope systems after the target detected scattered particles and breakup fragments. Preliminary analysis of data from the post-target telescope system yielded the ΔE-E two-dimensional particle identification spectrum shown in Figure 16 [Figure 16: see original paper], where elastic scattering events of 9C and breakup events producing 8B and 7Be can be clearly seen. Data and theoretical analysis are ongoing.

In 2019, Chilug et al. at RIKEN-RIBF used a 230 AMeV 18O beam bombarding a 2 mm 9Be target to produce 9C secondary beams with intensity 4.7$\times10^{4}$ pps and energy 160 AMeV. They then bombarded a 425 m natural C target to study breakup processes and a 150 m natural Pb target to study Coulomb breakup reactions [113-115]. They planned to use single and coincidence measurement data of 9C breakup reactions from the SAMURAI spectrometer to study 9C breakup reaction mechanisms and extract the astrophysical S_{18} factor. The two-dimensional particle identification spectrum of the incident beam before the target obtained by Chilug et al. is shown in Figure 17 [Figure 17: see original paper], and further data analysis is ongoing.

A comparison of the two experimental setups for 9C breakup reaction studies is shown in Table 3 . The HIRFL-RIBLL experiment, due to its lower energy, allows detection equipment to measure position and energy information of reaction particles more precisely, mainly by measuring angular distributions of elastically scattered particles and breakup products combined with theoretical model analysis to study 9C reaction mechanisms on heavy targets. The RIKEN-RIBF experiment, with higher energy and better beam quality, mainly uses single and coincidence measurements of 9C breakup products, combined with invariant mass and detailed balance principles, to analyze breakup reaction cross sections and extract the astrophysical S_{18} factor [113]. Data analysis for both experiments is ongoing and expected to yield more information about 9C' s exotic structure and reaction mechanisms.

7. Discussion and Outlook

Despite extensive experimental and theoretical work on 9C' s exotic structure and properties, many questions remain unresolved due to large experimental uncertainties, such as whether 9C has 8B + p or 7Be + 2p halo structures, whether 9C' s ground state has a cluster structure similar to 3^3He, whether asymmetry exists in the decay processes of 9C and 9Li, and how 9C' s exotic structure affects reaction mechanisms. These questions all merit in-depth investigation.

To address these issues in the future, on one hand, new and effective experimental methods need to be developed, and on the other hand, experimental precision must be improved to reduce data uncertainties. For the former, theorists have proposed some promising approaches, such as studying single-particle structures of weakly bound nuclei by measuring the ratio of elastic scattering to breakup reaction cross sections [116], and experimental researchers have conducted a series of explorations, such as domestic research teams using kinematically complete measurement methods to study reaction mechanisms of weakly bound nuclei [117-118]. For the latter, the main reason for large experimental data uncertainties is insufficient statistics, because as a proton drip-line nucleus, producing high-quality 9C beams with existing facilities is very difficult, and detection equipment efficiency is insufficient, resulting in low beam utilization.

Within the next decade, newly built and upgraded radioactive beam facilities at major laboratories worldwide will be commissioned, such as China' s High-

Intensity Heavy-Ion Accelerator Facility (HIAF) [119-120], the U.S. Facility for Rare Isotope Beams (FRIB) [121], Germany' s Facility for Antiproton and Ion Research (FAIR) [122], and France' s System for Production of Radioactive Ion Beams Online (SPIRAL2) [123]. Among these, China' s HIAF integrates the advantages of next-generation heavy-ion accelerator facilities and, upon completion, will provide the most intense medium-low energy heavy-ion beams [124-126]. Combined with higher-efficiency and higher-precision detection equipment, this will greatly enhance the capability to conduct high-precision radioactive beam physics experiments and deepen our understanding of 9C' s exotic structure and reaction mechanisms.

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