Evaluation of experimental data in nuclear astrophysics: Status and challenges*

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Abstract
Nuclear reaction rate databases serve as essential inputs for nucleosynthesis and stellar evolution modeling, directly influencing the accuracy and physical reliability of calculations in various nuclear astrophysics processes. This work comprehensively reviews the major reaction rate databases i.e. REACLIB, STARLIB, and BRUSLIB, highlighting their objectives, data structures, and representative applications, and discussing their coverage, fitting methods, and uncertainty evaluation. These databases have been instrumental in advancing the standardization of nuclear reaction network calculations. However, although these databases have significantly lowered the barrier to performing network modeling, there remains substantial room for improvement in aspects such as database unit structures, update mechanisms, and organizational frameworks. For example, detailed information on the underlying nuclear physics experiments or data analyses is often not included in REACLIB. Therefore, enhancing the stored metadata deserves careful consideration, as it can significantly improve the reliability of astrophysical modeling. At the same time, the advancement of nuclear astrophysics reaction rate databases depends heavily on continuous progress at the experimental frontier. In recent years, innovative experimental techniques, such as novel 4π high-resolution detector arrays and γ-charged particle coincidence measurements, have been widely applied to studies of key nuclear astrophysics reactions, significantly expanding research capabilities. To meet the demands of cutting-edge astrophysical studies for accurate reaction rates, the real-time updating and systematic evaluation of experimental data for key reactions present both an important opportunity and an urgent challenge for the development of modern databases. Several important achievements of the JUNA Collaboration at the Jinping underground nuclear astrophysics facility are also presented in this paper, where low-background experiments are conducted. Compared with traditional extrapolations used in databases, these new low-energy measurements are found to

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provide more direct constraints on key reactions in nuclear astrophysics and crucial experimental support for continuously optimizing databases in the future.

Keywords: nuclear astrophysics, nuclear reaction rate database, stellar nucleosynthesis, underground experiment

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1 Introduction

In the mid-20th century, nuclear astrophysics emerged as an interdisciplinary field aiming to address fundamental questions such as "Where do stars obtain their energy?" and "How are elements synthesized in the universe?" This discipline has driven sustained efforts to understand the distribution of chemical elements from cosmological, galactic evolutionary, and nuclear physics perspectives[1]. As illustrated in Figure 1, nuclear astrophysics is closely linked to numerous distinct yet complementary research directions, playing an irreplaceable role in addressing diverse cosmic problems. Early theoretical pioneers, including Hans Bethe and Fred Hoyle, constructed chains of nuclear reactions to theoretically elucidate the mechanisms of stellar energy generation and the evolutionary pathways from light to heavy elements[2]. Nevertheless, although these models provide a crucial framework for cosmic evolution, their predictive accuracy critically depends on the input nuclear reaction rates within the reaction network. For charged-particle-induced nuclear reactions, the energy region of interest typically lies far below the Coulomb barrier, where reaction cross sections become extremely small, rendering them among the most challenging physical quantities to measure in the laboratory[3].

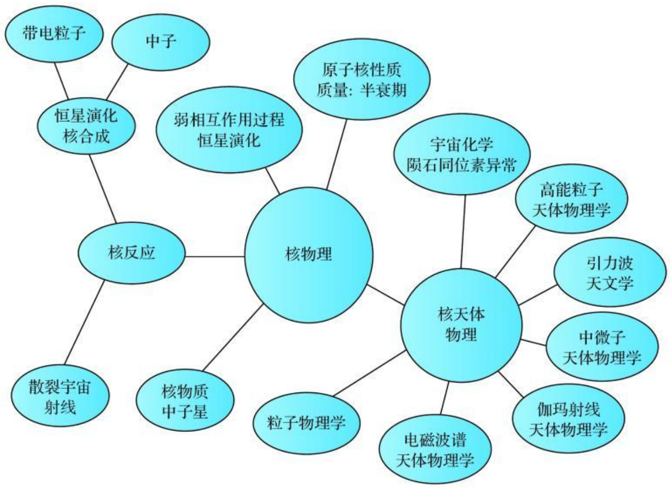

Fig. 1 Diagrammatic presentation of possible connections of nuclear astrophysics with other major fields of physics.

From the 1950s to the 1980s, experimental nuclear physics entered a period of rapid development, driven by the construction of large-scale accelerators and continuous innovation in key experimental techniques. In the 1950s, systematic neutron time-of-flight measurements were conducted at the Harwell electron linear accelerator, enabling the systematic acquisition of resonance parameters and cross sections[4]; meanwhile, the Kellogg electrostatic accelerator at Caltech accumulated extensive low-energy charged-particle reaction rate data[5]. Starting in 1965, the High Flux Beam Reactor (HFBR) at Brookhaven provided a stable reactor-based neutron beam, establishing a crucial platform for nuclear data measurements and materials research[6]. In 1967, CERN commissioned the ISOLDE facility and began delivering on-line radioactive ion beams to users, systematically expanding the experimental window for studying short-lived nuclides far from the valley of stability[7]. Subsequently, the SuperHILAC and Bevatron at Berkeley were operated in tandem to form the Bevalac complex accelerator, followed by the commissioning of GSI's UNILAC. Coupled with the use of the SHIP separator, these facilities enabled systematic investigations into complex reaction mechanisms-including deep inelastic scattering, nuclear transfer, fusion-evaporation, and fission/quasi-fission-and facilitated the separation and identification of numerous short-lived and superheavy nuclides[8]. In parallel, nuclear astrophysics experiments gradually established a neutron capture measurement framework based on activation and neutron time-of-flight methods[9-11], laying a critical experimental foundation for evaluating s-process reaction rates. These experimental results were scattered across various journal articles, recorded in diverse formats-some presented in tables, others embedded only in figures-and often lacked error estimates for individual data points, reflecting a general absence of standardized structure and conventions[12].

In 1967, despite the shadow of the Cold War, international scientific cooperation quietly advanced. In August 1967, the International Atomic Energy Agency (IAEA) convened the "Four-Centre" coordination meeting, which involves the United States, the Soviet Union, the OECD/NEA European Nuclear Data Bank, and IAEA/NDS, to initiate pilot exchanges of nuclear reaction data using punched cards and other data-storage media. In 1969, the "Four-Centre" group formally adopted the EXFOR (EXchange FORmat) data exchange standard during a meeting in Moscow/Obninsk. Regular data exchanges via magnetic tape commenced in 1970, and routine operations were fully established by 1971. Much like Lockyer's founding of *Nature* in the 19th century to create a platform for scientific communication, the creation of EXFOR represented a "meta-scientific" advancement: it focused not only on the content of research but also on ensuring the accessibility, verifiability, and reusability of scientific results. From this point onward, nuclear reaction data were no longer confined to scattered publications and supplementary figures; instead, they entered the "toolkits" of theoretical modelers, engineering designers, and astrophysicists through a unified exchange format and traceable data structure. EXFOR systematically cataloged experimental nuclear reaction data using a rigorous system of data fields and a comprehensive bibliographic information framework, significantly enhancing the efficiency of data sharing and reuse[13].

However, although the EXFOR experimental data exchange format offers unique advantages in preserving original pointwise data and experimental details, it is not directly suited for numerical modeling in astrophysics. For users, its data structure is complex, it lacks reaction rates tabulated on standard temperature grids, and it does not provide functional representations amenable to direct integration into stellar evolution or nucleosynthesis network calculations. Consequently, a series of reaction-rate-oriented database systems emerged. These databases de-emphasize the retention of individual experimental data points and instead deliver nuclear reaction rates integrated over temperature grids, tailored to the needs of stellar evolution and nucleosynthesis network simulations. Examples include interpolatable fitting functions (e.g., REACLIB)[14] and tabulated reaction rates at discrete temperatures (e.g., STARLIB, BRUSLIB)[3,15,16]. Some databases also incorporate uncertainty propagation frameworks, making them suitable for sensitivity analyses of key nuclear reactions within network computations. The development of these "reaction-rate-oriented databases" not only signifies an expansion in the target user base and a shift in structural design but also reflects the enduring tension between high-fidelity preservation of experimental data and computational efficiency in modeling. Understanding their design principles, construction methodologies, and applicable domains is essential for evaluating the reliability and suitability of nuclear reaction rates. The following sections will focus on the content characteristics and astrophysical applications of representative databases such as REACLIB[14] and STARLIB[16], and will discuss current challenges facing nuclear reaction rate databases in light of recent advances in nuclear astrophysics.

2 Nuclear Astrophysics Reaction Databases for Theoretical Modeling

REACLIB (Reaction Library) is one of the earliest thermonuclear reaction rate databases used in nuclear astrophysics. Its conceptual foundation traces back to the pioneering charged-particle reaction rate tables introduced by Fowler et al.[17] in 1967. That table provided the first systematic compilation of nuclear reaction data relevant to astrophysical environments and profoundly influenced stellar nucleosynthesis modeling. However, due to limitations in experimental sensitivity, beam intensity, and the difficulty of producing exotic nuclides, experimental data typically cover only a small fraction of the parameter space required for practical modeling. Consequently, the REACLIB database incorporates both experimentally compiled results[17-21] and theoretical predictions derived from shell-model and statistical-model calculations (e.g., using the NON-SMOKER code)[22], encompassing the majority of proton-, α-, and n-induced reactions on both stable and unstable nuclei. Reaction rates are expressed using a standardized seven-parameter formula (see Equation (1)), facilitating direct implementation in large-scale network computations:

$$N_{\mathrm{A}}\langle\sigma v\rangle = \exp\left(a_0 + \frac{a_1}{T_9} + \frac{a_2}{T_9^{1/3}} + a_3 T_9^{1/3} + a_4 T_9 + a_5 T_9^{5/3} + a_6 \ln T_9\right). \quad (1)$$

Since 2000, to incorporate a large volume of new experimental and theoretical results promptly into thermonuclear reaction databases-thereby enabling different research groups to compare model outcomes at specific time points-the Joint Institute for Nuclear Astrophysics (JINA) in the United States has updated and developed a new public thermonuclear reaction database, JINA REACLIB[14], based on the original REACLIB reaction rate library. This database adopts the core criterion of "selecting the optimal reaction rates available in the literature at the time of update." It thoroughly evaluates existing experimental and theoretical data and expresses all reaction rates in analytical functional forms, achieving numerical fitting accuracy better than 5% relative to published values. Currently, REACLIB V1.0 provides an updated set of reaction rates tailored for hydrogen- and helium-burning environments. Future plans include extending updates to reactions relevant to the s-process and r-process, along with enhancing precision and accuracy by adding two additional terms to the standard seven-parameter expression[14].

In contrast to the parametrized format of the REACLIB database, the BRUSLIB database[15,23] supplies reaction rates in tabular form. This database comprises two main components: Part 1 integrates the NACRE[3] and NACRE II[24] compilations with experimental datasets for radiative capture reactions compiled by Iliadis et al.[25] and Bao et al.[26], delivering a series of astrophysically significant nuclear reaction rates. Part 2 employs the Hauser-Feshbach (HF) reaction model to compute approximately 100,000 thermonuclear reaction rates across nuclides with atomic number Z ranging from 8 to 110. These calculations, based on consistent nuclear structure and reaction inputs, cover common reaction channels-including (n, γ), (p, γ), (α, γ), (n, p), (n, α), (p, α), and (α, p)-as well as their inverse processes. To ensure global consistency and portability, BRUSLIB applies a unified microscopic nuclear model chain across its theoretical component to predict required nuclear inputs-such as level densities, γ-ray strength functions, and partition functions-and adopts a consistent optical potential[27,28] and parameter settings across the entire nuclide chart, thereby providing continuous, directly callable inputs for network calculations in regions where experimental data are scarce.

Concurrently, STARLIB[16], as a next-generation general-purpose nuclear reaction rate database, together with JINA REACLIB and BRUSLIB, constitutes the primary database framework currently used in nuclear astrophysics research[14]. Compared with other databases, STARLIB not only provides reaction rates in tabular form but also introduces a novel methodology for quantitatively defining reaction rate uncertainties[29,30]. In thermonuclear reaction rate uncertainty analysis, the total rate often involves multiple contributing sources, rendering analytical error propagation methods rapidly ineffective. Moreover, the "upper and lower bounds" commonly reported in literature typically reflect authors' empirical guesses about uncertainty origins and lack statistical rigor[16]. STARLIB addresses this by implementing a Monte Carlo approach based on physically motivated probability distributions for nuclear physics input quantities. Within this Monte Carlo sampling framework, each input quantity used in reaction rate calculations is assigned a specific probability density function: resonance strengths follow a log-normal distribution, while partial width upper limits adhere to the Porter-Thomas distribution. After selecting appropriate probability density functions for all inputs, the total reaction rate and its associated uncertainty are derived using standard Monte Carlo techniques. STARLIB typically describes reaction rates using a log-normal distribution and provides a quantitative metric-the Anderson-Darling test statistic-to assess the reliability of this log-normal approximation. Consequently, the reported upper and lower bounds and recommended values possess rigorous statistical definitions[29-32], with the recommended rate denoted as x_{med}, the uncertainty as f.u., and the bounds as x_{low} and x_{high}, satisfying:

$$x_{\mathrm{med}} = \sqrt{x_{\mathrm{low}} \cdot x_{\mathrm{high}}}, \mathrm{f.u.} = \sqrt{\frac{x_{\mathrm{high}}}{x_{\mathrm{low}}}}. \quad (2)$$

The nuclear reaction temperatures of interest in astrophysical network calculations, along with the recommended reaction rates and their associated uncertainties, are organized into three columns of data, forming the fundamental tabular structure of STARLIB. This format facilitates direct integration into modeling codes or comparison with other databases. Such quantitative uncertainty estimates are essential for accurately simulating energy generation and nucleosynthesis processes in stellar environments[16]. Studies have revealed that thermonuclear reaction rates for nearly all reactions have undergone significant revisions[31], primarily due to the adoption of a novel Monte Carlo-based reaction rate calculation methodology[29] and the incorporation of recent nuclear physics data[32].

Table 1 summarizes the key features of the three principal nuclear astrophysics databases: REACLIB, BRUSLIB, and STARLIB. REACLIB's analytical representation of reaction rates offers distinct advantages for reactions involving low level densities. For instance, transitions such as direct capture to low-lying resonant states or between individual resonances often exhibit non-smooth behavior, which tabular interpolation methods typically fail to reproduce accurately at these "discontinuity points"[15]. Moreover, the fitting parameters are constrained by physical considerations, enabling the reaction rates to remain physically reasonable beyond the original fitting temperature range[36,37]. Regarding experimental data, BRUSLIB incorporates the NACRE compilation, which provides careful re-evaluations and updates for more than half of the reaction rates previously compiled in CF88[21]. BRUSLIB also includes astrophysically significant unstable nuclides such as ^{7}Be, ^{22}Na, and ^{26}Al. Its Hauser-Feshbach (HF) theoretical calculations are particularly well-suited for stable nuclides with high level densities. In contrast to BRUSLIB's upper and lower bounds, STARLIB provides reaction rate uncertainties with rigorous statistical meaning. The reaction rate probability density functions in STARLIB can be directly invoked in Monte Carlo-based global sensitivity analyses, thereby facilitating studies of key reaction sensitivities within reaction network calculations.

Table 1. Expression methods and characteristics of three major nuclear reaction rate databases.

Database	Data format	Database characteristics
REACLIB	Seven-parameter analytical expression	It has a unified analytical form and is suitable for large-scale stellar evolution and nucleosynthesis networks (such as XNet [33], MESA [34], Kepler [35]), and usually does not directly provide reaction rate uncertainty information.
BRUSLIB	Tabulation (temperature *vs.* nuclear reaction rate)	It includes two parts: the compilation based on experiment (such as NACRE/NACREII) and the large-scale Hauser-Feshbach (HF) prediction ; it is more reliable [15] in the study of compound nuclei with mass number > 40 and located in the region close to the stable nuclide band.
STARLIB	Tabulation (temperature *vs.* nuclear reaction rate *vs.* reaction uncertainty)	The probability density function of each reaction rate at a specific temperature is provided, and the uncertainty [29] of the reaction rate is strictly defined, so that the Monte Carlo global sensitivity analysis [16] of the nuclear reaction is conveniently carried out.

Moreover, several projects targeting specific reactions and large-scale theoretical calculation datasets are gradually being developed and widely used as supplementary resources. For instance, the KADoNiS project[38] integrates evaluated thermal neutron capture cross section data from Bao et al.[26,39] and Beer et al.[40], incorporates subsequent experimental data, and provides a convenient web-based interface. Nearly a decade after KADoNiS ceased updates, a new online database, ASTRAL (ASTrophysical Rate and rAw data Library)[41], was established for astrophysical calculations. This database compiles neutron capture cross section data derived from activation and time-of-flight experimental measurements, exhibiting notable differences compared to the KADoNiS v0.3 database[42]. Most of these discrepancies stem from revisions to the gold reference cross section[43], while for certain nuclides-such as ^{36}Ar and ^{38}Ar-experimental measurements have replaced prior theoretical estimates for the first time. Concurrently, the TENDL-astro database[44], based on theoretical calculations from the nuclear reaction code TALYS, focuses on evaluating the impact of different reaction models (e.g., level density, γ-ray strength function, optical model) to achieve a more comprehensive assessment of model uncertainties.

3 Recent Advances in Modern Nuclear Astrophysics and Nuclear Reaction Rate Databases

The advancement of astrophysical nuclear reaction rate databases relies heavily on the development of cutting-edge experimental techniques and the continuous updating of measurement data. In recent years, advanced experimental methods-including high-resolution 4π solid-angle detector arrays, novel gas detectors, superconducting solenoids, Cold Target Recoil Ion Momentum Spectroscopy (COLTRIMS)[45], and γ-charged particle coincidence measurements-have been widely adopted, significantly enhancing the capability to investigate key nuclear reactions in nuclear astrophysics. Simultaneously, rapid progress in deep-underground experiments has enabled direct measurements of astrophysically critical nuclear reactions in ultra-low-background environments, opening new opportunities to acquire experimental nuclear reaction rates within the Gamow energy window. The continuous emergence of these frontier experimental results is gradually establishing experimental anchor points in energy regions previously reliant solely on theoretical extrapolations from databases such as REACLIB. This section reviews recent advances in experimental techniques and methodologies in nuclear astrophysics, with a focus on the current frontier: deep underground nuclear astrophysics experiments. Furthermore, it summarizes the latest experimental measurements of key nuclear reactions, compares them with theoretical calculations from databases like REACLIB, and discusses the potential implications of updated reaction rates on astrophysical models, thereby offering insights into the uncertainties inherent in theoretical extrapolations of traditional nuclear reaction rate databases.

3.1 Frontiers in Nuclear Astrophysics Experimental Methods and Detection Techniques

3.1.1 Novel Large Solid-Angle γ Detectors

With the rapid advancement of digital acquisition systems (DAQ), modern nuclear physics experiments can now efficiently process signals from hundreds to thousands of detector channels simultaneously, supporting complex trigger logic and precise time-resolved analysis. This widespread adoption in nuclear physics experiments has ultimately driven the development of modular 4π γ-detector arrays. The experimental feasibility of total γ-absorption spectroscopy has further laid the groundwork for applying the β-Oslo method to study neutron-capture cross sections of radioactive heavy ions[46].

In the traditional Oslo method, nuclear reactions, such as (p, p'), (d, p), and (^{3}He, α), are used to populate excited states of the nucleus, yielding an E_x-E_γ matrix. In contrast, the β-Oslo method populates high-lying excited states of the target nucleus via β decay. Starting from the E_x-E_γ matrix (see Fig. 2(c)), the primary γ-ray spectrum is extracted to determine the nuclear level density (NLD) and the γ-ray strength function (gSF). Internationally, Spyrou et al.[47] recently employed the β-Oslo method to investigate the neutron-capture cross sections of $^{59}\mathrm{Fe}$. Figure 2(a) illustrates the astrophysical reaction pathways involving Fe and its isotopes. Existing studies indicate that the ^{59}Fe(n, γ) ^{60}Fe thermonuclear reaction rate is a critical input for calculating the galactic abundance ratio of the long-lived radioactive isotopes ^{60}Fe and ^{26}Al in astrophysical network models. In the experiment, a radioactive beam of $^{60}\mathrm{Mn}$, containing both the ground state ($J^\pi = 1^+$) and an isomeric state ($J^\pi = 4^+$), was implanted into a silicon surface-barrier detector. The summed γ-ray spectrum from the β-decay daughter nucleus was detected using the SuN (Summing NaI(Tl)) detector, with selected levels of ^{60}Fe shown in Fig. 2(b). The experimentally derived gSF exhibits a significant low-energy enhancement compared to previous measurements, leading to a Maxwellian-averaged cross section (MACS) for the $^{59}\mathrm{Fe}(n,\ \gamma)$ $^{60}\mathrm{Fe}$ reaction that is 1.5-2 times higher than the theoretical recommendation (NON-SMOKER)[22] commonly used in astrophysical models. This result exacerbates the discrepancy between astronomical observations and network model predictions, suggesting potential deficiencies in current massive star models.

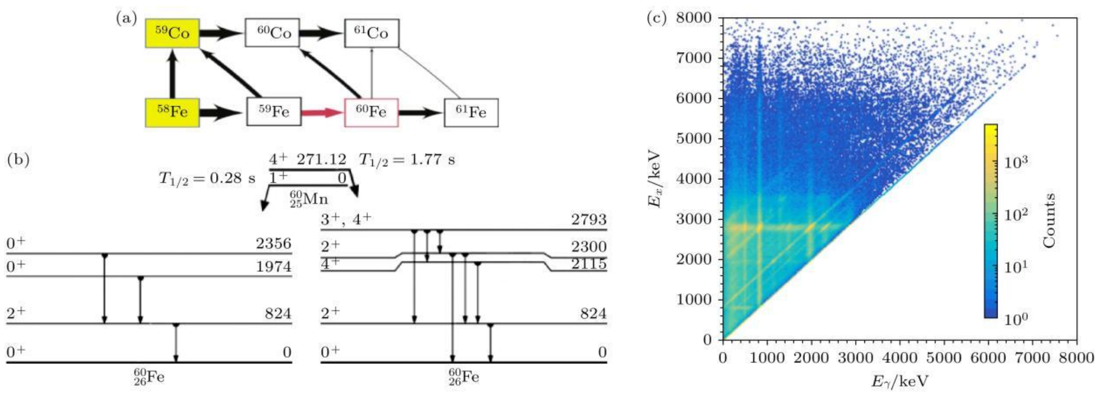

Fig. 2 E_x-E_γ **matrix and partial level scheme for** $^{60}_{26}$Fe **populated following the** β **decay of** $^{60}_{25}$Mn[47]**.**

Meanwhile, research teams in China have successfully developed large-scale modular BGO detector arrays (LAMBDA) with multiple configurations and proposed a method to suppress γ-ray background in ground-based laboratories[48]. When combined with high-intensity beams at the milliampere (mA) level, such low-background γ-ray detector arrays enable the study of various astrophysically relevant capture reactions in ground-based laboratories.

3.1.2 Novel Gas Detectors

Novel gas detectors-including the Multi-Sampling Ionization Chamber (MUSIC), Active-Target Time Projection Chamber (AT-TPC), and Micro-Pattern Gas Detectors (MPGDs)[49-51]-have been successfully applied to studies of nuclear structure and key nuclear astrophysical reactions owing to their flexibility, tunability, high detection efficiency, and trajectory reconstruction capability.

In 2018, β-delayed proton emission from ^{11}Be was directly measured for the first time using a prototype active-target time projection chamber (pAT-TPC) at the ISAC facility of TRIUMF, confirming that the decay proceeds through a narrow resonance in ^{11}B (Γ = 12(5) keV, J^π = (1/2$^+$, 3/2$^+$))[52]. This narrow resonance near 193 keV lies within the Gamow window of the ^{10}Be(p, α)^{7}Li reaction and thus dominates the reaction rate. Based on the updated ^{10}Be(p, α)^{7}Li reaction rate, the predicted ^{10}Be yield in core-collapse supernovae (CCSNe) is only approximately 1/33 of the value obtained using the REACLIB reaction rate[53].

Another significant advancement concerns the study of the ^{22}Mg(α, p)^{25}Al reaction, one of the most critical reactions in the nucleosynthesis flow of X-ray bursts. Comparing astrophysical model calculations with observed X-ray burst features can reveal properties of neutron star systems. Existing studies indicate that model predictions are highly sensitive to the thermonuclear reaction rates of several key reactions, including ^{22}Mg(α, p)^{25}Al. In 2020, Hu et al.[54] reported the first direct measurement of the ^{22}Mg(α, p)^{25}Al reaction using an AT-TPC, yielding rates several orders of magnitude higher than previous indirect measurements across a broad temperature range. However, recent experiments employing MUSIC to study the low-energy excitation function of this reaction indicate a new reaction rate approximately four times higher than that obtained in the earlier direct measurement, thereby enabling the ^{22}Mg waiting point in the X-ray burst nucleosynthesis flow to be directly bypassed via the (α, p) reaction.

Furthermore, high-precision measurements of several frontier topics-including the study of the low-energy cross section of the nuclear astrophysical "holy grail" reaction ^{12}C(α, γ)^{16}O via its inverse reaction ^{16}O(γ, α)^{12}C[55], and direct nuclear reaction measurements of ^{14}C proton inelastic scattering and ^{12}Be single-neutron pickup reactions using inverse kinematics[56]-have all been realized by leveraging the full trajectory reconstruction capability of the AT-TPC. These results are expected to provide critical constraints for precisely determining the carbon-to-oxygen abundance ratio after hydrogen burning and for studies of CNO-cycle-related nuclear reactions.

3.1.3 Superconducting Solenoids

The HELIOS spectrometer at the ATLAS facility of Argonne National Laboratory has been used in numerous nuclear reaction studies with unstable beams. Unlike conventional spectrometers, HELIOS employs a strong magnetic field generated by a superconducting solenoid, causing light charged particles to travel along helical trajectories. This decouples the detected particle energy from the initial emission angle, enabling reaction kinematics to be reconstructed using simple geometric relationships. Recently, angular distributions for the (p, d) and (d, t) single-neutron transfer reactions induced by a ^{15}C radioactive beam measured at this facility were used to extract the spectroscopic factor (SF) and asymptotic normalization coefficient (ANC) for the ^{15}C ground state. These SF and ANC values were then employed to calculate the ^{14}C(n, γ)^{15}C reaction cross section and rate in the astrophysically relevant energy region. The new results are 20%-25% lower than those from the most recent direct measurements (see Figure 3), leading to approximately 1.83-fold and 2.00-fold increases in the abundances of ^{14}N and ^{15}N, respectively, in the inner regions of asymptotic giant branch (AGB) stars. This work serves as a representative example of applying traditional radioactive beam nuclear structure data to the study of key astrophysical reaction cross sections. Ongoing radioactive beam experiments at facilities such as ATLAS, the Beijing Radioactive Ion Beam Facility (BRIF), and the Facility for Rare Isotope Beams (FRIB) are expected to yield more high-precision experimental data, thereby helping to optimize and validate nuclear reaction rate databases and providing more reliable input for nuclear astrophysical modeling[57].

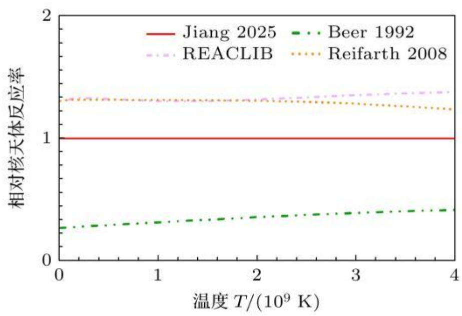

Fig. 3 Ratio of previous $^{14}C(n, \gamma)^{15}C$ reaction rates to the new indirect measurement results[52].

3.1.4 *γ*-Charged Particle Coincidence Measurement Technique and Multichannel R-Matrix Analysis Method

The *γ*-charged particle coincidence measurement technique constitutes a vital tool in nuclear physics research. By simultaneously detecting *γ*-rays and charged particles emitted in the same reaction event, this method effectively enhances selectivity for specific nuclear reactions, thereby improving energy resolution and reducing background interference. However, due to limitations in *γ*-detector efficiency, the sharp decline in cross sections of low-energy direct nuclear reactions, and persistent background interference, this approach still struggles to extend direct measurements of several key nuclear astrophysical reactions into the Gamow energy window. In recent years, a series of indirect methods[58-60] have been employed to investigate resonance parameters of the compound nuclei involved in these astrophysically critical reactions. These indirect techniques circumvent the Coulomb barrier suppression encountered in low-energy direct measurements, substantially increasing the yield of the relevant compound nuclei. Consequently, conventional experimental methods such as *γ*-charged particle coincidence measurements can now precisely determine exit-channel information, including excitation functions and angular distributions. Meanwhile, the maturation of the multichannel R-matrix analysis method now enables a comprehensive evaluation of compound nucleus resonance parameters derived from diverse exit-channel data. Taking the $^{12}C(\alpha, \gamma)^{16}O$ reaction as an example, recent major experimental advances have stemmed from indirect measurements: the ^{16}N β-delayed *α*-particle emission experiment in the early 1990s significantly reduced uncertainties in the E1 component, while transfer reaction measurements around 2000 markedly decreased uncertainties in the E2 component. deBoer et al.[60] integrated these indirect measurements with both high- and low-energy direct data, performing a multichannel R-matrix analysis to obtain a physically consistent fit to different datasets. This ultimately reduced the extrapolation uncertainty of S(300 keV) to 20%.

Concurrently, the multichannel R-matrix analysis method has also been applied to study resonance parameters of the $^{12}C+^{12}C$ fusion reaction in the extremely low Coulomb barrier energy region. This reaction directly influences the ignition depth-temperature relation of superbursts in accreting neutron star binaries and plays a crucial role in numerous stellar burning scenarios, including massive star evolution and Type Ia supernovae. In 2018, Tumino et al.[59] employed the Trojan Horse Method (THM) to conduct the first experimental investigation of the $^{12}C+^{12}C$ fusion reaction within the Gamow window, reporting excitation functions for four exit channels: p_0, p_1, α_0, and α_1. Subsequent multichannel R-matrix analysis extracted a series of resonance parameters for the compound nucleus ^{24}Mg, providing direct evidence for strong resonances in the $^{12}C+^{12}C$ fusion reaction within the Gamow window. The astrophysical S^* factor for the $^{12}C+^{12}C$ fusion reaction obtained from the THM experiment is shown as the black dashed line in Figure 4. Compared with the statistical model extrapolation from REACLIB, the new data predict an 800-fold enhancement in the $^{12}C+^{12}C$ reaction rate below 0.4 GK, ultimately shifting the ignition curve of Type Ia supernovae toward lower central densities. However, the S^* factor derived from the distorted-wave Born approximation (DWBA), which accounts for Coulomb interactions, exhibits a trend diametrically opposed to the plane-wave approximation (PWA) result reported by Tumino et al. The Coulomb-corrected S^* factor lies significantly below the recommended average value within the Gamow energy window[21].

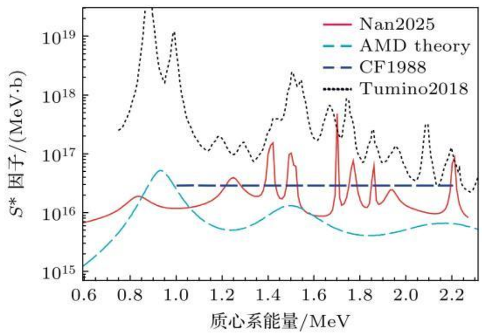

Fig. 4 Astrophysical S^*factor of the $^{12}C + ^{12}C$ fusion reaction, the results from TTIK experiments[58], evaluated database data[21], THM (Trojan horse method) experimental data[59], and AMD (antisymmetrized molecular dynamics) calculations are represented by the red solid line, dark blue dash-dotted line, black dashed line, and light blue dash-dotted line, respectively.

To further investigate the resonance parameters and exit-channel branching ratios of the compound nucleus ^{24}Mg, the Thick-Target Inverse Kinematics (TTIK) method[61,62] has recently been employed to study the excitation functions of various exit channels in the $^{12}C+^{12}C$ fusion reaction within the Gamow energy window[63]. By combining γ-charged particle coincidence measurements with a multi-channel R-matrix analysis, astrophysical S^* factors have been independently determined[58,64] (see Figure 4). Figure 4 reveals that, within the astrophysically relevant energy range, significant discrepancies persist among the $^{12}C+^{12}C$ fusion reaction S^* factors recommended by different experiments and theoretical models. Disagreements between various indirect measurement techniques can even span several orders of magnitude. Nevertheless, current reaction-rate evaluations still commonly adopt non-resonant low-energy extrapolations for rate evaluations[21]. This simplification inevitably compromises the accuracy of reaction rate assessments when significant low-energy resonances exist within the Gamow window. On the other hand, S^* factors calculated directly from resonance parameters extracted via the multi-channel R-matrix analysis using the Breit-Wigner formula may indeed be systematically underestimated, as they do not account for non-resonant contributions or potential interference effects.

3.2 Deep Underground Nuclear Astrophysics Experiments

Several key nuclear reactions exhibit highly complex resonance structures at low energies. However, existing databases typically rely either on empirical extrapolations from high-energy experimental data or on statistical models lacking specific resonance information. Consequently, they struggle to provide reliable input for astrophysical network calculations. Against this backdrop, high-resolution direct measurements of key reactions within the astrophysically relevant energy range-enabled by the ultra-low background environment of underground laboratories-have emerged as a frontier research focus in nuclear astrophysics.

3.2.1 Introduction to Deep-underground Nuclear Astrophysics Experiments

Nuclear astrophysics primarily concerns steady-state burning processes occurring in stellar interiors, which typically take place in relatively low-temperature and low-density astrophysical environments. The corresponding nuclear reaction energies, which define the Gamow window, lie far below the Coulomb barrier, resulting in extremely small reaction cross sections. Near the Gamow peak, cross sections reach only the picobarn to femtobarn range, yielding correspondingly low detection count rates that vary from a few counts per hour to only a few counts per year in the most extreme cases. Under surface laboratory conditions, such exceedingly weak signals are often overwhelmed by cosmic-ray background, making precise measurements unfeasible. Thanks to the natural shielding provided by overlying rock strata, deep-underground laboratories have evolved over recent decades into essential platforms for high-sensitivity nuclear astrophysics experiments.

Currently, three major experimental facilities are dedicated to underground nuclear astrophysics research: the LUNA project at Gran Sasso, Italy[65]; the CASPAR project at Sanford, USA[66]; and the JUNA platform at Jinping, China[67,68]. LUNA, a pioneer in underground nuclear astrophysics, has operated for over 30 years since its establishment in the 1990s. During this period, the LUNA collaboration has systematically investigated key nuclear reactions relevant to diverse astrophysical environments, including Big Bang nucleosynthesis (BBN), the proton-proton chain, the CNO and NeNa cycles in asymptotic giant branch (AGB) stars, and the s-process. Recently, the LUNA collaboration installed the LUNA MV facility and plans to focus on key reactions in stellar helium and carbon burning phases. CASPAR began full operations in 2018 and stands as the sole underground accelerator facility in the United States. It maintains close collaborations with institutions such as the University of Notre Dame and is dedicated to measuring primordial stellar burning reactions and stellar neutron-source reactions. JUNA is located in Hall A1 of the China Jinping Underground Laboratory (CJPL-II), shielded by 2400-m rock overburden, making it the world's deepest nuclear astrophysics experimental platform. Temporary access to CJPL-II Hall A1 during 2020-2021 enabled the JUNA collaboration to successfully conduct its first experimental phase (JUNA Run-1). The collaboration has since completed direct measurements of multiple key reactions at low energies. These results encompass a series of critical nuclear reaction cross sections in stellar hydrogen and helium burning cycles, substantially overcoming the long-standing reliance on theoretical extrapolations and providing more reliable data for database improvements and astrophysical network calculations.

3.2.2 Progress in International Deep Underground Nuclear Astrophysics

Experiments

LUNA employs high-intensity stable ion beams for direct measurements, a technique particularly well-suited for studying two types of astrophysical scenarios: (1) steady-state stellar burning phases at temperatures of 0.01-0.1 GK, and (2) explosive burning events at relatively higher temperatures (up to 1 GK), such as those occurring during BBN, novae, or pre-supernova (SN) and SN stages. Table 2 lists the major nuclear reactions studied by LUNA in recent years, primarily involving the CNO cycle during hydrogen burning, neutron-source reactions relevant to the s-process, and BBN. With the newly installed 3.5 MV single-ended accelerator, LUNA now aims to explore higher-temperature astrophysical environments, including advanced stellar burning stages, such as helium and carbon burning, as well as explosive carbon burning in Type Ia supernovae. Over the next five years, LUNA will prioritize two key reactions: the carbon-burning ignition reaction $^{12}C+^{12}C$ fusion, whose rate influences whether a star ultimately becomes a white dwarf or proceeds toward core collapse, and the s-process neutron-source reactions $^{13}C(\alpha, n)^{16}O$ and $^{22}Ne(\alpha, n)^{25}Mg$, which govern the production of approximately half of the elements beyond the iron peak via the subsequent s-process.

Table 2. Research on key nuclear reactions in LUNA and their corresponding celestial scenarios in the past 5 years.

Nuclear reaction	Celestial scene	References
$^{2}H(p, \gamma)^{3}He$	BBN	[69]
$^{6}Li(p, \gamma)^{7}Be$	Protostars, Cosmic Rays and BBN	[70]
$^{12, 13}C(p, \gamma)^{13, 14}N$	CNO cycle initiation reaction	[71]
$^{17}O(p, \gamma)^{18}F$	CNO cycle	[72]
$^{22}Ne(\alpha, \gamma)^{26}Mg$, $^{13}C(\alpha, n)^{16}O$	S-process	[73,74]

The CASPAR Phase I experiment operated until approximately 2021, when it was temporarily suspended to excavate the large underground caverns required for the Deep Underground Neutrino Experiment (DUNE). Its primary research activities included test experiments with the High-Efficiency Total Absorption γ-ray Spectrometer (HECTOR) for the $^{27}Al(p, \gamma)^{28}Si$ reaction, the primordial stellar burning reaction $^{10}B(\alpha, n)^{13}N$, and s-process neutron-source reactions $^{18}O(\alpha, \gamma)^{22}Ne$ and $^{22}Ne(\alpha, \gamma)^{26}Mg$. In its representative study of the $^{18}O(\alpha, \gamma)^{22}Ne$ reaction, the resonance strengths at 472 keV and 569 keV-dominant contributors to the reaction rate-were directly measured for the first time. This reduced the thermonuclear reaction rate in the stellar helium-burning temperature regime by $46^{+6}_{-11}\%$[75]. In July 2025, CASPAR successfully ignited its accelerator ion source, marking the restart of its deep-underground experimental program.

3.2.3 Progress of the JUNA Experiment

In China, the JUNA collaboration has successfully conducted direct measurements of several key nuclear reactions at the China Jinping Underground Laboratory (CJPL). These include the production reaction of the long-lived radionuclide ^{26}Al, namely $^{25}Mg(p, \gamma)^{26}Al$[76]; the stellar neutron source reaction $^{13}C(\alpha, n)^{16}O$[77]; the $^{19}F(p, \gamma)^{20}Ne$[78], which is important for understanding calcium production in extremely metal-poor stars; the fluorine overabundance-related reaction $^{19}F(p, \alpha)^{16}O$[79]; the neon isotopic abundance-related reaction $^{18}O(\alpha, \gamma)^{22}Ne$[80]; and the "holy grail" reaction of nuclear astrophysics, $^{12}C(\alpha, \gamma)^{16}O$. These direct measurements of key nuclear reaction cross sections-spanning the hydrogen and helium burning phases in stars-provide critical experimental support for refining nuclear data evaluations and thereby enhancing the precision of astrophysical nuclear reaction network simulations.

Taking $^{25}Mg(p, \gamma)^{26}Al$ and $^{19}F(p, \gamma)^{20}Ne$ as examples, the former is essential for understanding the 1.809 MeV γ-ray signature of Galactic nucleosynthesis. At an astrophysical temperature of approximately 0.1 GK, the ^{25}Mg(p, γ)^{26}Al reaction rate is primarily governed by a resonant capture process at 92 keV. During the JUNA Run-1 campaign, the collaboration precisely measured this resonance. The newly recommended ^{25}Mg(p, γ)^{26}Al reaction rate at ~0.1 GK is approximately 2.4 times higher than the value adopted in the REACLIB database[81], as shown in Figure 5(b). This implies significantly enhanced production of ^{26g}Al in the Mg-Al cycle of massive stars, thereby substantially increasing the predicted Galactic 1.809 MeV γ-ray line intensity. Figure 5(a) presents the JUNA collaboration's direct measurement of the ^{19}F(p, γ)^{20}Ne reaction in the astrophysically relevant energy range-a breakthrough for understanding primordial calcium abundances in stars[78]. The discovery of a new resonance at 225 keV elevates the latest thermonuclear reaction rate by a factor of 7.4 compared to the NACRE recommended value. Stellar model calculations indicate that this breakout reaction during hydrogen burning is considerably stronger than previously anticipated, potentially explaining the origin of calcium observed in the extremely metal-poor star SMSS0313-6708.

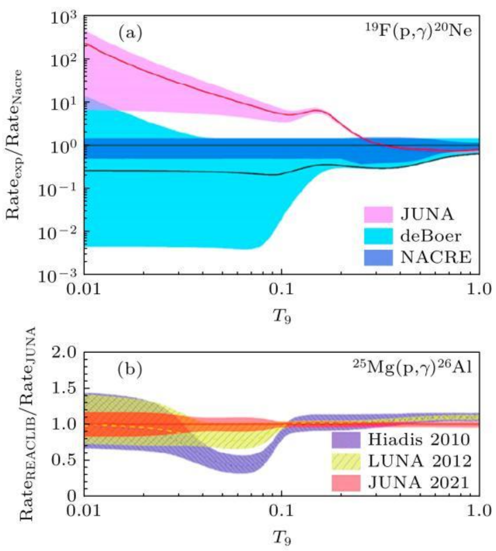

Fig. 5 The JUNA collaboration's direct measurement results of key nuclear reactions in the astrophysically relevant energy region[76,78].

The JUNA Run-1 experiment has already demonstrated promising prospects for conducting nuclear astrophysics experiments in an underground laboratory. In JUNA Run-2, scheduled to resume operations by the end of 2025, researchers plan to allocate more beam time, employ a higher beam intensity (approximately 1 emA), utilize radiation-resistant experimental targets, and deploy a more efficient detector array. These enhancements will enable measurements at lower energies and allow a broader Gamow window to be covered[82]. JUNA Run-2 will encompass three categories of experimental programs: (1) extending measurements of the "holy grail" reaction $^{12}C(\alpha, \gamma)^{16}O$ and the neutron-source reaction $^{13}C(\alpha, n)^{16}O$ to lower energy regions based on Run-1 achievements; (2) initiating new measurements of the neutron source reaction $^{22}Ne(\alpha, n)^{25}Mg$ and the neutrino-producing reaction $^{3}He(\alpha, \gamma)^{7}Be$; and (3) investigating other radiative-capture nuclear astrophysics reactions. Continued advancement of high-sensitivity, low-background detection techniques and direct measurements of key nuclear reaction cross sections within the Gamow energy window at deep-underground laboratories will provide stronger experimental support for constructing a high-precision, traceable reaction rate database.

3.3 Experimental Measurements of Key Nuclear Astrophysics Reactions and Database Inclusion

Advances in nuclear reaction detection technologies and experimental methodologies have driven significant progress in measuring key nuclear astrophysics reactions both in China and internationally. However, mainstream nuclear reaction rate databases still show notable delays in updates. For instance, the most recent update of the JINA REACLIB database was released in June 2021; the NACRE-II database within BRUSLIB includes data only up to 2013; and STARLIB, which constructs probability density functions for nuclear physics quantities, still covers a relatively limited set of key nuclear reactions. Table 3 summarizes recent experimental measurements of several key reactions in nuclear astrophysics and their inclusion status in reaction rate databases. Many of the latest measurement results have not yet been incorporated in a timely manner, a delay that may affect nuclear astrophysics research and theoretical modeling.

Table 3. Measurement and database inclusion of several key nuclear reactions in nuclear astrophysics in recent years.

Nuclear reaction	Experimental technique	Nuclear reaction rate database	References
$^{25}Mg(p, \gamma)^{26}Al$	Direct measurement of underground experiment	REACLIB not updated	[76]
$^{13}C(\alpha, n)^{16}O$	Direct measurement of underground experiment	REACLIB not updated	[74,77]
$^{19}F(p, \gamma)^{20}Ne$	Direct measurement of underground experiment	REACLIB not updated	[78]
$^{19}F(p, \alpha)^{16}O$	Direct measurement of underground experiment	REACLIB not updated	[79]
$^{18}O(\alpha, \gamma)^{22}Ne$	Direct measurement of underground experiment	REACLIB not updated	[75,80]
$^{2}H(p, \gamma)^{3}He$	Direct measurement of underground experiment	REACLIB not updated	[69]
$^{12,13}C(p, \gamma)^{13,14}N$	Direct measurement of underground experiment	REACLIB not updated	[71]
$^{59}Fe(n, \gamma)^{60}Fe$	β-Oslo method	REACLIB not updated	[47]
$^{22}Mg(\alpha, p)^{25}Al$	MUSIC, AT-TPC	REACLIB not updated	[54,83]
$^{14}C(n, \gamma)^{15}C$	Superconducting solenoid	REACLIB not updated	[57]
$^{12}C + ^{12}C$	THM, TTIK	REACLIB not updated	[58,59]
$^{12}C(\alpha, \gamma)^{16}O$	ANC	REACLIB not updated	[84,85]
$^{22}Ne(\alpha, n)^{25}Mg$, $^{22}Ne(\alpha, \gamma)^{26}Mg$	Transfer reaction, direct measurement	REACLIB not updated	[86]
$^{39}K(p, \gamma)^{40}Ca$	Transfer reaction	STARLIB, REACLIB	[87]
$^{18}Ne(\alpha, p)^{21}Na$	Mirror Nuclei, Transfer Reaction	STARLIB	[88]
$^{9}Be(n, \gamma)^{10}Be$	Activation method + AMS	REACLIB	[89]
$^{30}Si(p, \gamma)^{31}P$	Direct measurement	REACLIB	[90]

4 Challenges Facing Current Nuclear Reaction Rate Databases

REACLIB, STARLIB, and BRUSLIB remain the preferred data sources for astrophysical network calculations. However, as the precision requirements for reaction rates in such calculations continue to rise, these databases still face several challenges. On the one hand, although these nuclear reaction rate databases have significantly lowered the barrier to network modeling, there remains room for optimization in their database unit structure and data-fitting methodologies. On the other hand, recent experimental breakthroughs have provided experimental anchor points in energy regimes where previous evaluations relied solely on empirical extrapolations or statistical model calculations. Nevertheless, current nuclear reaction rate databases exhibit a lag in incorporating the latest experimental results. New data often appear in fragmented forms and have not yet been systematically consolidated. This section briefly discusses potential improvements to existing databases as well as the organizational frameworks and future directions for international database maintenance.

4.1 Exploring Optimizations for Database Unit Structure

Upstream evaluations-such as NACRE/NACRE II and specialized topical reviews-typically "absorb and process" extensive experimental details and discrepancies. In contrast, REACLIB, as a downstream reaction-rate library designed for network calculations, usually retains only the seven fitted parameters of the reaction rate and omits associated nuclear physics experimental and data analysis details. Within REACLIB, it is difficult to directly ascertain which experiments or evaluations underlie these seven parameters or what extrapolation assumptions were employed. If the temperature of interest lies near a threshold or a narrow resonance, or if high-temperature (or low-temperature) extrapolation is required, the absence of such information makes it challenging to assess whether the data are being used beyond their valid range. Furthermore, activation-based neutron capture measurements require nuclear structure quantities such as product half-lives and γ-ray branching ratios. When these quantities are revised in updated nuclear structure databases, upstream evaluations typically "recompute the MACS from raw data." However, if only the terminal REACLIB entry is available without detailed analysis, it becomes difficult to rapidly reconstruct and replace the relevant reaction rate. Moreover, for high-precision, sensitivity, or traceability-focused studies, the lack of experimental and analytical details imposes a substantive limitation on network modeling.

For existing nuclear reaction rate databases, it is advisable to incorporate literature links to primary data sources and provide metadata annotations for individual nuclear reactions. Such annotations should primarily address two aspects: experimental details and applicability ranges. The former includes target thickness and isotopic abundance, detector shielding, beam energy spread, detector type/geometry/efficiency calibration, and error decomposition. The latter focuses on specifying the valid temperature range of the reaction rate data, maximum and mean-square residuals, extrapolation assumptions, and whether stellar excited-state corrections are included. The absence of applicability range information can easily lead to out-of-bounds use of reaction rate data or inconsistencies with the corresponding "reverse reaction"[22].

This approach of metadata annotation and literature linking is already partially implemented in the nuclear physics database EXFOR. EXFOR comprehensively stores experimental conditions, numerical data, and references. Originally designed to support reliable data exchange among international nuclear data centers, EXFOR employs a fixed-width character format with hierarchical nesting, typically requiring preprocessing steps for programmatic parsing. Indeed, recent studies[91] have proposed converting EXFOR data into modern formats such as JSON or YAML to enhance programmatic accessibility and extensibility. Drawing on this emerging metadata organization paradigm, nuclear reaction rate metadata could be structured according to the following JSON storage example:


```
reaction: "18O(p, γ)19F"
projectile: "p"
target: "18O"
product: "19F"
reaction_type: "radiative_capture"
source:
  reference: "Sallaska, A. L. et al., ApJS 207, 18 (2013)"
  adopted_from: "Buckner, M. Q. et al., Phys. Rev. C 86, 065804 (2012)"
related_links:
  - "https://ui.adsabs.harvard.edu/abs/2013ApJS..207...18S"
  - "https://doi.org/10.1103/PhysRevC.86.065804"
method:
  evaluation_type: "Monte Carlo"
  uncertainty_distribution: "lognormal"
  data_origin: "STARLIB v6.5 (July 2013)"
experimental_setup:
  laboratory: "Laboratory for Experimental Nuclear Astrophysics (LENA), USA"
  accelerator:
```

name: "LENA 1 MV single-ended accelerator"
beam_energy_keV: [50, 215]
current_uA: 250
energy_uncertainty_keV: 1.0
target:
composition: "Ta2O5 on Ta backing"
isotope_enrichment: "99.3% 18O"
thickness_keV: 18.0
detection_system:
detectors:
- type: "HPGe"
relative_efficiency: "135%"
- type: "NaI(Tl)"
segments: 16
- type: "Plastic scintillator paddles"
role: "Cosmic-ray muon veto"
reaction_rate_data:
columns: ["T_GK", "low_rate", "median_rate", "high_rate", "lognormal_mu", "lognormal_sigma", "Anderson-Darling"]
data:
- [0.010, 2.92e-24, 4.97e-24, 8.79e-24, -5.364e+01, 5.49e-01, 7.33e+00]
- [0.011, 2.58e-23, 4.22e-23, 7.34e-23, -5.149e+01, 5.18e-01, 1.12e+01]
- [0.012, 1.72e-22, 2.68e-22, 4.47e-22, -4.964e+01, 4.78e-01, 1.63e+01]
- [0.015, 1.71e-20, 2.32e-20, 3.31e-20, -4.519e+01, 3.40e-01, 2.10e+01]
- [0.020, 4.82e-18, 6.04e-18, 7.72e-18, -3.964e+01, 2.40e-01, 6.73e+00]
- [0.050, 9.35e-11, 1.23e-10, 2.06e-10, -2.259e+01, 8.58e-01, 1.07e+03]
- [0.100, 2.44e-04, 3.24e-04, 4.35e-04, -8.031e+00, 3.05e-01, 6.39e+00]
- [0.200, 3.39e-01, 4.51e-01, 6.03e-01, -7.97e-01, 2.90e-01, 2.95e-01]
- [0.500, 1.30e+01, 1.71e+01, 2.27e+01, 2.842e+00, 2.79e-01, 2.91e-01]
- [1.000, 6.92e+01, 8.17e+01, 9.82e+01, 4.412e+00, 1.79e-01, 1.13e+01]
- [3.000, 2.80e+03, 3.23e+03, 3.77e+03, 8.086e+00, 1.53e-01, 7.12e+00]
- [5.000, 6.60e+03, 7.73e+03, 9.35e+03, 8.968e+00, 1.80e-01, 2.77e+01]
- [10.000, 2.03e+04, 2.46e+04, 2.97e+04, 1.011e+01, 1.90e-01, null]
temperature_range_GK: [0.01, 10.0]
usage_notes:
- "Rates are valid for stellar environments with T = 0.01 - 10 GK."
- "Monte Carlo method provides lognormal uncertainty quantification."

4.2 Optimization of Nuclear Reaction Rate Fits

In nuclear astrophysics network calculations involving key reactions, high precision in reaction rates is typically required. Taking the s-process as an example, the required precision for relevant nuclear reaction rates is generally within 5%, while for certain bottleneck and branching-point nuclides, the precision requirement tightens to within 1%[26]. Achieving such precision requires not only high-accuracy experimental measurements but also rigorous data evaluation methodologies. Among existing mainstream databases, NACRE and REACLIB each adopt multi-parameter fitting strategies to optimize their results. Specifically, NACRE typically models direct capture and various resonances separately before summing them to obtain the total reaction rate. In contrast, REACLIB directly employs a seven-parameter exponential form, as shown in Equation (1). Although REACLIB permits multiple parameter sets for the same reaction, it currently does not explicitly annotate the valid temperature ranges or residuals for each parameter set.

Zhou et al.[92] previously fitted extensive experimental data using the functional forms provided by REACLIB and NACRE and found that, for certain nuclear reactions, the fitting accuracy of both databases still fails to meet the requirements of nuclear astrophysics network calculations. To improve fitting performance, terms exhibiting high sensitivity to the reaction rate-such as $T^{7/3}$-have been added to the fitting formula, yielding significantly enhanced accuracy for specific reactions with multiple resonances (e.g., ^{9}Be(α, n)^{12}C). In fact, calls for optimizing reaction rate database fits have persisted. For instance, the reaction rate fitting functions currently adopted by databases may introduce substantial deviations within specific temperature intervals. It has been suggested that future database updates should not only refine temperature partitioning but also explore more flexible fitting forms-incorporating additional terms that better capture the temperature dependence of reaction rates, such as more complex models (with additional parameters or non-exponential correction terms) to account for effects like low-energy resonances, electron screening, and interference contributions. However, these discussions have largely remained confined to white papers, requirements reports, or conference presentations and have not yet been formally adopted for comprehensive database updates. Consequently, a key research direction for future nuclear reaction rate database development will be how to effectively integrate piecewise fitting strategies with physically motivated models underlying the fitting formulas, thereby enhancing both the reliability and physical interpretability of reaction rates.

4.3 Update Frequency and Organizational Structure

Current mainstream nuclear reaction rate databases still face notable challenges in update frequency and data coverage. Existing databases generally respond slowly to new experimental data, failing to promptly incorporate the latest measurement advances. As a result, reaction rates for certain critical reactions continue to rely on theoretical extrapolations over extended periods, compromising their reliability in high-precision astrophysical simulations. In terms of organization, major international databases are predominantly developed and maintained by research institutions in Europe and North America, typically operating with small teams that depend on a limited number of core personnel. For example, the NSAC-ND (2023) report notes that REACLIB, managed as a small-scale project by Michigan State University, has faced constrained maintenance capacity, resulting in several years of update stagnation. Furthermore, nuclear astrophysics data efforts in the United States lack a long-term, systematic, and standardized coordination mechanism. This situation not only hampers data-sharing efficiency but also limits the capacity to absorb and integrate rapidly accumulating experimental data.

Notably, the current mainstream database ecosystem lacks a publicly accessible reaction rate database platform led by Chinese research teams. Although significant experimental progress has been achieved in China in recent years—for instance, the Jinping Underground Nuclear Astrophysics (JUNA) facility has successfully directly measured several key reactions—these results have not yet been systematically integrated into international database frameworks. In the future, advancing independent capabilities in data evaluation, fitting, and dissemination would substantially enhance China's contribution and influence within the nuclear astrophysics data ecosystem.

5 Summary and Outlook

Nuclear astrophysics reaction rate databases serve as a critical bridge connecting nuclear physics experiments, theoretical modeling, and stellar evolution simulations. Recent years have witnessed significant advances in data coverage, computational efficiency, and accessibility. "Reaction-rate-oriented databases" such as REACLIB, NACRE, STARLIB, and BRUSLIB have played pivotal roles in mainstream stellar-evolution and nucleosynthesis networks like XNet and MESA, substantially lowering the barrier to modeling. Nevertheless, critical challenges remain unresolved in areas such as metadata annotation, traceability of experimental conditions, and database update speed. To further enhance the scientific rigor and further development of these databases, several measures can be considered: systematically documenting experimental conditions and enriching metadata details; leveraging underground accelerator facilities like JUNA and LUNA-MV to progressively replace high-uncertainty theoretical extrapolations with experimental data, thereby providing high-confidence anchor points for bottleneck reaction rates and significantly reducing uncertainties in stellar evolution and nucleosynthesis simulations; and strengthening the participation of Chinese data evaluation teams and nuclear astrophysicists in database maintenance and updates to improve update efficiency and reduce uncertainties in nuclear-physics inputs for elemental abundance calculations. Meeting the demand of cutting-edge nuclear astrophysics research for precise reaction rates-through real-time updates and systematic evaluation of key experimental data-represents both a significant opportunity and an urgent challenge for modern nuclear astrophysics database development. Looking ahead, as underground experimental facilities continue to expand, theoretical model uncertainties converge, and experimental analysis techniques improve, China should actively engage in international collaborations on nuclear astrophysics database construction, make rigorous use of newly generated nuclear astrophysics experimental data from China, and collaborate with scientists conducting numerical simulations to develop more adaptive data evaluation formats. By forming synergistic partnerships with international nuclear astrophysics data evaluation teams and exploring the application of artificial intelligence to determine appropriate weights for complex experimental datasets, China can meaningfully reduce the impact of nuclear physics data uncertainties on abundance predictions in stellar evolution simulations.

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