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Review

Challenges and Requirements in High-Precision Nuclear Astrophysics Experiments

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Abstract: In the 21th century astronomical observations, as well as astrophysical models, have become impressively precise. For a better understanding of the processes in stellar interiors, the nuclear physics of astrophysical relevance—known as nuclear astrophysics—must aim for similar precision, as such precision is not reached yet in many cases. This concerns both nuclear theory and experiment. In this paper, nuclear astrophysics experiments are put in focus. Through the example of various parameters playing a role in nuclear reaction studies, the difficulties of reaching high precision and the possible solutions are discussed.

Keywords: nuclear astrophysics; nuclear experiments; cross-section measurements; stellar energy generation; nucleosynthesis

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1. Introduction

Soon after nuclear physics was born early in the 20th century, the role of nuclear reactions in the energy generation of stars and in the synthesis of chemical elements was realized, leading to the birth of an interdisciplinary field of science called nuclear astrophysics. Only a few decades later the discipline became mature enough so that two seminal papers were published [1,2] which summarized the available knowledge about nuclear processes in stars which provide their source of energy, determine stellar evolution pathways, and lead to the synthesis of chemical elements making up our Universe.

Owing to the wide range of astrophysical processes from hydrogen burning to the synthesis of the heaviest elements, thousands of nuclear reactions play important roles. The most important quantity characterizing these nuclear reactions is the thermonuclear reaction rate at a given stellar temperature, which determines the rate of energy generation and the number of nuclear species created or destroyed in an astrophysical process. The thermonuclear reaction rate is related to the reaction cross section, therefore the cross section is the key nuclear physics quantity that must be known for astrophysical purposes[1].

While nuclear theory is often unavoidable in the determination of reaction cross sections, reliable reaction rates should preferably be based on measured cross sections. Therefore, the experimental study of astrophysically important nuclear reactions is of crucial importance. Triggered by this requirement, experimental nuclear astrophysics has been very active and successful in the latest several decades in measuring reaction cross sections of astrophysical relevance. Consequently, most of the astrophysical processes envisaged by stellar models are supported by some—although often not complete—experimental data.

During the decades of experimental nuclear data collection, astrophysical observations and models have also been developed tremendously leading to the present era of high-precision astrophysics. Just to mention a few recent achievements: Earth-based and space-borne telescopes are able to measure elemental abundances of the rarest elements or in the most metal-poor stars [4]. Solar neutrino flux originating from the CNO cycle of hydrogen burning [5] can now be measured, providing information about the metallicity of the Sun's core [6]. The Planck satellite has measured the cosmic microwave background radiation with unprecedented accuracy giving invaluable information about the early Universe [7]. Supercomputers allow detailed 3D simulations of e.g., supernova explosions [8]. A new window has been opened to the Universe by the first successful detection of gravitational waves [9].

Such new and high precision results in observation and modeling of astrophysical objects mean that often nuclear physics represents the largest uncertainty of the models. Indeed, the uncertainty of reaction cross sections propagates into the uncertainties of astrophysical models, hindering the comparison with precise observations. For example, the ^{7}Be solar neutrino flux has been measured to a precision of better than 5% [10], while the cross section uncertainty of the ^{7}Be(p,γ)^{8}B nuclear reaction, influencing the ^{7}Be solar neutrino production rate, is 7.5% [11].

It is therefore necessary to reduce the uncertainty of measured nuclear physics quantities, such as radioactive decay half-lives and branching ratios, nuclear structure data, energies and strengths of resonances, and most importantly the reaction cross sections. As an example, Figure 1 shows the evolution of ^{44}Ti half-life measurements. This isotope is of great importance as it is synthesized mainly in core-collapse supernova explosions and its decay can in principle be detected with γ-ray astronomy in supernova remnants, as is the case in the Cassiopeia A remnant [12]. The half-life must be known in order to be able to determine from the observation the amount of isotope produced by the supernova. Up to a few decades ago the half-life was not known to a good accuracy. Later, motivated largely by astrophysical interest, further measurements led to a precise value. Such an increase in precision is required in many other cases of nuclear physics parameter determinations.

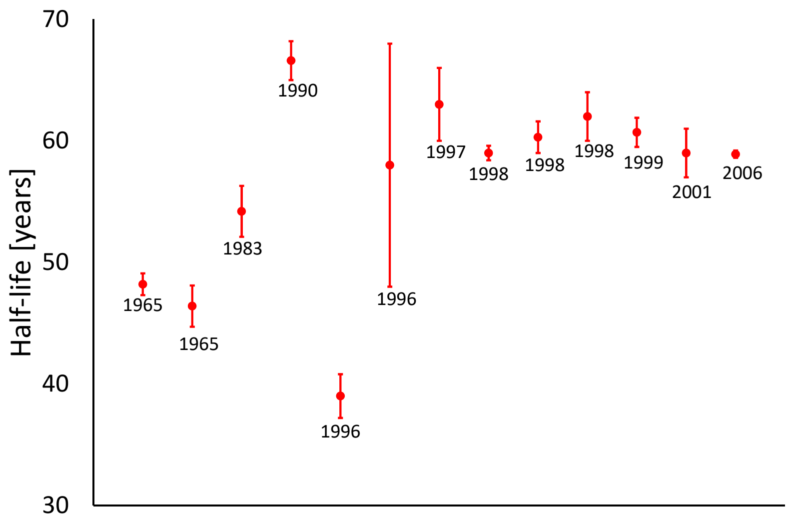

Figure 1. Half-life values of ^{44}Ti and its uncertainty measured in the last 60 years. The increasing precision is obvious. For the source of the data see [13].

In the following sections, the most important uncertainties burdening a typical nuclear physics experiment will be surveyed through some examples. Some difficulties will be pointed out and in some cases, recommendations will be given. It is needless to say that experimental nuclear astrophysics is a huge field and this review cannot cover all parts of it. Therefore, only those topics are discussed where the author has enough experience, i.e., cross-section measurement of charged particle induced reactions with direct methods and mostly with rather conventional experimental techniques which are still widely used in nuclear astrophysics.

2. Requirements for a Precise Cross-Section Measurement

As emphasized above, perhaps the most important nuclear physics quantity in astrophysics is the reaction cross section. In a standard cross-section measurement, a target is bombarded by a beam of projectiles, and the number of reactions is determined through the detection of some emitted radiation. In its simplest form, the cross section $\sigma(E)$ (in a unit of cm^2) at a given interaction energy E is obtained from some measurable quantities through the relation

$$\sigma(E) = \frac{\mathrm{N_r}}{\mathrm{N_p} \cdot \mathrm{N_t}}, \quad (1)$$

where $\mathrm{N_r}$ [s^{-1}] is the number of reactions per unit time, $\mathrm{N_p}$ [s^{-1}] is the number of projectiles hitting the target per unit time, and $\mathrm{N_t}$ [cm^{-2}] is the areal number density of the target atoms. If these quantities are measured, the cross section can be determined. The uncertainties of these parameters will determine how precisely the cross section can be obtained, thus the aim is to measure these three quantities as precisely as possible. The measurement of them has different requirements and difficulties, which will be outlined below.

2.1. Determination of the Number of Projectiles

With the exception of the s- and r-processes of heavy element nucleosynthesis where neutron-induced reactions play a role [14,15], the reactions of astrophysical interest take place between charged particles, the lighter one being either a proton or an α-particle in most of the cases. Therefore, charged particle beams provided by an accelerator are used for the cross-section measurements. This makes the determination of the number of projectiles relatively easy. The electric charge deposited by the beam on the target is measured with a current integrator and a simple division by the charge of the projectile gives $\mathrm{N_p}$. Care must be taken to guarantee that the beam can hit only the target surface and no electric charge can escape from the reaction chamber. With a well-designed chamber serving as a Faraday cup, this can be achieved. Modern electric instruments are able to measure the absolute charge with a precision of much better than 1% in the current range of microamps typical in nuclear astrophysics experiments. Therefore, the uncertainty of the measured cross section caused by the determination of the number of projectiles remains typically low compared to other sources of uncertainty.

An important exception to the above statement is the case when a gas target is applied, which is often necessary in nuclear astrophysics experiments (for example, when reactions on noble gas isotopes are to be studied). When the beam passes through the target gas, charge exchange reactions take place, the projectiles reach the beam dump in an uncertain charge state and thus the charge integration may not be used. One possibility is to place the whole gas target inside the Faraday cup in the form of e.g., a thin window gas cell [16]. If this is not possible, a calorimetric technique can be used where $\mathrm{N_p}$ is determined based on the measurement of the beam power deposited on the beam dump [17]. If such a method is not possible either, then $\mathrm{N_p}$ can be measured using some kind of indirect approach. For example, the well-known cross section of Rutherford scattering allows the beam intensity measurement based on the detection of elastically scattered beam particles on the target gas nuclei [18]. The application of these latter methods usually leads to increased uncertainty on $\mathrm{N_p}$, but with careful experimental design, the uncertainty can be kept below 2–3%.

Although not related directly to the $\mathrm{N_p}$, the beam energy uncertainty is mentioned in this section. The determination of the reaction rate from the cross section necessitates the precise knowledge of the interaction energy. Indeed, at low energies encountered in astrophysics, the cross section depends very strongly on the energy due to the effect of the Coulomb-barrier penetration. Therefore, even a small error in the energy translates into a large uncertainty of the reaction rate. Similarly, if the reaction exhibits narrow resonances in the astrophysically relevant energy range, the reaction rate depends linearly on the resonances' strength, but exponentially on the resonance energy. The energy of the beam must thus be known with a relative uncertainty of less than 0.1%. The energy calibration of low energy accelerators can be done using nuclear reactions possessing resonances of well-known energy or threshold reactions where the location of the reaction threshold can be calculated precisely from the accurately known nuclear masses [19,20]. Care must be taken on the nonlinearity of the calibration and on the short- and long-term stability of the beam energy [19].

2.2. Determination of the Number of Target Atoms

Compared to the number of projectiles, the determination of the areal density of the target atoms N_t (often referred to as target thickness) is a diverse problem. There are innumerable methods to measure this quantity in nuclear physics experiments. It is beyond the scope of this paper to review all of them. Only some problems are mentioned which often cause difficulty in trying to reduce the uncertainty of N_t.

Several methods are based on ion beam analysis where the slowing down of the beam plays a role in the target thickness determination. For example, Rutherford backscattering spectrometry (RBS) or nuclear resonant reaction analysis (NRRA) are such techniques. The slowing down of the beam is controlled by the stopping power of the target material which thus must be known. Stopping power values are taken from some computer codes like SRIM [21] which uses experimental as well as theoretical stopping powers. The uncertainty of the stopping power depends on the ion, on its energy, and on the stopping material, but typical values are around 3 to 5%. If the target thickness determination is based on such a method, this uncertainty will inevitably contribute to the final cross section uncertainty. In cases where high accuracy is needed, dedicated stopping power measurements are recommended especially because most of the stopping power experiments date back to several decades ago. One example is the stopping power of protons in nitrogen. This represents a common systematic uncertainty in most of the cross-section measurement of the ^{14}N(p,γ)^{15}O astrophysical key reaction, whose cross section is not known to the required precision [22].

The precise determination of the target layer composition, i.e., the target stoichiometry is also of high importance. If the target is made of a chemical compound, the ratio of the active and inactive target atoms does not only influence the effective stopping power but may also introduce additional uncertainty in the target thickness determination. Pure elemental targets are thus preferred, but if this is technically not possible, dedicated measurements are needed to reveal the target composition. Depending on the actual compound, various methods may be used [23,24].

The low cross sections encountered in nuclear astrophysics experiments necessitate the usage of high beam intensities. Intense beams especially during long irradiations may deteriorate the targets, resulting in a reduced target thickness and modified stoichiometry. The latter effect is caused by the implantation of the beam particles as well as the mixing of the target atoms into the backing material. Surface contamination of the target layers is also an issue to be investigated. Target characterization must thus be done not only before the cross-section measurement but also after it or preferably regularly in the course of the measurement. An example of such a detailed study leading to a precise target thickness determination and controlled target deterioration can be found in [25].

Target degradation is not a problem in gas targets and the determination of the target thickness is also relatively easy. It can be based on pressure and temperature measurement supplemented by the exact knowledge of the geometry of the target volume. Pressure, temperature, and geometry can be measured to a precision better than 1%, hence the thickness of the gas target is usually accurately known. (The case of jet gas targets is largely different and not discussed here, see e.g., [26].) Some effects may still spoil the precision of the thickness measurement. If the gas is contaminated, the pressure measurement can give a false N_t value. The local thinning of the gas when the intense beam passes through it—the so-called beam heating effect—may also lead to a reduced target thickness not perceived by the pressure sensor. A dedicated experimental setup, based e.g., on the detection of elastically scattered beam particles on the target gas, can be used to control both effects. Such an experiment is presented for example in [27]. The beam heating effect can also be studied by measuring a narrow nuclear resonance, as the energy loss of the beam is directly related to the magnitude of the beam heating. Details of this technique can be found for example in [28].

2.3. Determination of the Number of Reactions

The determination of N_r practically means the detection of one of the reaction products. In most of the cases (see the exceptions below) the light particle created in the reaction is detected which is either a light charged particle (typically proton or α-particle), a neutron, or very often γ-radiation as radiative capture reactions play a central role in most of the astrophysical processes.

The uncertainty of N_r comes from three different sources: counting statistics, detection efficiency, and the relation of the number of emitted particles (at a given energy and angle) to the total number of reactions. Counting statistics is a central problem in nuclear astrophysics as the low cross sections to be measured result in a limited number of events even if high-intensity beams are applied and several months' long experiments are carried out. The statistical uncertainty is also increased by background radiation including beam-induced and natural background. Beam-induced background can be effectively reduced by using high purity materials for target and reaction chamber, by using coincidence techniques or some advanced methods of data analysis like pulse shape discrimination [29]. Natural background can be reduced by shielding the detectors against environmental radiation. High energy cosmic rays, however, are practically impossible to shield in a laboratory on the surface of the Earth. Deep underground laboratories, on the other hand, can provide the necessary cosmic background reduction for a nuclear astrophysics experiment, owing to the thick rock overburden. Such a location is exploited by the pioneering LUNA (Laboratory for Underground Nuclear Astrophysics) collaboration which studied many key reactions of astrophysics in the last 25 years [30]. Nevertheless, in some cases, the low number of events leads to such a high statistical uncertainty that this remains the dominant source of error (see e.g., ref. [31] where the lowest measured cross section was based on one single detected event).

The determination of the detection efficiency is easiest in the case of charged particle detection as those detectors have practically 100% intrinsic efficiency. Therefore, only the exact geometry of the target-detector setup must be known. Complications can arise from the finite beam spot size and if close target-detector geometry is used, it is difficult to reduce the uncertainty below a few percent [32,33].

Detection efficiency is a much more complicated issue in the case of γ-detection. The high penetrability of γ-rays in the detector material means that the intrinsic efficiency of γ-detectors is almost always less than 100% and strongly depends both on the energy and on the angle of incidence of the γ-ray. Monte Carlo simulations are very useful and often used for efficiency determination, however, the geometrical sizes of the active detector volumes are not always known to the required precision. Therefore, the direct measurement of the efficiency is usually inevitable. This can be done with commercially available radioactive calibration sources. The activity of these sources is provided by the supplier with good precision of typically 1%. These sources, however, can be used only in the low energy range up to about 3 MeV. If higher energy γ-radiation is to be measured, nuclear reactions emitting high energy γ-rays in cascade transitions should be used [34]. The not precise knowledge of decay branching ratios in the typically used reactions introduces an uncertainty in the efficiency determination. Therefore, new measurements of these calibration reactions are recommended. Luckily, in some cases pure cascade transitions with 1:1 intensity ratios are available, like in the case of the decay of the $E_p = 278$ keV resonance in $^{14}N(p,\gamma)^{15}O$ [35]. Close target-detector geometry is usually preferred in nuclear astrophysics experiments in order to maximize efficiency. In such a case, the true coincidence summing effect increases the uncertainty of the efficiency [36]. The efficiency calibration of γ-detectors is on its own right a large field of nuclear physics technology [37]. Despite the various methods and huge efforts, the efficiency of γ-detectors remains typically one of the largest sources of uncertainty in cross-section measurements.

Neutron detection efficiency is perhaps even harder to be determined than γ-efficiency. Fortunately, there are only a few astrophysically important reactions that lead to neutron emission (although some of them are very important, like ^{13}C(α,n)^{16}O and ^{22}Ne(α,n)^{25}Mg which produce neutrons for the s-process of heavy element nucleosynthesis [14]). After being emitted, high-energy neutrons follow a complicated path while they slow down and reach thermal energy. This path depends a lot on the material surrounding the target, thus they reach the detector having an energy spectrum that is characteristic of the actual experimental setup and it is hard to estimate. Various types of neutron detectors exist and their intrinsic efficiency usually strongly depends on the neutron energy. These complications require that the efficiency in any kind of neutron detection experiments should be determined exactly in the applied geometry taking into account the primary energies of the neutrons emitted from the studied reactions. Neutron sources (like AmBe or PuBe) may be used, however, these sources have typically very specific energy spectra. Neutron emitting calibration reactions may also be applied where the number of emitted neutrons is determined indirectly. Monte Carlo simulations are also hard to avoid. Details of a recent, extensive neutron detection efficiency measurement can be found in [38]. Even with such a careful and manifold experiment, the uncertainty of the neutron detection efficiency was about 8%, indicating the difficulty of such an efficiency measurement.

From the detection of the light particle emitted from the reaction, it is not always easy to determine the number of reactions itself and thus to obtain the total cross section. The emitted radiation can have a non-isotropic angular distribution which thus needs to be measured. This introduces additional uncertainty whose magnitude depends on the measurement geometry and on the magnitude of the anisotropy. Unfortunately, the angular distribution effect is often ignored or underestimated, which leads to unreliable cross section results, like in the case of e.g., [39]. Especially in radiative capture reactions the produced isotope often decays to its ground state via the emission of multiple γ-rays from cascade transitions. In such cases, all γ-rays need to be detected in order to obtain the total cross sections. Weak transitions of only a few percent branching may easily escape detection if for example they are buried in the background. Such a missing transition means an underestimated cross section. The above two problems (angular distribution and missing transitions) and their associated uncertainty can be avoided when the number of reaction products is directly measured. This is discussed shortly in the next section.

Direct Determination of the Number of Reaction Products

For the determination of N_r, an alternative way to the detection of the light reaction products is the direct determination of the number of produced isotopes. Such a method is for example the activation where the detection of the radioactive decay of the produced isotope is used to derive the cross section [40]. This method of course necessitates that the reaction product is radioactive and its decay can be measured by the detection of some kind of decay radiation (in most of the cases γ-rays). However, if this is fulfilled, the method is free from some uncertainties discussed above. The emission of decay radiation is isotropic, there is no need for angular distribution experiments. The total cross section is provided with no risk of missing weak transitions. If the half-life allows removing the target from the irradiation chamber, the counting can be done in a setup of well-defined geometry where the efficiency can be measured precisely. Only low energy γ-rays are emitted from the decay, the complication with high energy efficiency calibration can thus be avoided. Beam-induced background plays a minor role (only the created parasitic activities must be avoided) and the off-line counting setup can be efficiently shielded against environmental background.

Although several possible sources of uncertainty can be avoided in activation experiments, some others will on the other hand enter the cross section calculations. For example, the decay parameters of the produced isotopes must be known. Even very close to the valley of nuclear stability it is often found that the half-lives of radioactive isotopes are not known with the required precision. In many cases, the half-lives were measured several decades ago with outdated experimental techniques. Sometimes the literature a half-life value is based on one single measurement [41], in other cases contradicting results can be found [42]. Therefore, it is often necessary to supplement the cross section determination with a dedicated half-life measurement. Another important decay parameter is the relative intensity of γ-radiation following the decay, as this quantity provides the connection between the number of detected events and the actual number of created isotopes. Sometimes this parameter is found in the literature with very high uncertainty, see e.g., the case of the ^{64}Zn(p,α)^{61}Cu and ^{64}Zn(p,γ)^{65}Ga cross-section measurements where the almost 20% uncertainties of the relative γ-intensities were the limiting factor of the precision of the cross section determination [43]. Relative intensity measurements are more difficult than half-life measurements, however, such experiments would be highly needed to reduce the uncertainty of some measured cross sections.

Classical activation is not the only experimental technique, which directly determines the number of reactions. There are various ways where instead of the light reaction products, the heavy produced isotopes are counted for the cross section determination. Such methods are for example the accelerator mass spectrometry (AMS) [44], the application of recoil separators [45], or storage ring experiments [46]. These techniques involve rather complicated experimental procedures with their characteristic uncertainties and their discussion is beyond the scope of the present paper. The interested reader is referred to the rich literature of the topics, for example, the above-cited papers.

If possible, the combination of different types of experiments can be very advantageous as the uncertainty can be significantly reduced, and hidden systematic errors may be revealed. A good example is the ^{3}He$(\alpha,\gamma)^7$Be astrophysical key-reaction which was studied in many experiments including in-beam γ-spectroscopy [47], activation [48], and recoil separator [49].

3. Conclusions

From the point of view of the available experimental data, nuclear reactions of astrophysical relevance span between two extreme cases. In astrophysical processes which involve thousands of reactions mostly in the region of unstable nuclei (such as the astrophysical r- [15] or p-processes [50]), most of the reactions have not been studied experimentally yet. In these cases, the primary goal is to increase the number of measured reactions with the aim of testing nuclear reaction models which are generally used in nucleosynthesis calculations. Depending on the type of reaction, the predictions of various models may differ by up to one or even two orders of magnitude. A good example is the reactions involving alpha particles where the poor knowledge of low energy alpha-nucleus optical potential leads to highly uncertain theoretical predictions [51]. In such cases, owing to the large differences between various calculations, the experimental uncertainty is typically not the limiting factor. However, realizing the astrophysical importance, there is a strong effort of improving the low energy optical potential [52]. The high precision experiments will thus hopefully be important in the future also in the case of these astrophysical processes.

The other extreme is represented by those astrophysical reactions which were studied many times in the past. Contrary to the heavy element synthesis processes where—owing to the huge number of reactions—there are practically no key reactions, in the case of processes involving light isotopes, there are typically a few highly important reactions that deserve special attention. Hydrogen and helium burning processes are examples of such cases which strongly influence the energy generation and evolution of stars. As opposed to the thousands of reactions responsible for heavy element synthesis, only a few dozens of reactions play a role in all processes of hydrogen and helium burning. Some of these reactions are especially important, such as ^{3}He$(\alpha,\gamma)^7$Be, ^{14}N(p,γ)^{15}O, and ^{12}C$(\alpha,\gamma)^{16}$O, just to mention a few. These reactions were studied many times in the past with various techniques. The common problem with them is that the astrophysically important energy range (with only a few exceptions [31]) cannot be covered by the experiments. The measurements are thus carried out at higher energies and theoretical extrapolations are used to calculate the reaction rates. The precision of reaction rates is strongly determined by the precision of cross sections measured at higher energies. As the astrophysical models become more and more precise, the uncertainties of nuclear input parameters must also be reduced more and more. Therefore, no matter how many times a nuclear astrophysical reaction was studied in the past, further cross-section measurements are strongly required, aiming for higher accuracy, as emphasized in this paper.

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Note

1 For the exact formulae relating the cross section to reaction rate and to the energy generation and nucleosynthesis yields, see e.g., [3].

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