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## Nuclear astrophysics with exotic nuclei and rare ion beams

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**Abstract.** Nuclear astrophysics has become a major motivation for nuclear physics research in the latest few decades. The quests to understand grand scale cosmic phenomena, the origin of elements and isotopes, the sources of energy in stars, were advanced by studies at the microscopic scale of nuclei. Advances in the production, separation and acceleration of unstable nuclei lead not only to new knowledge in the structure of nuclei and nuclear matter, but also have revolutionized nuclear physics for astrophysics. I will review some of the many contributions that nuclear astrophysics made to our fundamental knowledge, and then will describe a few indirect methods used in nuclear astrophysics using radioactive beams, concentrating on those used by the groups I work with.

### 1. Introduction

I need to start not merely by thanking the organizers for inviting me here, but also by "justifying" my presence here at this school that celebrates the 80<sup>th</sup> year of life of prof. Aurel Sandulescu! He was, and is, a theoretician in nuclear physics! And I am an experimentalist! Most of the speakers before me are reputed theoreticians, his collaborators, or experimentalists working in fields where prof. Sandulescu made important contributions. And I am neither! However, he was my diploma advisor, most probably the only experimentalist to claim this qualification! He may or may not remember, but I do remember very well: I was for 3 months in Dubna for my diplomawork, in the Laboratory for Nuclear Reactions (today the Flerov Laboratory), where he was at the time deputy director. We had long conversations at the time: I was learning "deep inelastic collisions" (DIC) from their discoverer, dr. V.V. Volkov; he was "munching" at the time the idea of cluster radioactivity. I said munching, and I believe it is not the wrong word, because they were mostly physical images prof. Sandulescu was using to try to figure out the phenomena, not equations or existing models. And the idea of the double nuclear system used at the time in DIC, a dynamical nuclear system at temperature  $T \neq 0$ , was probably encouraging his ideas about cluster decay from  $T=0$  systems. I wish him good health and a long, productive life!

Going into the subject of my lecture: after attending the lectures of the first days I realized that I have to rethink and retool my own presentation! I am the first, and the only one for some time, talking about *nuclear astrophysics* (NA). Even though the actual subject is better called '*nuclear physics for astrophysics*', a brief introduction in nuclear astrophysics is in order. I will start by making a few general considerations about the contributions of nuclear astrophysics to fundamental science, to our

understanding of the Universe in general. Contributions made in the last 100, or 60 years, but more so in the last few decades. Given the many students in the audience, I find that going directly into the details of the subject to which the title refers specifically would be counter-productive! These should also be good starting points for discussions with “the adults” in the audience. Second, I will introduce the domain we call nuclear physics for astrophysics (NPA), including its specific vocabulary and main problems (very low energies on nuclear scale, very low cross sections and reactions involving in many cases unstable nuclei, far from stability). Third, I will go into the subject of the indirect methods for nuclear astrophysics using rare ion beams (RIB). I will insist on a few only and will use mostly examples from I studies I was participating.

The above was the structure of the lecture. For this paper I will retain some of the points made in the general, introductory discussion. I will treat only briefly the second part, as those can be found in many books, or lectures at other conferences. And I will review the third part, with only one example for each of the methods treated. References to which I send throughout should be good reading to cover some of the details missing here, for those students wanting to go deeper into the subject.

## 2. Nuclear Astrophysics

As essentially a fundamental science, in addition to so many practical applications that it brought us, Nuclear Physics (NP) was from its beginnings taking a front place in the human endeavour of understanding of the Universe. Our Universe! It was and continues to be part in understanding its composition, its dynamics, its origins and history, and possibly, its future. Some of these advances were made through its branch which we call *nuclear astrophysics*. Here is a short, non-exhaustive, list of the important successes of nuclear astrophysics:

- **Nuclear physics for astrophysics** – is increasingly motivation for NP research:
  - We know that nuclei are the fuel of the stars
  - Origin of chemical elements: nucleosynthesis = a large series of nuclear reactions & elemental/isotopic abundances are indelible fingerprints of cosmic processes. We need better nuclear data to have convincing quantitative descriptions of various scenarios.
- **Big successes of NA:**
  - **BBN** (Big Bang Nucleosynthesis) – is a quantitative, parameter free theory explaining the formation of the lightest elements. Alternatively, we should say that BBN theory was the first to determine that fundamental parameter of the standard model which is the baryon-to-photon ratio  $\eta$ . CMB (Cosmic Microwave Background) studies later confirmed the value and decreased the error bar! BBN theory lead also to the demonstration that there are 3 types of neutrinos, before the 3<sup>rd</sup> type was discovered.
  - **Heavier elements were created in stars** through a number of complex processes.
  - **Solar reactions are basically understood** (pp-chains, CNO cycle, solar neutrinos, neutrino oscillations...)
  - Nucleosynthesis is an **on-going** process!
  - We (quasi-) understand **novae, XRB, neutron stars** ...,
  - but not the super-novae – mechanisms, quantitative description, etc...

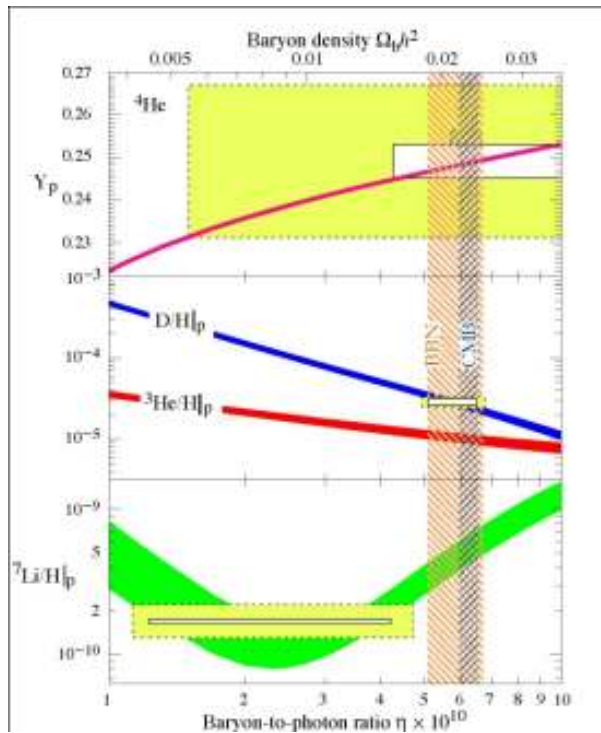
We study our Universe through observations, but also through experiments in the laboratory. It is actually considered that cosmology went from the realm of philosophy and speculation into that of science when physicists started to use nuclear physics data to model the genesis of chemical elements (Bethe and Critchfield, 1938 [1]; Alpher, Bethe and Gamow, 1948 [2]) and compare their quantitative predictions with the observations. Since then, many and fundamental advances were made, a large and rich spectrum of new astrophysical observations was added to our knowledge, and for their interpretation more detailed nuclear and particle data were necessary. Isotopic abundances, available from astronomical observations, are unique fingerprints of the evolution of stars. Sir A. Edington was the first to suggest that nuclei only can hold the key to the production of solar energy. In the 1920s and

'30s the hypothesis was advanced that nuclear reactions are the source of the solar energy, the very source that made and makes possible life on Earth, our life. It was only possible to explain the origin of the solar energy when nuclear processes started to be understood in the 1930s. The detailed mechanisms of this energy production could only be described, in part yet, much later with the advance of *nuclear physics for astrophysics*, or *nuclear astrophysics* (NA). Because nuclear reactions could not happen at the measured temperature of the solar spectrum! One can say that only in the early '70s the existence of the nuclear reactions was proved by the detection of solar neutrinos originating from the much hotter interior of the Sun. This was a joint achievement of *nuclear astrophysics*, *nuclear chemistry* and *astroparticle physics*.

Nuclei are the fuel of the stars! And all chemical elements in the Universe as we know it were produced in processes that we call generically nucleosynthesis. Nucleosynthesis occurred in various stages of the evolution of the Universe, in various places and in different types of events: Big Bang Nucleosynthesis (BBN) or later stellar evolution, far away or around us, explosive or steady burning. And we have firm evidence collected in the latter decades that nucleosynthesis happens today, even in our own galaxy, close to where we live. We also know today that the nuclear processes occurring in stars are not only the source of energy for cosmic processes, but also that nucleosynthesis gives us unique and indelible fingerprints of these processes. Many nucleosynthesis scenarios exist today. Some were formulated for some time, beginning with the seminal works by Burbidge, Burbidge, Fowler & Hoyle, 1957 [3] and independently by Cameron, 1957 [4]: Big Bang Nucleosynthesis (BBN), Inhomogeneous Big Bang Nucleosynthesis (IBBN), the s-process, the r-process, the rp-process, etc., and some are newer proposals. The possibilities to check the detailed predictions of specific models occurred only recently, with the availability of more and better astrophysical observations, of more nuclear data, of advances in understanding the dynamics of non-equilibrium processes, and of increased computing power. It turns out that an important component of all these nucleosynthesis model calculations is represented by the data for the nuclear processes involved. Only good nuclear physics data permit to make definite, quantitative predictions that can be checked against the ever increasing observational data sought and obtained by astrophysicists. This is the object of the nuclear physics for astrophysics, a subject that is most often called *nuclear astrophysics*. It does not deal with the specificities of the dynamics of different stellar processes, but only with the nuclear reactions involved, in particular with how we obtain these data from direct or indirect measurements. However, more recently the modeling of stellar processes and the dynamics of stars came closer and closer to the realm of interest of nuclear physicists and there is increased synergy of the two fields.

There are thousands of nuclear reactions and nuclear processes that occur in stars. Some are very important, some are less important and some are irrelevant in one type of process, while becoming important in another, depending on the conditions of the particular process: composition, densities and temperatures involved. There are also many nucleosynthesis processes, and our knowledge about them differs.

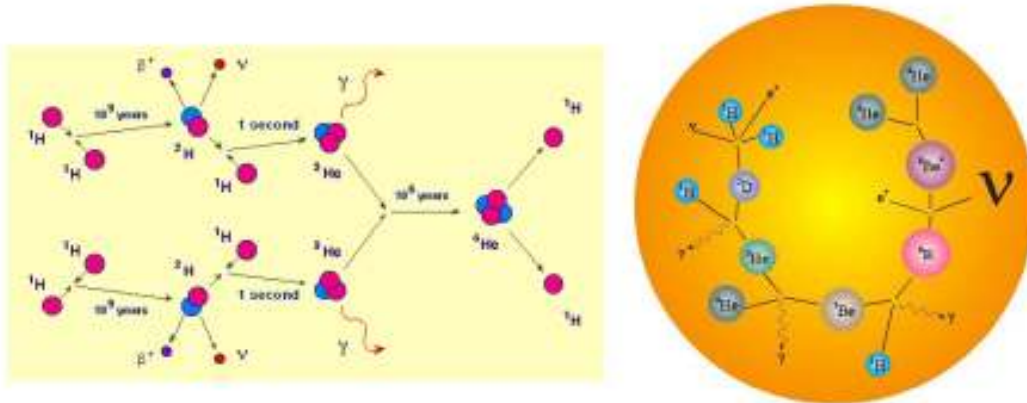
It is an important success of physics in general that we can describe now the **primordial abundances** (in BBN) over ten orders of magnitude. This description is parameter free after the baryon-to-photon ratio was determined independently and quite exactly  $\eta_{WMAP}=6.19(15)*10^{-10}$  from the measurement of the Cosmic Microwave Background using 7-year WMAP data. Only the abundance of  ${}^7\text{Li}$  is not exactly matching the observations and remains "the Li puzzle of BBN" (see Fig. 1). It is not clear now if this is due to the existing nuclear reaction data, to the list of 11 reactions important being incomplete, or is due to observational problems.



**Figure 1** The abundances of  $^4\text{He}$ ,  $\text{D}$ ,  $^3\text{He}$ , and  $^7\text{Li}$  as predicted by the standard Big Bang Nucleosynthesis, as function of the baryon-to-photon ratio  $\eta$ . The vertical bands show the  $\eta$  values given by the CMB and by the BBN. Boxes indicate the observed light isotopes abundances ( $\pm 1\sigma$ , and  $\pm 2\sigma$  errors). From Ref. [5].

Closer to home, we have a good understanding of how our **Sun** works. Nuclear astrophysics measurements provide currently good data for most of the reactions important in Sun: those in the pp-I and pp-II chains responsible for most of the energy production and those in the CNO cycle. And for the  $^3\text{He}(^4\text{He},\gamma)^7\text{Be}$  and  $^7\text{Be}(p,\gamma)^8\text{B}$  reactions at the end of the pp-III chain (Figure 2, right), reactions crucial for the evaluation of the solar neutrino production. However, the cross sections accuracies of around 5% called for by the current Standard Solar Model are not met in all cases. Much progress was made lately through the work of the underground facility LUNA at Gran Sasso National Laboratory, in Italy, where for the first time cross sections were measured into the energies in the Gamow peak. See for these the lecture of M. Junker at the recent Sinaia Carpathian School [6]. The “solar neutrino puzzle”= the discrepancy between the number of solar neutrinos produced and measured on Earth, lead to the discovery of neutrino oscillations, and implicitly to the proof for neutrino mass, and all current revolution in neutrino physics (see, e.g [7]).

Jointly nuclear astrophysics and observational astrophysics have also proven that **nucleosynthesis is an on-going process** in the Universe: it happened at various evolution stages in the past, but is still happening now. This very important concept has been proven by the gamma-ray space-based telescopes like COMPTEL and INTEGRAL, through the identification of characteristic gamma-rays emitted following the  $\beta$ -decay of long-lived isotopes like  $^{26}\text{Al}$  ( $T_{1/2}=0.7$  My) or  $^{60}\text{Fe}$  ( $T_{1/2}=1.5$  My), or not so long-lived ones, like  $^{44}\text{Ti}$  ( $T_{1/2}=60$  y) or  $^{22}\text{Na}$  ( $T_{1/2}=2.6$  y). The detection of gamma-rays originating from  $^{26}\text{Al}$ , with a lifetime considerably shorter than that of the Universe, or of that of our Galaxy, was the first proof that nucleosynthesis is an on-going process. (Note: this is a common statement! However, we should not forget that He was first identified in Sun’s spectra, and



**Figure 2** The reactions in the pp-chains taking place in Sun and producing most of the energy (pp-I left) and most of the observed neutrinos (pp-III, right).

the element Tc ( $Z=43$ ), which does not have a stable element, was also first identified in stellar spectra). Figure x of Ref. [8] presents schematically the nuclear process involved and a sky map of the measured distribution of  $^{26}\text{Al}$  sources. The distributions of sources can give information not only about the location of the nucleosynthesis sites, but also of the dynamics of mixing of the matter in the galaxy by measuring distributions for sources of various lifetimes. However, we do not have yet a precise and quantitative understanding of the nuclear processes leading to the production of these isotopes. Nor of the transport dynamics of the matter ejected from the underlying cosmic processes and more nuclear physics data are needed.

We can presently describe relatively well **H- and He-burning** in some environments like novae and X-Ray Bursters (XRB) and we have models for various types of **supernovae** (SN), more or less successful, but we do not know major things, for example the cosmic environments of the **s- and r-processes** [8]. We should say here that these processes account, each, for the production of about 50% of the chemical elements heavier than Fe, essential for life and our own existence. The origin of these heavy elements is considered one of the greatest unanswered questions of contemporary physics. The least we know today about the formation of heavier elements through the repeated absorption of neutrons at high neutron densities and high temperatures, the so called r-process. It is not clear what the exact path of these reactions is because we do not know key elements like the lifetimes of very neutron-rich nuclei or their neutron absorption cross sections. And for sure we do not know the exact location of the neutron dripline for medium and heavy elements. As this is dominantly a fast chain of reactions, followed by decays, it may not be needed to know all reactions precisely, but currently we have very limited knowledge even about the crucial ones at the waiting points at  $N=82$  and  $N=126$  shell closures. For many of the reactions involved the uncertainties are a few orders of magnitude! Therefore, much more work is needed before we fully understand and describe stellar nucleosynthesis and it is to be expected that the new facilities will bear answers to some of the above questions and to new ones that will appear.

### 3. Introduction to Nuclear Physics for Astrophysics

A number of particularities occur when we talk about nuclear data needed to describe reactions taking place in stars or in stellar environments. *Cross sections* are needed, but for practical reasons, in cases where barrier penetrations are important, it is helpful to introduce the *astrophysical S-factors*. In fact,

what the nucleosynthesis modelists are using are *reaction rates*, averaging cross sections' contributions over the whole energy ranges in gases at the appropriate energies. The weighing with the Maxwell-distributions lead to the so called *Gamow peak*, which specifies for what energies we would actually need to know/measure reactions cross sections. In reactions we can have *direct* and *resonant contributions*, etc... Discussions of these notions and their precise definitions can be found in books (like [9], e.g.) and in some previous lectures [10]. I will not repeat them in print, here.

#### 4. Indirect methods for nuclear astrophysics with RIBs

The use of indirect methods in nuclear astrophysics is prompted by the difficulties that one encounters in attempting to make direct nuclear astrophysics measurements. Direct experiments mean trying to measure exactly the reactions that happen in stars, in those exact conditions (targets and projectiles, energies, charge states, etc...). The main difficulties arise because:

- Stars are cold! Compared with the energies typical in our nuclear physics laboratories, the energies of the partners in stars are very small (10s-100s keV) and the corresponding cross sections, in particular when charged particles are involved, are very small, therefore difficult to measure.
- In stars many reaction partners are unstable nuclei, and some are so short-lived that even with the recent advances in the rare isotope production they are not available, or not easily available, for the exact projectile-target combination at the energies they have in stars.

We have to resort to indirect methods. Several such methods are known in literature, some dedicated and labelled as such, some not. All these experiments are done at laboratory energies (1-10-100 MeV/nucleon) to extract nuclear structure information. This nuclear structure information is then used for nuclear astrophysics, that is, to evaluate reaction cross sections at low energies (10s-100s keV) and the resulting reaction rates at appropriate stellar temperatures. There are two steps here where theoretical calculations occur, and these calculations need to be seriously tested, well parameterized if necessary, using a large variety of data. For this, the use of good quality data with stable beams is still crucial. I want to stress this, because even if common sense, it is too many times overlooked and neglected.

In this lecture I will present three of these indirect methods:

1. One-nucleon transfer reactions (the ANC method)
2. Breakup reactions at intermediate energies
3. Decay spectroscopy. Beta-delayed gamma and proton decays.

In all three cases they are being used to evaluate reaction rates for radiative proton capture, with the difference that the first two are applied to find the continuum (non-resonant) component of the reaction cross sections, while the latter is used for resonant capture.

This being a school, I will not attempt below to be exhaustive in the description of the methods, but rather to be illustrative. I will also prefer to use relevant cases as illustrations, not necessarily 'newest' data. All of the examples will be from work done in the group I am working at Texas A&M University, even though many groups in the world have by now accepted these methods and are using them.

##### 4.1 One-nucleon transfer reactions (the ANC method)

A direct transfer reaction is characterized by the rearrangement of only a few nucleons during a fast process. From the early days of nuclear physics, nucleon transfer reactions were the tool to study the single-particle degrees of freedom of nuclei and were crucial in establishing our current understanding of the structure of nuclei. Typically, spectra of final states and angular distributions were measured. Due to the direct character of the interaction, the tool of choice for the description of transfer reactions was the Born Approximation, either in the Plane Wave (PWBA), or the Distorted Wave (DWBA) form. By comparing the shape of the measured angular distributions with DWBA, the quantum numbers  $nlj$  of the single-particle orbitals involved could be determined, and by comparing the

absolute values of experimental cross sections with those calculated, the spectroscopic factors  $S_{nlj}$  were found for the states populated. The spectroscopic factor is proportional to the "probability" that a many-body system is found in a given configuration. In the case we are talking about, single particle orbitals  $nlj$ , the classical definition (from Macfarlane and French, 1960 to Bohr and Mottelson, 1969 etc...) relates the spectroscopic factors to the occupation number for the  $nlj$  orbital in question. One nuclear state may present several spectroscopic factors: e.g. the ground state (g.s.) of  ${}^8\text{B}$  has  $S(p_{3/2})$ ,  $S(p_{1/2})$ ... related to the probability that the last proton is bound around the g.s. of the  ${}^7\text{Be}$  core in a  $1p_{3/2}$ , or a  $1p_{1/2}$  orbital. The determination of spectroscopic factors from one-nucleon transfer reactions was and is crucial in building our current understanding of the fermionic degrees of freedom in nuclei and their coupling to other types of excitations. The Asymptotic Normalization Coefficient (ANC) method is an indirect NA method introduced by our group more than a decade ago to determine astrophysical S-factors for the non-resonant component of radiative proton capture at low energies (tens or hundreds of keV) from one-proton transfer reactions involving complex nuclei at laboratory energies (about 10 MeV/u) [10]. The method was explained in detail in many previous publications, I summarize the main ideas below.

We can choose peripheral proton transfer reactions to extract the ANCs, which can be used to evaluate  $(p,\gamma)$  cross sections important in different types of H-burning processes. The idea behind it is that in peripheral processes it is sufficient to know the overlap integral at large distances, and this is given by a known Whittaker function times a normalization coefficient  $C_{nlj}$ , to be determined by experiment. Figure also stresses the importance of having good and reliable optical model potentials (OMP) to make the DWBA calculations, a problem I will not discuss here.

The technique was used in several experiments of this type; I will mention one of the latest studies, on the  ${}^{12}\text{N}(p,\gamma){}^{13}\text{O}$  proton capture reaction at stellar energies. It uses the proton transfer reaction  ${}^{14}\text{N}({}^{12}\text{N}, {}^{13}\text{O}){}^{13}\text{C}$  with a  ${}^{12}\text{N}$  beam at 12 MeV/u [11]. Figure 3 below, also the image of a slide shown during the lecture, summarizes the whole process. Going from bottom left, clockwise: we have measured the elastic scattering and the one-proton transfer using a  ${}^{12}\text{N}$  beam produced and separated with the MARS spectrometer [12] at Texas A&M University. The elastic scattering data (lower left corner) were used to determine the OMP needed in the DWBA calculations for transfer. The ANC for the system  ${}^{13}\text{O} \rightarrow {}^{12}\text{N}+p$  was extracted from the transfer data (top left) after which was used to evaluate the non-resonant component of the astrophysical S-factor for the radiative proton capture  ${}^{12}\text{N}(p,\gamma){}^{13}\text{O}$  and the corresponding reaction rate as a function of stellar temperature (top right). Finally, the astrophysical consequences are shown in a plot (bottom right) which shows the region of density-temperature where the capture process competes with its competitor ( $\beta$ -decay), in first stars. For comparison, the curves from literature before our data were measured are shown. There is a big change from the original estimates (dashed curves) based on theoretical estimates only.

A variation of the ANC method uses one-neutron transfer reactions to obtain information about the mirror nuclei, for example studying the  ${}^{13}\text{C}({}^7\text{Li}, {}^8\text{Li}){}^{12}\text{C}$  reaction to determine the ANC for  ${}^8\text{Li}$  which we then translate into the corresponding structure information (the proton ANC) for its mirror  ${}^8\text{B}$  and from there  $S_{17}(0)$  for the reaction important in the neutrino production in Sun  ${}^7\text{Be}(p,\gamma){}^8\text{B}$  [4]. We did this using the mirror symmetry of these nuclei: the similarity of their wave functions, expressed best by the identity of the neutron and proton spectroscopic factors for the same  $nlj$  orbital in the two nuclei  $S_p(nlj)=S_n(nlj)$  (of course, the radial wave functions are not identical!). The experiment using these concepts and the results were published in Ref. [13].

I mentioned before that in order to extract data, either the spectroscopic factors, or the ANCs, the experiments have to be compared with calculations, and in the above conditions, the knowledge of the optical potentials is crucial. We established a procedure based on double folding, starting from an effective nucleon-nucleon interaction we call JLM. Florin Carstoiu of Bucharest was instrumental in this work. I will not insist on all these here, but I send you to literature [14].



4.2 Breakup reactions at intermediate energies

Work done in the last decade in several laboratories has demonstrated that one-nucleon removal reactions (or breakup reactions) can be a good and reliable spectroscopic tool. In a typical experiment a loosely bound projectile at energies above the Fermi energy impinges on a target and loses one nucleon. The momentum distributions (parallel and/or transversal) of the remaining core measured after reaction give information about the momentum distribution of the removed nucleon in the wave function of the ground state of the projectile.

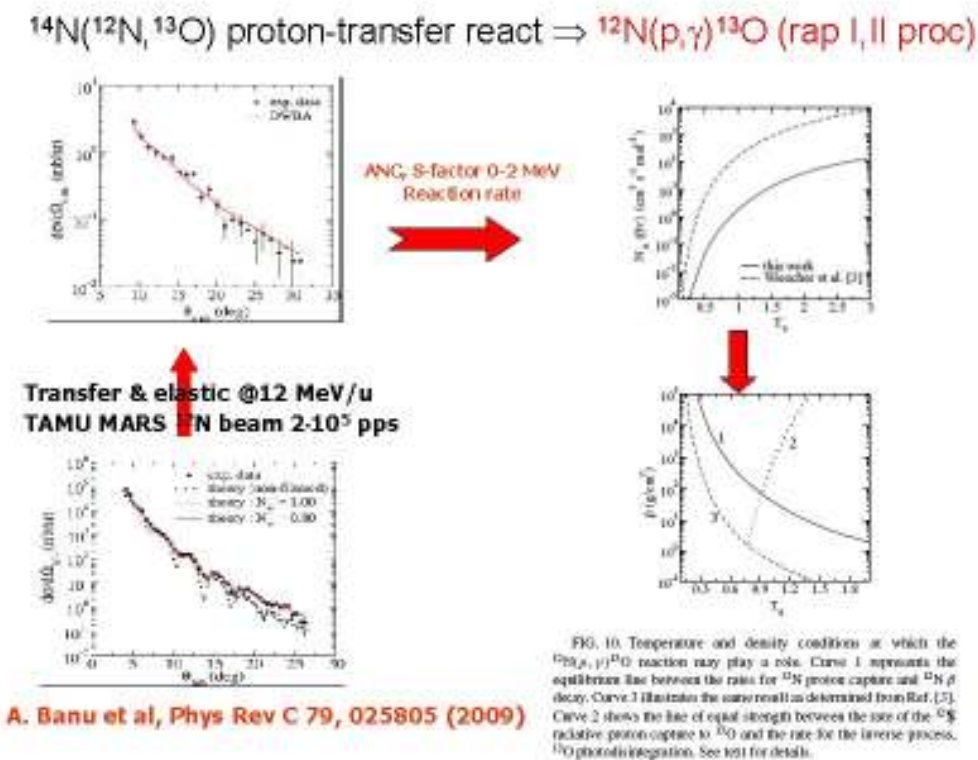


Figure 3. Summary of how elastic and one-proton transfer data measured with secondary RIB (left side) are transformed in nuclear astrophysics information (right side).

The shape of the momentum distributions allows determining the quantum numbers  $nlj$  of the s.p. wave function (unambiguously only  $l$  is determined; shell model systematics are needed for the others). It was shown in Ref. 15 that on a large range of projectile energies breakup reactions are peripheral and, therefore, the breakup cross sections can be used to extract asymptotic normalization coefficients. For this to be true, we need, again, careful and reliable reaction model calculations. They need to reproduce all available data from such measurements if they are to be believed. This is a very important point, which I stressed in the lecture. The method to use breakup reaction for nuclear astrophysics was first applied in [15,16] to the breakup of  $^8\text{B}$  to determine  $S_{17}(0)$ . All available breakup data, on targets from C to Pb and at energies from 27 MeV/u to 1400 MeV/u were used to determine the ANC for  $^8\text{B} \rightarrow ^7\text{Be} + p$ . Different reaction models and different nucleon-nucleon effective interactions were used. Consistent ANCs values were obtained, with an overall uncertainty estimated at about 10%. This is a very good agreement, a fact that validates both the  $S_{17}(0)$  adopted in the neutrino production calculations pertinent to what was called the “solar neutrino puzzle” before the neutrino oscillations were demonstrated, and the validity of indirect methods in NA.

Another example is the breakup of  $^{23}\text{Al}$  and  $^{24}\text{Si}$  at intermediate energies [17,18]. The first is a good example as it takes a case where several configurations contribute to make the ground state of the projectile. The participating configurations were disentangled using the detection of gamma-rays from the de-excitation of the remaining core after a proton is removed from the projectile moving at 50-60 MeV/nucleon. It also shows how it is important to combine the results of this nuclear breakup reaction to evaluate the continuum contribution to the reaction rate with those of Coulomb breakup of the same projectile to evaluate the contribution of the resonant part. It is treated in the paper by A. Banu *et al.* and I refer the reader to it [17].

#### 4.3 Decay spectroscopy. Beta-delayed gamma and proton decays.

Among the indirect methods, a large class is the spectroscopy of resonances, in general (transfer reactions, gamma-ray in-beam spectroscopy, decay spectroscopy, etc...). These resonances are meta-stable states in the compound nuclear system produced in reaction as an intermediate step. To evaluate the corresponding contributions to the reaction rates (for narrow, isolated resonances) it is sufficient to determine the location of the resonances ( $E_r$ ) and their resonance strengths ( $\omega\gamma$ ):

$$\langle\sigma v\rangle_{res} = \left(\frac{2\pi}{\mu kT}\right)^{3/2} \hbar^2 \omega\gamma \exp\left(-\frac{E_r}{kT}\right)$$

These may be obtained by studying the spectroscopic properties of the corresponding meta-stable states, populated through another, more convenient method. The decay spectroscopy is one such method: instead of measuring radiative proton capture ( $p,\gamma$ ) one can study the inverse of its first step, the proton decay of the same state. The states populated by beta-delayed proton decay: in the same compound nucleus, states above the proton threshold are populated by  $\beta$ -decay, and then they decay emitting a proton. This happens if the selection rules for ( $p,\gamma$ ) and  $\beta p$  allow for the population of the same states (energy and spin-parity selection rules). One can determine that way the energy of the resonance, determine or restrict the spins and parity and determine the branching ratios. This simple connection is schematically presented in figure 1 of Ref. [ ] for the case of the  $^{22}\text{Na}(p,\gamma)^{23}\text{Mg}$  radiative proton capture: we aim at populating and study states in the  $^{23}\text{Mg}$  daughter nucleus following the  $\beta$ -decay of  $^{23}\text{Al}$ . The selection rules allow that: s-wave radiative capture involves  $J^\pi=5/2^+$  and  $7/2^+$  states; beta-decay populates predominantly positive parity states with spins  $3/2$ ,  $5/2$  and  $7/2$ . Figure 1, a slide from the actual lecture, underlines that we need to locate the resonances and determine their properties (spin and parity and partial widths). Similar situations for the other two proton capture in our list, which we study through the decay of  $^{27}\text{P}$  and  $^{31}\text{Cl}$ , respectively. I will skip these in favor of sending the reader to the recent papers describing these experiments, the equipment and experimental methods involved, and their results [20,21].

## 5 Conclusions

After a brief review of nuclear astrophysics most important contributions to our understanding of the Universe, I showed that in many cases we need to use indirect methods to obtain data leading to the evaluation of stellar reaction rates. Three methods involving rare ion beams are described: one-nucleon transfer (the ANC method), nuclear breakup at intermediate energies and decay spectroscopy.

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collaborated on the beta-delayed proton-decay spectroscopy. I thank them all. The original articles or planned publications are cited throughout this paper. The work presented in this paper was supported by U.S. Department of Energy under Grant No. DE-FG03-93ER40773.

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