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Direct charged-particle measurements with stable beams

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A number of examples for direct measurements in nuclear astrophysics are given in order to address several important issues. First, recent results for the ^{16}O(p,γ)^{17}F reaction are discussed and it is shown how an improvement in reaction rate precision allows for significantly improved astrophysical predictions in connection with massive AGB stars. Second, we discuss improved experimental techniques for measuring astrophysically important (p,γ), (α,γ), (p,α) and (α,n) reactions. Emphasis is placed on the application of coincidence techniques in order to substantially reduce unwanted background signals. Third, the question of how a measured quantity and its associated uncertainty influences the derived reaction rate is explored. Recent advances employing the Monte Carlo method for estimating reaction rates are presented. The new reaction rates will allow for nucleosynthesis studies that were previously not feasible.

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1. Introduction

Direct charged-particle measurements of astrophysical importance with stable beams have been performed for more than half a century with essentially the same basic components: a high-intensity ion accelerator, useable targets and appropriate radiation detectors. It is interesting to note that early measurements of the ^{16}O(p,γ)^{17}F reaction, performed exactly 50 years ago [1], had access to beam currents of up to 10 mA. A number of modern low-energy accelerators, dedicated to nuclear astrophysics, are in existence, but none of these labs have performed so far experiments with beam intensities in excess of 1 mA on target. Thus, in terms of beam intensity at low bombarding energies, we seem to have made a step back. (However, at the LENA-TUNL facility we have recently produced a proton beam intensity of 3.5 mA on target; development work is ongoing.) And although modern stopping power tabulations allow us to characterize much better the beam energy loss in the target, there have been no fundamental improvements in target fabrication techniques. On the other hand, the improvement in detector technology over the past decades in terms of energy resolution and detection efficiency has been truly stunning. It is no exaggeration to state that a large part of the progress in nuclear astrophysics is directly linked to fundamentally improved detector technology.

We take the opportunity here to discuss a number of important issues related to direct charged-particle measurements with stable beams. We will start by stressing the importance of precise measurements and it is shown how improved precision has a direct impact on stellar model predictions. Next, we comment on improved detection schemes, often involving coincidences between signals, that are used in order to reduce the radiation background not just by small factors, but by orders of magnitude. Without such drastic improvements important future measurements will not be successful. Finally, we attempt to quantify the impact of measured nuclear physics quantities (mean values and associated uncertainties) on the derived reaction rates. To this end, a Monte Carlo method is employed, allowing for the calculation of the reaction rate probability density function that is used to derive low, recommended and high reaction rates.

2. Precision

In many respects, the ^{16}O(p,γ)^{17}F reaction is a textbook case study. It represents a capture of a proton by an inert core, resulting in a rather smooth energy dependence of the cross section, devoid of narrow resonances at low energy. For many years it has been a prime example of the so-called direct proton capture model, which interprets the reaction mechanism in terms of a single-step, direct interaction. Since target fabrication is straightforward, the reaction has also been measured many times. Thus it is surprising that the rate, for example at temperatures of 60-100 MK, has a reported uncertainty of 40% [2]. It has been shown recently [3] that varying the rate within this uncertainty results in ^{17}O/^{16}O ratios from hot bottom burning in massive AGB stars that reproduces the observed anomalous ^{17}O/^{16}O ratio in the extraordinary presolar grain OC2. For this particular reason, a reevaluation of the rate seemed worthwhile.

As a first step, existing measurements where evaluated. It turned out that among the many previous studies only two [4, 5] were useful considering the demand of high precision. Also, both report cross sections for the transitions to the ground and first excited state in ^{17}F separately. Nevertheless, problems were found with the original data: while Chow et al. had underestimated their uncertainties, Morlock et al. did not correct their data for coincidence summing. Luckily enough information was presented in the original publications in order to perform the necessary corrections. The strategy was to analyze both data sets separately, with two entirely independent nuclear reaction models (potential model and R-matrix theory). Other existing measurements [6, 7] could not be analyzed since not enough information was provided in the original papers in order to perform the necessary corrections (for example, modern stopping powers). Another study [1] could be considered (and the corresponding data corrected), but they reported only *total* cross sections instead of cross sections for the individual transitions. Thus, these data cannot be analyzed in a straightforward manner using the reaction models mentioned above. Nevertheless, their information provides an important consistency check.

A sample of the new results is displayed in Fig. 1, showing the analysis of the total cross section (sum of ground and first excited state) in the low-energy region by using the potential model. The black and the red lines correspond to the fits for the Chow et al. and Morlock et al. data, respectively. The results are in excellent agreement and, furthermore, are consistent with the total cross section of Hester et al. (blue data points). A similar level of agreement is obtained in the analysis of the data using the R-matrix model.

Numerical integration of the combined S-factors obtained for different transitions and different reaction models yields a new recommended reaction rate with an uncertainty of only $< 7\%$ at all temperatures. In other words, the ^{16}O(p,γ)^{17}F reaction exhibits now the most precisely determined thermonuclear rates among any charged-particle capture reactions in the A$\geq$12 mass range. This level of precision is crucial for astrophysical predictions. Although the measured ^{17}O/^{16}O ratio of grain OC2 (1.25×10^{-3}) could be reproduced in models of massive AGB stars within the large uncertainty range of the NACRE rate compilation [2], it appears now that the models clearly disagree with observation when the new, much more precise reaction rates are used. Consequently, there is no clear evidence to date for any stellar grain origin from massive AGB stars. Of course, stellar model uncertainties, such as mixing prescriptions or mass loss rates, still need to be evaluated carefully in this context. For more detailed information on the new ^{16}O(p,γ)^{17}F reaction rate, see [8].

3. Experimental techniques

It is a well-known, albeit unfortunate, fact that in nuclear counting experiments the sensitivity for detecting a signal above background is approximately directly proportional to the signal count rate, but inversely proportional to the *square root* of the environmental background count rate. In other words, a background reduction by a factor of 100 corresponds to an improvement in sensitivity by only a factor of 10. Thus a substantial effort of reducing the background is required in order to observe very weak cross sections or resonance strengths.

Most reaction measurements of type (p,γ) or (α,γ) have been performed using a large-volume Germanium detector, surrounded by lead in order to reduce environmental background. Such a system is limited to observing resonances with strengths down to about $\approx10^{-8}$ eV. Recently the sensitivity has been significantly improved by adding a second, large coincidence counter, for example, NaI(Tl). See Ref. [9] for details. The improvement comes because most nuclear reactions

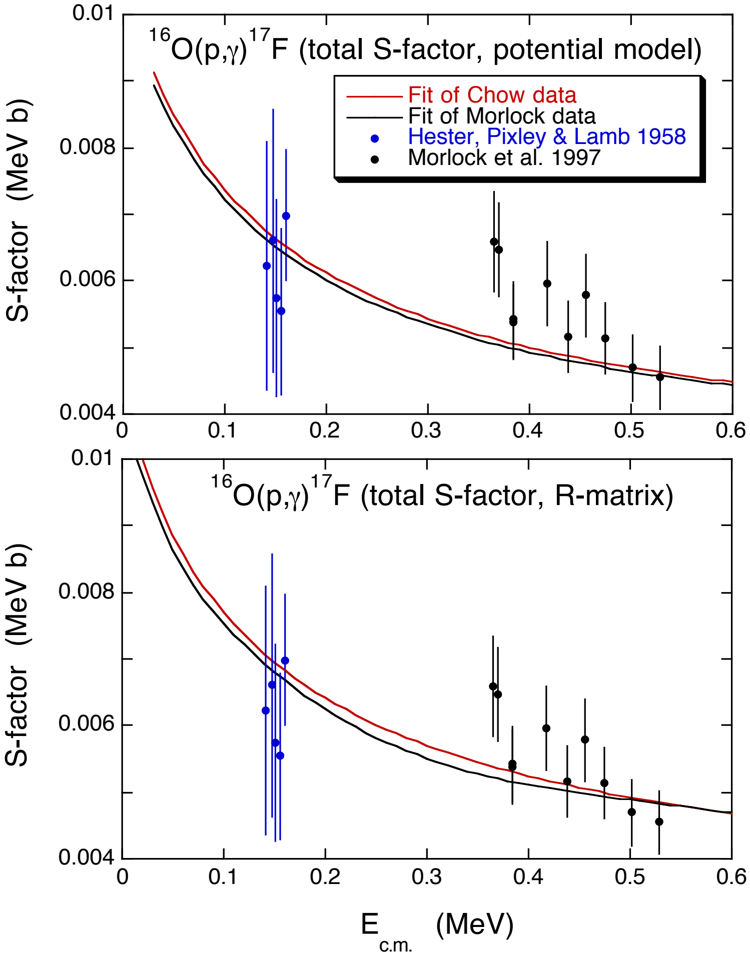

Figure 1: Total S-factor for ^{16}O(p,γ)^{17}F at low bombarding energies. The black and red lines show fits to different data sets by using a potential model (top) and R-matrix theory (bottom). Note that the low energy data below 200 keV [1] cannot be used directly in our analysis since the individual transitions have not been observed. From Ref. [8].

emit γ-rays in a cascade instead of emitting a single photon. Since environmental background decays produce a different decay pattern compared to the nuclear reaction of interest, requiring a coincidence between primary and secondary counters will reduce the background substantially (up to 3 orders of magnitude below 3 MeV γ-ray energy). This detection scheme has been applied in a recent measurement of the ^{23}Na(p,γ)^{24}Mg reaction at 150 keV bombarding energy and, as a result, the reaction rates could be significantly improved. For details, see Ref. [10]. Some of the astrophysical implications are presented in Fig. 2, showing ejected mass fractions of nuclides that are predicted by hydrodynamical simulations of classical novae. The open bars cover the yield range obtained by using the previous ^{23}Na(p,γ)^{24}Mg rate, while the full bars indicate the range when the new reaction rates are used. The level of improvement is obvious. (Note the vertical logarithmic scale.) For example, the yield variation for the important radioisotope ^{26}Al is reduced from a factor 3 to only 24%. Similar improvements are obtained for elemental magnesium and aluminum abundances. Clearly, reliable nuclear reaction studies are indispensable when confronting observed

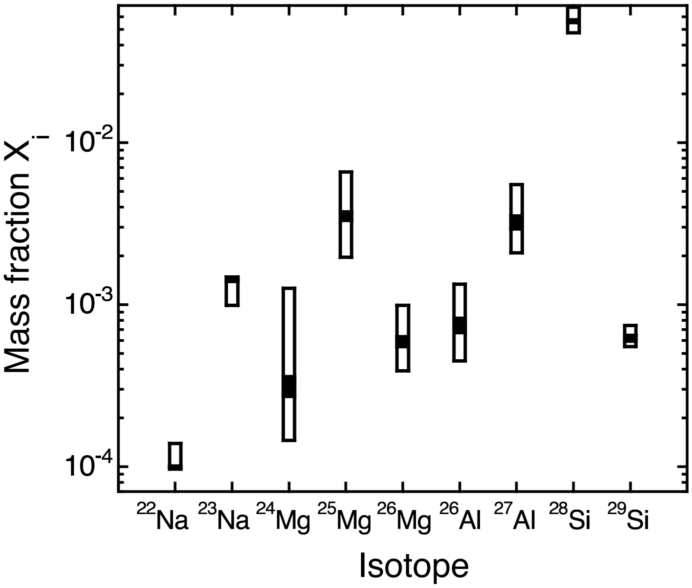

Figure 2: Mean ejected abundances from hydrodynamical classical nova simulation. The vertical bars represent the range of values resulting from ^{23}Na+p uncertainties only; open and filled bars are obtained using previous and new ^{23}Na+p rates, respectively. From Ref. [10].

abundances with stellar model predictions.

Most (p,α) type experiments are performed with the same technique: a high-intensity proton beam is directed onto a thick beamstop target, while a large-area particle detector is positioned in close geometry for detecting reaction α-particles. Of crucial importance is the placement of a thin foil in front of the particle detector to prevent the large flux of elastically scattered protons from reaching the detector and obscuring the weak signal of interest. An example of such an experiment is the recent detection of the 190 keV resonance in ^{17}O(p,α)^{14}N by the Orsay group [11]. This particular resonance is relatively strong, with a strength of $\omega\gamma \approx 2 \times 10^{-3}$ eV, and impacts significantly on the nucleosynthesis in classical novae. Because of its importance we remeasured the resonance at LENA with a similar technique [12] and our results agree with the previous study. We were particularly interested in exploring the effects of the thin foil that is placed in front of the particle detector. Results are shown in Fig. 3. The bottom part displays the measured ^{17}O(p,α)^{14}N spectrum, where the symmetric peak corresponds to the reaction α-particles. The top part shows the result of a numerical simulation using the GEANT4 package (similar results are obtained with SRIM). For the foil thickness we assumed 2.0 μm, the same value as the nominal thickness of the foil used in our measurement. It can be seen that the energy resolution in the simulated spectrum is much higher, by more than a factor of 4, compared to the measured spectrum. Obviously, the resolution directly impacts the detection sensitivity. It appears now that the measured resolution (90 keV) is not dominated by straggling of reaction α-particles in the foil, as previously thought, but is mainly caused by foil non-uniformities (on the order of $\approx$0.2 μm). Since this issue will become important for future measurements of much weaker (p,α) resonances in other reactions, we are now exploring ways of producing highly uniform layers for shielding the particle detector.

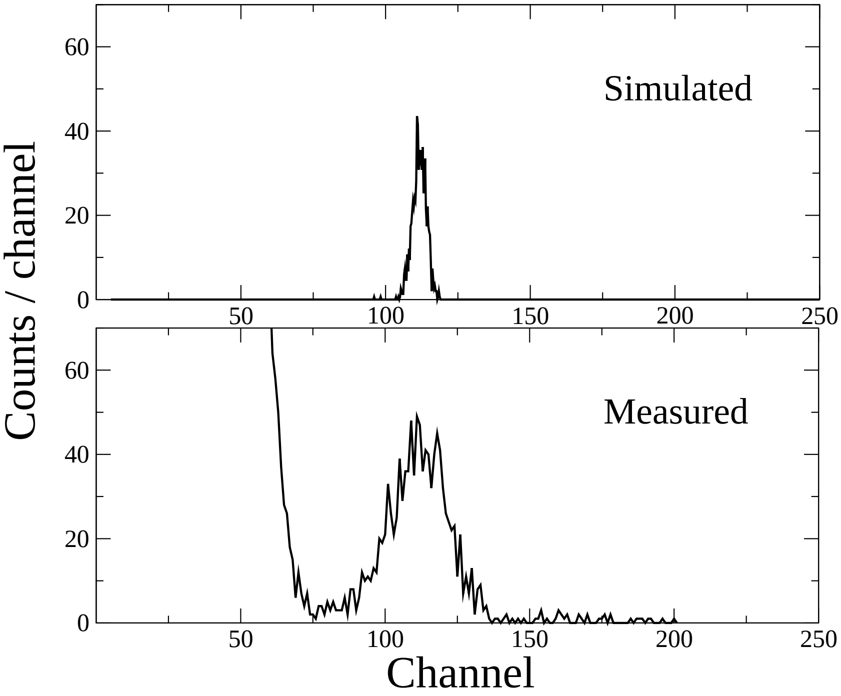

Figure 3: Simulated (top) and measured (bottom) α-particle spectrum in ^{17}O(p,α)^{14}N at $E_p = 195$ keV. The difference in peak widths arises from foil inhomogeneities. From Ref. [12].

Our final example concerns (α,n) type measurements and in particular the ^{22}Ne(α,n)^{25}Mg reaction, which is an important neutron source for the s-process. The situation is shown in Fig. 4, displaying the energy location of known levels in the ^{26}Mg compound nucleus, which could show up as resonances in the ^{22}Ne+α system. The neutron channel opens at a laboratory α-particle energy of ≈560 keV. In other words, between 0 and 560 keV only the ^{22}Ne(α,γ)^{26}Mg channel is energetically allowed, while the (α,γ) and (α,n) reactions compete above the neutron threshold. A few features are notable: first, 41 levels exist between the α-particle threshold (zero bombarding energy) and the lowest lying directly measured resonance at $E_\alpha^{lab} = 840$ keV. Second, only 3 of these levels are known to possess unnatural parity and thus cannot contribute to the ^{22}Ne+α reaction rates. Third, only 13 of these levels were taken into account for calculating the most recent ^{22}Ne+α reaction rates [2]. Obviously, much more experimental work is required until a reliable reaction rate can be derived. All of the previous ^{22}Ne(α,n) measurements were performed by using moderated proportional counters [13], but it appears that this technique has now reached its sensitivity limit. At TUNL we are exploring a different approach, which is based on a coincidence scheme. A prototype detector (boron-loaded liquid scintillator, BLLS) has been purchased for testing purposes. The scintillator is placed very close to the target and is surrounded by a large NaI(Tl) annulus. Consider a fast reaction neutron that enters the scintillator: first, it will scatter elastically on protons until thermalized, thereby producing a signal which is proportional in height to the energy of the incoming neutron; second, the thermal neutron is captured by undergoing a ^{10}B(α,n)^{7}Li reaction, thus producing another signal (with ≈10 μs delay) with a constant height determined by the reaction Q-value; third, the ^{7}Li nucleus is left in an excited state and de-excites by emission of a 478 keV γ-ray, which is detected in the NaI(Tl) counter. In addition, as with any

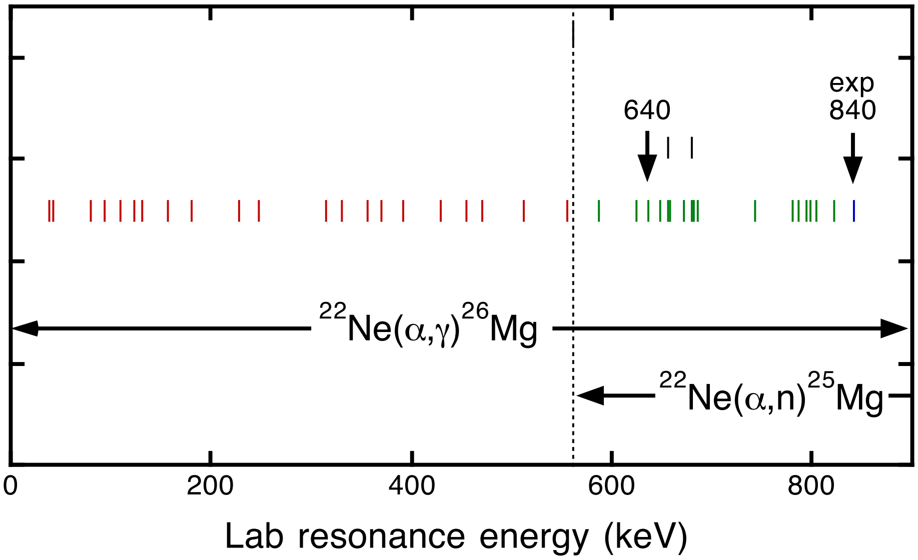

Figure 4: Possible resonances in ^{22}Ne+α at low energies, based on the known level structure of ^{26}Mg. None of the resonances below the measured $E_r^{lab} = 840$ keV resonance have been observed directly yet.

liquid scintillator, standard pulse-shape discrimination can be applied to separate neutrons from γ-rays. It appears that this 4-fold coincidence may increase the detection sensitivity significantly. Results have been encouraging so far.

4. Monte Carlo reaction rates

It is crucial for an experimentalist to understand the impact of a new measurement on the derived reaction rates. However, the procedures that we applied until very recently lack any statistical meaning. This may come as a surprise, but reflects reality: what is the precise meaning of a published recommended reaction rate? How are we to interpret a published lower or upper rate limit? And, in general terms, what is the probability density function of a published reaction rate? None of these questions have clear answers using the commonly accepted procedures in nuclear astrophysics.

We have recently developed a Monte Carlo method of estimating reaction rates that will impact our field in a number of ways. An example is given in Fig. 5, showing results for a single, hypothetical resonance in ^{22}Ne(α,γ)^{26}Mg ($E_r = 300 \pm 15$ keV, $\omega\gamma = 4.1 \pm 0.2$ eV). Each nuclear physics quantity is associated with a (input) probability density function. Random samples are drawn from each of these distributions and the resulting reaction rates are calculated according to the conventional formalism (analytical expressions or numerical integrations). The procedure is then repeated many times until the (output) reaction rate probability density function can be determined accurately (red histogram in top part). The corresponding cumulative distribution (red line in bottom part) is computed and the 16, 50 and 84 percentiles are determined, which are interpreted as low, recommended and high reaction rate, respectively. This simple example already reveals the power of the Monte Carlo method. The resulting rates have a statistical meaning: half of the samples lie below and above the recommended rate, while the coverage probability between low and high rates

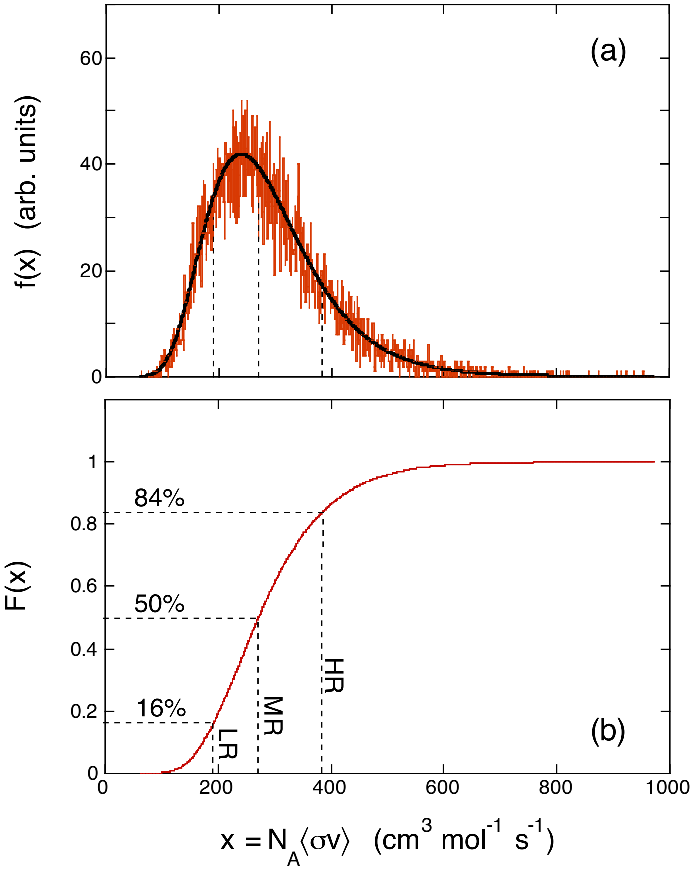

Figure 5: Results of Monte Carlo calculation for a fictitious resonance in ^{22}Ne(α,γ)^{26}Mg at a temperature of T=0.5 GK ($E_r = 300 \pm 15$ keV, $\omega\gamma = 4.1 \pm 0.2$ eV), calculated with 10,000 samples. (top) Reaction rate probability density function, shown in red; (bottom) Cumulative reaction rate distribution. The vertical dotted lines represent the low, median and high Monte Carlo reaction rates which are obtained from the 16, 50 and 84 percentiles, respectively.

amounts to 68%. (Of course, the low and high rate boundaries can be determined according to any desired coverage probability).

The new Monte Carlo method is the foundation of our new A=16-40 thermonuclear reaction rate evaluation, which will be submitted for publication in the near future. Preliminary results already indicate that the rates for many reactions will change dramatically. It is obvious that the new results not only quantify for the experimentalist the impact of measurements, but they are of substantial interest to the stellar modeler as well since the reaction rate probability density function can be used to derive reliable stellar model abundances.

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