Extracting capture from transfer reactions

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Abstract. Indirect reaction techniques are very important in astrophysics as they provide information that is complementary to direct measurements or that otherwise cannot be obtained directly. It is then critical to have a reliable reaction theory that can connect the reaction measurement with the astrophysical information desired. This is a brief report on the progress made in the theory for transfer reactions when used to determine neutron capture rates for r-process and proton capture for rp-process nuclei. We will discuss the different types of experiments and their connection to astrophysics. An overview of the current status of the theory will be provided, with emphasis on several recent theory developments, including transfer to continuum, the improvement of the optical potential and uncertainty quantification. Applications to a couple of neutron rich and proton rich cases will be discussed.

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1. Motivation

Understanding the nucleosynthesis in hot astrophysical environments requires the knowledge of capture reactions on unstable nuclei. In the rp-process, cross sections for proton capture on proton rich nuclei need to be determined within the Gamow window where, due to Coulomb, the cross sections are forbiddingly low. These low cross sections, coupled with the low intensity associated with unstable beams, make it exceedingly hard to measure \((p, \gamma)\) directly. In the r-process, neutron capture reaction rates on unstable neutron rich nuclei are needed. In this case, neither the neutron nor the nucleus of interest can be made as a target due to their short decay lifetime which renders the direct measurement currently unfeasible.

In both these cases, indirect experiments have been measured with the aim of extracting the desired astrophysically relevant cross sections. Nuclear reactions offer the most versatile probe for these processes, and in particular transfer reactions have been widely used in this context: measurements of \((d,p)\) have been used to extract \((n, \gamma)\) and measurements of \((d,n)\) have been used to constrain \((p, \gamma)\).

In deuteron induced transfer reactions, the process of transferring a nucleon (either proton or neutron) to the nucleus of interest contains the same final state of interest. This indirect method has experimental advantages: deuterated targets are readily available and \((d,p)\) and \((d,n)\) cross sections are large enough to make these measurements feasible, even when considering the low intensity beams for rare isotopes. Moreover, using \((d,p)\) and \((d,n)\) as indirect methods also has a theoretical advantage: it presents the case of lowest complexity where a three-body reaction model may work the best, and where the only inputs are nucleon-nucleus interactions (nucleon optical potentials).

Here we collected recent applications of the methods ([1, 2, 3, 4, 5, 6, 7, 8]) as well as a discussion of the status of the theory. In Section 2 we briefly summarize recent applications of \((d,n)\) as an indirect method to extract proton widths. In Section 4 we consider the recent benchmark of \((d,p\gamma)\) as a method for \((n, \gamma)\). We follow with a description on the recent status of reaction theory for \((d,p)\) and \((d,n)\) (Section 5) and the quantification of uncertainties in the model (Section 6). We close with conclusions in Section 7.

2. Reactions for determining proton widths

When considering proton capture rates relevant to the rp-process, most cases are dominated by resonant capture whereby specific resonances dominate the capture cross section. In many of these cases, the decay probability through \(\gamma\)-emission is much larger than that through proton emission. Then, the resonant strength, which determines the contribution to the corresponding capture reaction rate, is uniquely obtained from the proton width \(\Gamma_p\). This is the quantity that can be extracted from \((d,n)\) reactions.
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One of the difficulties in measuring (d,n) to resonant states is that often one needs to separate close by resonances which are strongly populated in the (d,n) process. This can only be achieved by measuring the recoiling isotope in coincidence with the γ-ray, with high precision. This has been achieved at NSCL, with the coupling of the S800 spectrograph [9] and the GRETINA γ-array [10].

The first example of the application of this technique was the measurement of $^{26}$Al(d,n)$^{27}$Si at 33 MeV/u in inverse kinematics [1]. Total cross sections to a number of states, both bound and unbound, were obtained from the coincidence spectrum. On the theory side, we used the adiabatic wave approximation (see Section 5) to determine the total cross section to each state of interest. From the comparison with the measured (d,n) cross sections and the theoretical predictions, Kankainen et al. extracted spectroscopic factors for the states below the proton threshold, and proton widths for the states above the proton threshold. A state-by-state comparison with predictions of the shell model provided assurance that the reaction method was adequately calibrated.

The technique was then applied to $^{30}$P(d,n)$^{31}$S using a $^{30}$P beam at 30 MeV/u [2]. As for the $^{26}$Al case, the angle-integrated measured cross sections populating states in $^{31}$S were compared to theoretical predictions, resulting in the extraction of spectroscopic factors and proton widths. Kankainen et al. found that the deuteron induced reaction populated mostly negative parity states. We also found that the extracted spectroscopic factors and strengths were typically an order of magnitude lower than shell model predictions, suggesting that the effective interaction used in the shell model may not be appropriate this far from stability. The results in [2] offered key constraints on the important reaction $^{30}$P(p,γ)$^{31}$S.

A third example measuring $^{56}$Ni(d,n)$^{57}$Cu was recently reported [3]. In this case, data for both the inverse kinematic (d,p) and (d,n) were analyzed. The spectroscopic factors obtained with (d,n) and (d,p) are very similar, confirming the mirror symmetry properties of the pair $^{57}$Ni and $^{57}$Cu, as expected for a double-magic core of $^{56}$Ni. More importantly for astrophysics, the (d,n) results provided the needed resonance strengths to update the $^{56}$Ni(p,γ)$^{57}$Cu reaction rate in the energy region relevant for novae.

All three cases mentioned above rely on the comparison of theory and experiment at the level of angular-integrated cross sections. Angular distributions provide an important input. First and foremost it narrows down the angular moment of the final state enabling avoiding the guess work done when matching measured states with shell model predicted states. Second, it provides a verification for the reaction model used. Thus, ideally one would like to also have the neutron angular distribution. Because measuring the neutron is challenging, Pain et al. [4] chose to use mirror symmetry and instead measure $^{26g}$Al(d,p)$^{27}$Al. This experiment was performed at HRIBF and used the coincidence of SIDAR (for the recoil isotope) [11] and ORRUBA (for the proton) [12] to obtain proton angular distributions to key resonances in $^{27}$Si. The extracted strength for the 127 KeV state is considerably larger than in previous work, and Ref.[4] discusses the important implications for astrophysics.

Recently, the first attempt to couple a neutron detector (LENDA [13]) with the
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![Figure 1](Color online) Spectroscopic factors (left) and ANCs (right) for $^{12}$N(d,n)$^{13}$O(g.s.) at 3 MeV and 10 MeV with different bound state geometries, parameterized in terms of the single particle ANC. Using the ANC, the bound state geometry can be fixed, better constraining the spectroscopic factor.

S800 and GRETINA was successfully completed [5]. The reaction $^{23}$Al(d,n)$^{24}$Si was measured in inverse kinematics with beam energy 48 MeV/u. Although statistics from the neutron detector did not enable the separation of the various final states, the summed angular distribution (summed over final states) agrees well with theory predictions.

3. Reactions for determining direct neutron capture

Neutron capture reactions on neutron rich nuclei at the limits of stability are dominated by direct capture to bound states. These can be studies through (d,p) experiments in inverse kinematics. One important source of uncertainty is related to the details of the bound state wavefunctions, however the ambiguities can be greatly reduced by analysing (d,p) at two significantly different energies, one where the process is peripheral, and the other with important contributions from the interior of the bound final state. Following the original theory benchmark, demonstrating that a combined analysis of (d,p) measurements could provide the necessary information to extract $(n,\gamma)$ rates [14], a number of experiments have been performed.

One example concerns the systematic (d,p) measurements on the Sn isotopes, performed and analysed with the adiabatic wave approximation [6]. This study enabled a robust determination of the direct capture component to $^{132}$Sn$(n,\gamma)^{133}$Sn. Through the consistent isotopic analysis, the authors caution us on adopting the simple systematics often assumed in general purpose codes.

In addition to the $^{132}$Sn case, a measurement of $^{86}$Kr(d,p)$^{87}$Kr at 33 MeV/u was combined with a previous low energy measurement at 5 MeV/u to constrain the details of the $^{86}$Kr-n effective interaction [7]. The essential idea is that by having both the low energy and the high energy measurement, one obtains separate information regarding the interior and the asymptotic $^{87}$Kr final state. This in turn provides an optimum constraint on the direct capture $^{86}$Kr$(n,\gamma)^{87}$Kr.
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The main drawback of the combined method is that it required two separate experiments, often at different facilities. However, we are now entering a new era in nuclear physics, the era of active target time projection chambers (AT-TPC). With these sophisticated tracking devices, one can obtain in a single experiment information for a whole range of energies. The idea is to apply the combined method in a single experiment, by using the range of energies that exist due to stopping the beam in the active target. An application to $^{12}$N(d,n)$^{13}$O of this novel method is shown in Fig. 1. The range of expected energies 3-10 MeV is enough to go from a fully peripheral process at 3 MeV (constant ANC shown in the right panel of Fig.1) to a process with a significant contribution from the interior (varying ANC). The intersection of these two lines offers a constrain on the single particle parameters of the final state. Although this application is for a case on the proton dripline, we expect this method to become most useful for (d,p) reactions and cases in neutron dripline.

4. Reactions for determining compound neutron capture

Many of the cases of interest for the r-process, involve compound neutron capture reactions, reaction populating the continuum of the final state, that then $\gamma$-decays to the ground state. Again (d,p) reactions can be used and provide essential information for the extraction of the $(n,\gamma)$ of interest, by measuring the $\gamma$ in coincidence with the proton. This so-called surrogate method [15], has recently been validated through a benchmark on $^{95}$Mo with a deuteron beam at 12.4 MeV [8]. Reaction theory specific for such reactions [16, 17] assume the neutron is absorbed following the breakup of the deuteron. The theory predicts the spin distributions for the compound nucleus formation in $(d,p\gamma)$ and allows to extract the necessary information to reconstitute the $(n,\gamma)$ cross section. This neutron capture cross section obtained from (d,p) agrees well with the direct measurement and opens the door to use this method more widely.

5. Advances in the reaction theory

Most of the analysis for the reactions mentioned earlier have been performed with the finite range adiabatic wave approximation [18, 19]. This approach represents an important improvement over DWBA (distorted wave Born approximation) in that it includes deuteron breakup to all orders. However it is not expected to do very well at the lowest energies.

The complete three-body framework to describe (d,p) reactions across the nuclear chart is the Faddeev framework. Currently the Faddeev implementation in our field relies on Coulomb screening which works well for lighter systems and intermediate energies. However for most of the cases of interest to the r-process, the Coulomb screening technique breaks down. Hlophe and collaborators have been working on a new implementation of the Faddeev formalism that avoid Coulomb screening altogether. Benchmarks of this new approach have validated the method [20, 21] and we expect to
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be able to apply in the near future.

Many neutron capture reactions of interest are dominated by compound nuclear formation. Disentangling neutron compound states is extremely difficult and one needs to resort to inclusive approaches. A theory for \( \Lambda(d,p)B \) populating the \( n+A \) compound continuum had recently been revived with several implementations [17]. As discussed in Section 4, the assumption is that \( (d,p) \) populates the same compound states as \( (n,\gamma) \), though with different spin distributions. The reaction models reviewed in [17] enable the connection between the two.

A decade ago, one of the stumbling blocks to apply \( (d,n) \) reaction methods to the proton dripline has to do with the fact that the final states are resonances. We have demonstrated that only for high lying states \( (E_x > 2 \text{ MeV}) \) and for the lowest partial waves is this a problem. In those cases one can use a wavepacket description [1] or resort to the Green’s function approach presented in [16].

6. Uncertainty quantification

One critical component of developing a reliable theory for \( (d,N) \) reactions concerns uncertainty quantification. It is understood that one of the largest sources of uncertainty in our problem is the introduction of the effective \( N+A \) interactions, when modeling the reaction as a three-body problem. Following earlier works when the traditional frequentist approach was used to evaluate uncertainties coming from the optical potential parameterization, we have performed a comparative study between the Bayesian and the frequentist approach [22] and showed that the frequentist method strongly underestimates the error particularly for the higher confidence levels, while the Bayesian offers a more reliable picture. Also we showed that the correlations between parameters that usually emerge from the covariance matrix in the frequentist approach, mostly disappear when performing the full MCMC Bayesian calculation.

Given that the large errors resulting from the Bayesian analysis, it has become imperative to find ways to reduce the errors bars by incorporating more experimental information in the likelihood. Work along these lines is ongoing but results so far [23] already show that both the reaction cross section (or total cross section for neutrons) as well as elastic angular distributions at nearby energies, can significantly reduce the width of the uncertainty bands on the \( (d,N) \) cross sections.

7. Conclusion

Deuteron induced transfer reactions offer an excellent indirect method to extract neutron capture or proton capture in cases for which direct measurements are challenging or unfeasible. This probe is versatile and can provide capture rates to bound, resonant or compound states, depending on the application. There have been a number of applications of the method, both on neutron-rich and proton-rich nuclei, resulting in capture rates of relevance to the r-process and the rp-process respectively. En par
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with the experimental developments, theory has made progress toward a more complete description of deuteron-induced single-nucleon transfer based on a three-body approach. We expect in the near future, to be able to interpret (d,N) experiments in a full Faddeev formalism. In addition, studies on uncertainty quantification in nuclear reactions are providing important information on what is the best combination of data to constrain the parameters in the model, thereby reducing the uncertainties.

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