Transfer reactions as an Indirect Method in Nuclear Astrophysics

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Abstract. In my presentation, I will discuss the use of transfer reactions as an indirect method of determining information important for nuclear astrophysics. Specifically, I will focus on peripheral reactions and their analysis with the Asymptotic Normalization Coefficients (ANC) method. I will present results from related experiments that have been conducted at the Cyclotron Institute, Texas A&M University with focus on the Optical Model Parameters obtained and the need for reliable calculations. Additionally, I will describe the improvements in the measured data that we obtained after upgrading the detection system used.

1 Introduction

The use of indirect methods (IM) in nuclear astrophysics is prompted by the known difficulties that one encounters in attempting to make direct nuclear astrophysics measurements. One of the main sources of difficulties is the fact that in stars, many reaction partners are unstable nuclei. Some of them 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. Another main source is the fact that reactions in stars occur at very small energies (10s-100s keV). Given that the Coulomb barrier is, in general, on the order of a few MeV, it leads to cross sections that are very small and as such, difficult to measure. Last, but not least, in a stellar plasma there are particles other than the reaction participants who can have unknown contributions to the reaction cross-section [1].

So IM are used to measure reactions at lab energies (1-10-100 MeV/nucleon) in order to evaluate cross-sections at stellar energies. The most used IM are: Coulomb dissociation, breakup, transfer reactions, the Trojan Horse Method and resonance spectroscopy.

2 Transfer reactions and the ANC method

A direct transfer reaction is characterized by the rearrangement of only a few nucleons during a fast process. In the early days of nuclear physics, nucleon transfer reactions were the preferred method to study the single-particle degrees of freedom of nuclei and were critical in establishing our current understanding of the structure of nuclei [2]. By comparing the

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shape of the measured angular distributions of the experimental cross-section with theoretical calculations, information could be determined such as: the quantum numbers *nlj* of the single-particle orbitals involved in the reaction, spectroscopic factors, as well as asymptotic normalization coefficients (ANC) for the states populated.

The ANC method [3–5] is an indirect method introduced by the Nuclear Astrophysics group at Texas A&M-Cyclotron Institute (TAMU) roughly 2 decades ago to determine astrophysical S-factors for the non-resonant component of radiative proton capture at low energies (tens or hundreds of keV) by using one-proton transfer reactions involving complex nuclei at laboratory energies (about 10 MeV/u). The idea behind it is that in peripheral processes it is sufficient to know the overlap integral in the asymptotic region, where it is given by a known Whittaker function multiplied by a normalization coefficient C_{nlj}, which is to be determined experimentally.

The general algorithm of an ANC-based experiment is as follows. The first step is to measure the elastic scattering and obtain the angular distribution of the differential cross-section. This distribution is then used to extract the Optical Model parameters (OMP). These parameters are important because they in turn are needed for the distorted wave Born approximation (DWBA) calculation of the transfer reaction cross-section angular distribution. This angular distribution is also measured experimentally and from the comparison with theory, we extract spectroscopic factors or ANCs. In essence, we need good elastic and transfer data, and especially we need reliable OMP and DWBA codes.

3 The study of ^{26}Si(p,γ)

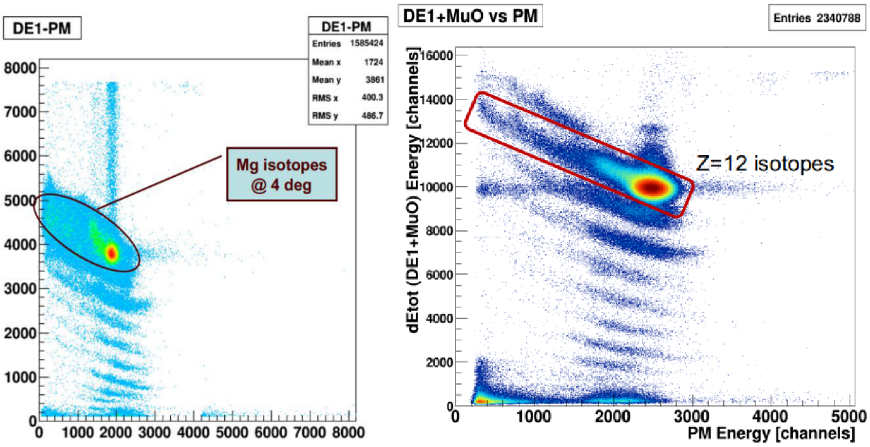
As mentioned above, the ANC method has been used with success by the Nuclear Astrophysics group at TAMU for roughly 20 years. The group studied radiative proton capture reactions important in nuclear astrophysics, using proton transfer [6] and neutron transfer combined with mirror symmetry [5, 7, 8].

The most recent experiments were focused on the study of proton capture on ^{26}Si, a reaction considered important for its role as one of the destruction mechanisms of ^{26}Al in stellar environments, as well as for its presence in the rp-path. A direct method for this is difficult as it requires either an unstable ^{26}Si beam or an unstable target, both of which are extremely difficult to obtain given its short half-life ($\approx$ 2.2 s).

At TAMU, this reaction was studied using peripheral neutron transfer in the mirror system. A ^{26}Mg beam at 12 MeV/n was used on a thin ^{13}C target to measure the elastic channel, ^{13}C(^{26}Mg,^{26}Mg)^{13}C, as well as the single neutron transfer channel. The K500 superconducting cyclotron at TAMU was used to accelerate the Mg beam and the Multipole-Dipole-Multipole (MDM) [9] spectrometer with the Oxford focal plane detector [10, 11] was used to separate the reaction products. One issue that was discovered in the first experiment was the detector's inability to completely separate the Mg nuclei from the Na ones, as can be seen in Figure 1, (a). This prevented us from being able to correctly estimate the differential cross-section for the elastic channel at larger angles and, thus, it was not possible to constrain the OMP sets obtained in fits.

This issue lead to the decision to upgrade the Oxford focal plane detector with Micromegas [12] technology. A Micromegas-based detector is similar to a two stage parallel-plate avalanche chamber. There are two sections, a drift region and an amplification region separated by a thin micro-mesh. Depending on the electric field created between the mesh and the Micromegas anode plats, and more importantly its ratio to the drift field, amplification factors as high as 10^5 can be obtained. The upgrade of the Oxford detector was intended to be low-cost, low-modification and fast to implement. As such it involved replacing one of the existing aluminum anode plates with a Micromegas anode, carefully integrating the necessary electronics into the original scheme. The benefit of this modification was the ability to amplify the small ionization signal without increasing the electronic noise. A more detailed description of this project and its results can be found in Ref. [13].

The upgraded detector was used in a second experiment and the improvement in the particle identification plot can be seen in Figure 1, (b). A preliminary analysis shows that the significantly better separation improved the angular range of the differential cross-section, as well as the number of usable measurement points.



(a) (b)

Figure 1: Particle identification plots showing energy loss on Y-axis in channels versus residual energy on X-axis in channels.(a) The data was obtained with the pre-upgrade Oxford detector (b) The data was obtained with the post-upgrade Oxford detector.

4 Conclusion

Indirect methods are a valuable tool for nuclear astrophysics. However, because they rely heavily on comparisons with theory, there is a strong need for more systematic studies to develop and improve structure and reaction theories, as well as related computer codes. The data obtained for the study of the ^{26}Si(p, γ) reaction is undergoing thorough analysis using the neutron transfer reaction (^{26}Mg,^{27}Mg). We could make these measurements only due to a successful upgrade of the energy loss in the Oxford detector using an innovative technique based on Micromegas. The analysis needs to be finalized and published.

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