THEORETICAL AND EXPERIMENTAL PERSPECTIVES OF NUCLEAR REACTION STUDIES WITH RADIOACTIVE ION BEAMS*

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Nuclear reactions are one of the most powerful probes to study the properties of nuclei, in particular nuclei at the limits of stability. Reactions also play an important role in astrophysics and other applications. In order to extract useful information from reaction measurements, experiment goes hand-in-hand with reaction theory. While the last five decades have provided very good qualitative understanding of the processes, the challenge in the field of reaction theory is to have a grasp on the systematic uncertainties, such that predictions can be truly quantitative. Here, we provide some examples of ongoing efforts aimed at advancing the theory for (d,p) reactions and reducing the associated uncertainties. We present the status of using the ^{86}Kr(d,p) reaction and the combined method to control the uncertainties introduced by the overlap function. We also discuss the ambiguities of using only data to constrain the optical potential and will show recent results on the role of non-locality in transfer reactions.

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1. Introduction

Nuclei are complex many-body systems and pose significant challenges as we move away from the valley of stability. For a good understanding of the role of the various components of the underlying force, it is critical that

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theory gets confronted with experiment. Indeed, experiment guides theory, which, in turn, provides feedback to experiment. It is thus desirable that theory is integrated in the experimental programs. This is particularly true for reaction experiments, whereby the interpretation of the data relies heavily on the translation of the reaction cross section into structure information through reaction theory.

Over the last decade, reaction theory for one-neutron $A(d,p)B$ transfer has seen significant advances, namely to include breakup channels explicitly (*i.e.* continuum discretized couple channel method (CDCC)) and through an exact treatment of the coupling of transfer and breakup channels, as done in the Faddeev formalism [1–4]. However, the connection of these advanced methods to data for states that do not fall into the pure single-particle category is rather obscure. In those cases, one had traditionally relied on the Distorted Wave Born Approximation (DWBA) [5], which does not take into account deuteron breakup. More recently, DWBA is replaced by an approximate version of CDCC, referred to as the Adiabatic Wave Approximation (ADWA) [6], which includes deuteron breakup but makes the adiabatic approximation. In either DWBA or ADWA, the theoretical cross section for $A(d,p)B$ factorizes into a single-particle cross section multiplied by the corresponding spectroscopic factor. In this case, the connection to experiment is straightforward: by taking the ratio of the experimental cross section and the theoretical prediction for the single-particle cross section, one can extract an experimental spectroscopic factor for states between A and B. The problem is that there are a number of uncertainties in determining the $A(d,p)B$ theoretical cross section.

The combined method [7] was proposed as a means to control the uncertainty introduced by the overlap function between A and B, which for most cases above mass $A = 12$ is not well known. Transfer $A(d,p)B$ reactions are predominantly surface peaked, which means that the cross section is strongly dependent on the normalization of the overlap function $\langle A|B\rangle$ in the asymptotic region, the so-called asymptotic normalization coefficient (ANC). If one tried to extract a spectroscopic factor without constraining the ANC, the resulting value can vary tremendously just based on different choices for the mean field $n + A$. A way to reduced this ambiguity is by using a low-energy transfer measurement, only probing the peripheral region, to extract the ANC, and combining it with a higher energy measurement sensitive to both interior and exterior contributions. Here, we present an example of experiments being performed as an application of the combined technique.

Another important source of uncertainty in the prediction of $A(d,p)B$ cross sections is the optical potential. Direct reaction theories rely on the reduction of the full many-body problem into a few-body problem, which

retain the active and relevant degrees of freedom in the process. In this reduction, one needs to introduce effective $N + A$ interactions, the so-called optical potentials. When derived from the many-body problem, these potentials are intrinsically non-local. However, traditionally they have been determined by fits to elastic scattering data assuming local representations. Recent work has shown that the local approximation can introduce a significant change in the magnitude and shape of the angular distributions for the (d, p) cross sections [8]. Here, we discuss these results and the prospects for the future.

2. The combined method

In a traditional DWBA analysis of experimental transfer reactions at energies near the Coulomb barrier, the uncertainties depend upon the experimental errors, as well as the uncertainties in determining the mean field $n+A$. An example was demonstrated in Ref. [9] where the spectroscopic factor extracted for states populated in the ^{84}Se(d, p) reaction at 4.5 MeV/u varied by a factor of three when bound-state parameters were changed slightly from the nominal values of 1.25 fm for the radius and 0.65 fm for the diffuseness parameters for the bound neutron in a Woods–Saxon potential. In contrast, the asymptotic normalization coefficient $C^2_{\ell j}$ was independent of the choice of the bound state parameters, that determine the single-particle ANCs $b^2_{\ell j}$. The uncertainties in $C^2_{\ell j}$ come from experimental uncertainties only. The spectroscopic factor $S = C^2_{\ell j}/b^2_{\ell j}$. The combined method proposes that if the same ^{84}Se(d, p) reaction could be measured at two very different energies, *e.g.*, $\approx$ 5 MeV/u and $\approx$ 35 MeV/u, the single-particle ANC $b^2_{\ell j}$ could be constrained enabling the spectroscopic factor to be deduced with uncertainties dominated by experimental uncertainties. A schematic diagram of how this approach would be implemented is displayed in figure 1. The measurement near the Coulomb barrier would constrain the $C^2_{\ell j}$ value. The behavior of the ratio $R = \sigma^{\mathrm{DW}}/b^2_{\ell j}$ at higher energies when combined with the $C^2_{\ell j}$ at lower energies would constrain $b^2_{\ell j}$. Therefore, the spectroscopic factor S would be deduced from $C^2_{\ell j}$ measured at the lower energy and the constrained $b^2_{\ell j}$.

To test this method, in March 2014 we measured the ^{86}Kr(d, p) reaction at 35 MeV/u at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University. When the analysis of these data is complete, results will be combined with earlier measurements of the ^{86}Kr(d, p) reaction at 5.5 MeV/u [10]. Reaction protons were measured at back angles in the laboratory with the Oak Ridge Rutgers University Barrel Array (ORRUBA) [11] of position-sensitive and the SIlicon Array

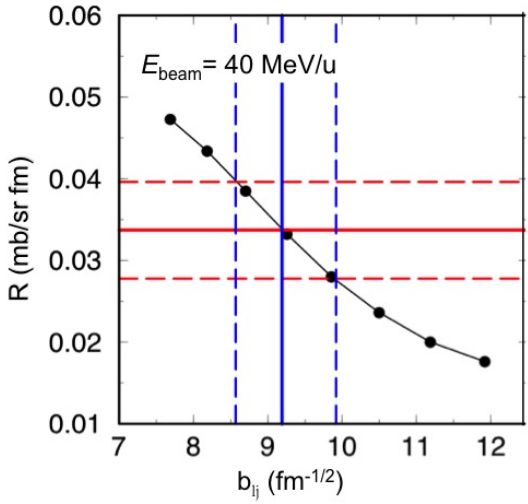

Fig. 1. (Color online) Expected dependency (black points) of the ratio $R = \sigma^{\mathrm{DW}}/b^2_{\ell j}$ (units of mb/sr-fm) at $\approx$ 40 MeV/u as a function of the single-particle ANC $b_{\ell j}$ in units of fm$^{-1/2}$. The solid/red horizontal line is the centroid of the R value determined from the peripheral reaction with uncertainties given by the dashed/red lines. The solid/blue vertical line is the central value for the $b_{\ell j}$ constrained by the R measured at $\approx$ 5 MeV/u, with the dashed/blue lines giving the uncertainties in determining $b_{\ell j}$.

(SIDAR) [12] of segmented silicon strip detectors. The ORRUBA chamber was in front of the S800 spectrograph that was used to measure heavy reaction products. The ANCs have been extracted from the 5.5 MeV/u data [13] and indeed are relatively independent of the single-particle ANCs. Preliminary results from the NSCL measurement are promising, displaying the kinematic curves expected from reaction proton energies as a function of laboratory angle. In the future, we propose to measure the (d, p) reaction with the rare isotope ^{84}Se at $\approx$ 35 MeV/u to deduce spectroscopic factors in the unstable $N = 51$ isotone ^{85}Se with reduced ambiguities once combined with the earlier [9] measurements at 4.5 MeV/u.

3. The optical potential and non-locality

Due to antisymmetrization effects and channel couplings, one expects the nucleon–nucleus effective interaction to be energy dependent and non-local. While for momentum space formulations this aspect does not pose a technical challenge, the same cannot be said for coordinate space formulations of reaction theory. Most of the standard methods for analyzing transfer

reactions rely on coordinate-based codes and therefore it is important to understand the magnitude of the effect of non-locality, prior to performing a general upgrade.

In Ref. [8], we studied the effect of the Gaussian non-locality introduced by Perey and Buck in the sixties [14] on (p, d) angular distributions. First, the local and non-local N–A interactions are made phase equivalent (producing the same elastic scattering). Then scattering waves for the final state are obtained for both the local and non-local version. As known, non-locality produces a reduction of the wave function in the nuclear interior. The bound state wave function is also calculated assuming a local and a non-local mean field with similar properties as the corresponding optical potential. For the bound states, the reduction of the wave function in the nuclear interior is typically accompanied with an increase of the asymptotic normalization. One then constructs the DWBA T-matrix with the wave functions resulting from the local interactions and compares the cross section obtained when the T-matrix is obtained with the wave functions resulting from the non-local interactions. Results in Ref. [8] show that in most cases the shape of the distribution is preserved but there are important magnitude differences of 20–30%. Generally, the cross section resulting from the explicit inclusion of non-locality produced larger cross sections, which would then translate into smaller spectroscopic factors.

In the systematic study performed in Ref. [8], there were particular cases in which not only was the magnitude affected by non-locality, but the angular distribution changed substantially. These effects could be justified by the existence of a node in the bound state which produced higher sensitivity to the short range differences in the wave functions.

In Ref. [15], a similar study was performed for the $^{40}\mathrm{Ca}(p, d)^{41}\mathrm{Ca}$(g.s.) at several beam energies, replacing the Perey and Buck interaction by the dispersive optical model [16]. The dispersive relation connects the real and imaginary parts of the optical potential. The framework implemented in Ref. [16] provides an interaction where scattering and bound states are linked. Indeed, this semi-phenomenological approach contained both scattering observables as well as bound-state properties in the fit. In the preliminary results presented in Ref. [15], transfer cross sections are again significantly modified by the explicit introduction of non-locality in the initial scattering and bound state. Further work along these lines is in the pipeline.

4. Summary

We have provided two examples of how nuclear reaction theory is working hand-in-hand with experiments to reduce the uncertainties in extracting spectroscopic properties of nuclear excitations. The validity of the combined

method, measuring the same (d, p) reaction at two very different energies, is currently being tested with stable beams of ^{86}Kr at ≈ 35 MeV/u, and applications to unstable beams have been proposed. Recent theoretical studies have shown that non-locality must be fully implemented to obtain valid differential cross sections. In addition, the important effects of non-locality call for guidance from many-body microscopic theories, namely in what concerns the shape and magnitude of the non-locality in the optical potential, and the dependence on isospin.

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