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LLNL-TR-471594

TORUS: Theory of Reactions for Unstable iSotopes - Year 1 Continuation and Progress Report

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February 25, 2011

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This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Office of Science, U.S. Department of Energy
Office of Nuclear Physics
Nuclear Theory Division

TORUS:
Theory of Reactions for Unstable iSotopes

A Topical Collaboration for Nuclear Theory
Project Period: June 1, 2010 – May 31, 2015

Annual Continuation and Progress Report
Year-1: June 1, 2010 – February 28, 2011

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February 28, 2011

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1 Introduction

Background

The TORUS collaboration derives its name from the research it focuses on, namely the **T**heory **o**f **R**eactions for **U**nstable i**S**otopes. It is a Topical Collaboration in Nuclear Theory, and funded by the Nuclear Theory Division of the Office of Nuclear Physics in the Office of Science of the Department of Energy. The funding started on June 1, 2010, it will have been running for nine months by the date of submission of this Annual Continuation and Progress Report on March 1, 2011. The extent of funding was reduced from the original application, and now supports one postdoctoral researcher for the years 1 through 3. The collaboration brings together as Principal Investigators a large fraction of the nuclear reaction theorists currently active within the USA.

Mission

The mission of the TORUS Topical Collaboration is to develop new methods that will advance nuclear reaction theory for unstable isotopes by using three-body techniques to improve direct-reaction calculations, and, by using a new partial-fusion theory, to integrate descriptions of direct and compound-nucleus reactions. This multi-institution collaborative effort is directly relevant to three areas of interest: the properties of nuclei far from stability; microscopic studies of nuclear input parameters for astrophysics, and microscopic nuclear reaction theory.

Highlights

1. Publication of paper [18]: *Unitary correlation in nuclear reaction theory: Separation of nuclear reactions and spectroscopic factors.* — Section 2.1.
2. Two more papers submitted — Section 6.2.
3. Completed analysis of recent ^{14}C(d,p)^{15}C and ^{34,36,46}Ar(p,d) transfer experiments — Sections 2.1 and 2.2.
4. Appointment of postdoctoral researcher Dr N. Upadhyay at MSU — Section 4.
5. Extensive tests of Continuum-Discretized Coupled Channels (CDCC) methods for treating deuteron breakup in (d,p) stripping reactions — Section 2.2.
6. Development of theory for transfers to neutron states defined by R-matrix parameters — Section 2.4.
7. Development of coupled-channels theory for semi-direct capture mechanisms via giant-resonance intermediate states — Section 2.5.
8. Exploitation of advanced optical potentials for direct reactions — Section 2.7.
9. Proposal for INT workshop in 2012 – Section 6.7.

2 Topics

The first-year milestones are:

1. Completion of a full comparative study between CDCC-BA and Faddeev integral equations, and
2. Systematic calculation of semi-direct contributions in capture reactions.

This report details our progress on the achievement of these milestones within the first 9 months of Year 1, and of our plans for the following Year 2.

In order to accomplish these and later milestones, a number of related issues must be addressed. These are fundamental questions in reaction theory concerning the proper characterization of what is actually observed in transfer reactions, whether it is the nuclear periphery, or its interior (subsection 2.1). Basic questions about the characterization of resonances also need to be answered, especially concerning how they are measured by transfer reactions (subsection 2.4). On the modeling side, we also need to understand how to use the more advanced optical potentials generated by recent research (subsection 2.7), and furthermore how treatments of continuum states are needed in modeling two-nucleon transfer reactions to measure nuclear pairing (subsection 2.6). Our report therefore details these related works, as essential steps towards our overall goals.

2.1 Distinguishing Peripheral and Interior Contributions

Personnel involved: A.M. Mukhamdezhanov, F.M. Nunes and I.J. Thompson

The crucial deliverable of any reaction theory is to determine what information can eventually be extracted from the analysis of the deuteron stripping data. It is well recognized by now that these reactions are mainly peripheral, i.e. up to $\geq 70\%$ of the contribution to the reaction amplitude comes from the external region. The normalization of the external region is controlled by the asymptotic normalization coefficient (ANC) while the spectroscopic factor (SF) controls only small contribution from the internal region. Moreover, the parameterization of the reaction amplitude in terms of the SF appears only in the DWBA and not in the Faddeev approach. One of the main controversies [22] of the existing DWBA is the inconsistency between extracted SF and ANC values. That is, if one introduces in the analysis information about the ANC, then the extracted SF deviates from its shell model prediction. This once more underscores a flaw in the existing approach. Two of us, A. M. Mukhamedzhanov and F. M. Nunes, took part in the analysis of the ^{14}C(d,p)^{15}C reaction measured at 17 MeV at the Nuclear Physics Institute, Prague-Rez, Czech Academy of Sciences in the collaboration with Texas A&M University and MSU/NSCL. This reaction is one of the first candidates to which we may apply a generalized AGS equations because the target is unstable with two neutrons above the ^{12}C core and the loosely bound state ^{14}C + n is almost of a single-particle nature. Furthermore, the direct radiative capture ^{14}C(n,γ)^{15}C plays an important role in nuclear astrophysics. An analysis of the reaction has been done within the ADWA and the ANC has been extracted. For comparison, a standard DWBA analysis has been also performed and it has been shown that a standard DWBA, despite giving a good description of the experimental angular distribution, gives an incorrect ANC value. The paper "Asymptotic

Normalization Coefficients From the ^{14}C(d, p)^{15}C Reaction" will very soon be submitted to Phys. Rev. C with DOE support being acknowledged.

The question of what spectroscopic information can be extracted from transfer and breakup reactions has been further examined in our paper of [18]: "Unitary correlation in nuclear reaction theory: Separation of nuclear reactions and spectroscopic factors", with acknowledgment to the support of DOE through the TORUS collaboration. Dr. A. S. Kadyrov, of Curtin University, Perth, Australia, is involved in the project as an external consultant. The generalized Faddeev approach, which we are developing for analysis of the deuteron stripping reactions, includes realistic NN potentials. However, it is well known that these potentials are not observable, i.e. there is an infinite number of the phase equivalent potentials which are connected through unitary transformations. It has been demonstrated in the above paper that the amplitudes of the (d,p), (d,pn), and (e,e′p) reactions are invariant under finite-range unitary transformations, while spectroscopic factors are not. The invariance of the ANC under finite-range unitary transformations has been demonstrated. This implies that in any microscopic approach based on the usage of the realistic NN potentials the SFs cannot be extracted from analysis of transfer or breakup reactions. One of the ways to determine SFs is to calculate microscopically the overlap function and its norm, which one cannot extract from reaction theory. Moreover, the reaction amplitudes in the Faddeev approach are not parameterized in terms of the SFs. That is why this work is called "Separation of nuclear reactions and spectroscopic factors". Since many existing and future quite-expensive programs on modern facilities with stable and exotic beams include determination of the SFs, this paper has important consequences for these projects.

Since the latest advances in nuclear reaction theory demonstrate that the only model-independent quantity, which can be extracted from transfer reactions, and, in particular, the deuteron stripping are the ANCs (resonance partial widths which are related with the ANCs), we are going to develop a new approach for deuteron stripping to bound states, which we call the R-matrix theory for transfer reactions. This approach is based on the separation of the matrix element into internal and external regions in the subspace $A + n$. The volume integral over the internal region transformed into the surface integral plus some small addition. The surface integral and the external integral are expressed in terms of the ANC, which can be determined from the fitting of the theoretical cross section to experimental data. This should demonstrate a general method for analysis of transfer experiments.

We will finalize and publish the theory of transfers to bound states defined by R-matrix parameters, and numerically examine the accuracy of this approach.

2.2 Breakup and Transfer Models

Personnel involved: N. Upadhyay (postdoc), F.M. Nunes, and Ch. Elster

As we initiate a new reaction theory development, it is crucial to have a solid understanding of the limitations of the current state-of-the-art models. From the work performed in [6] it became clear that the Continuum Discretization Coupled Channel approach fails in the particular example of ^{11}Be(p,d)^{10}Be, when compared to the exact Faddeev solution. Our goal here is to understand why.

A direct comparison of wavefunctions is not possible because in the AGS method [5] only

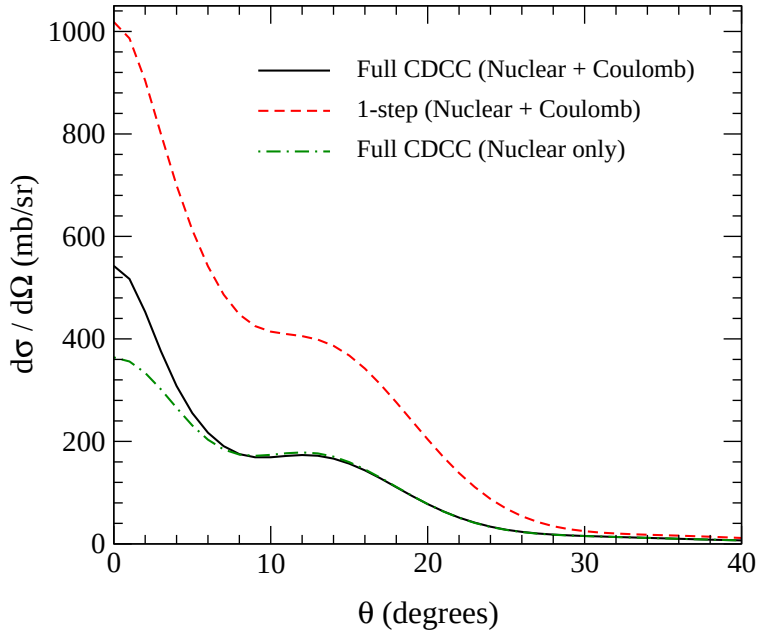

Figure 1: Breakup of deuterons on ^{10}Be at 35 MeV/u: angular distribution.

T-matrices are computed. Exploring different reactions at different energies provides an indirect way of exploring the same information. A number of (d,p) reactions have been identified and detailed comparisons between the Continuum Discretized Coupled Channel (CDCC) and the Faddeev (AGS) approaches are being performed to better understand the limitations of CDCC. These include ^{10}Be(d,p)^{11}Be, ^{12}C(d,p)^{13}C, ^{48}Ca(d,p)^{49}Ca and ^{132}Sn(d,p)^{133}Sn, at both low and intermediate energies, as well as the corresponding reverse reactions. Through these tests, the new post-doctoral fellow (Neelam Upadhyay) is being introduced to nuclear reaction theory.

Comparison of the adiabatic wave approximation with Faddeev results

Because often the spectroscopic factors extracted from the data rely on the adiabatic wave approximation (ADWA) [19], we performed a comparison between results for ADWA and those from the solution of the AGS equations [5] starting from the same effective three-body Hamiltonians and including spin and neutron absorption. This work was developed in collaboration with Arnas Deltuva from the Lisbon group. Results are being analyzed and a publication is in preparation [21].

Deuteron breakup in CDCC

Previous work of [6] compared CDCC with the AGS method for one single transfer reaction ^{11}Be(p,d)^{10}Be within a very simplified model, namely neglecting spins, introducing a single central Gaussian for the deuteron interaction and neglecting neutron absorption. We consider it essential to revisit this reaction in a more realistic framework where CDCC has traditionally been applied.

For our first test case ^{11}Be(p,d)^{10}Be, with the CDCC method, it is best to write down the T-matrix in prior form, in such a way that the exact solution to the 3-body final state is replaced by

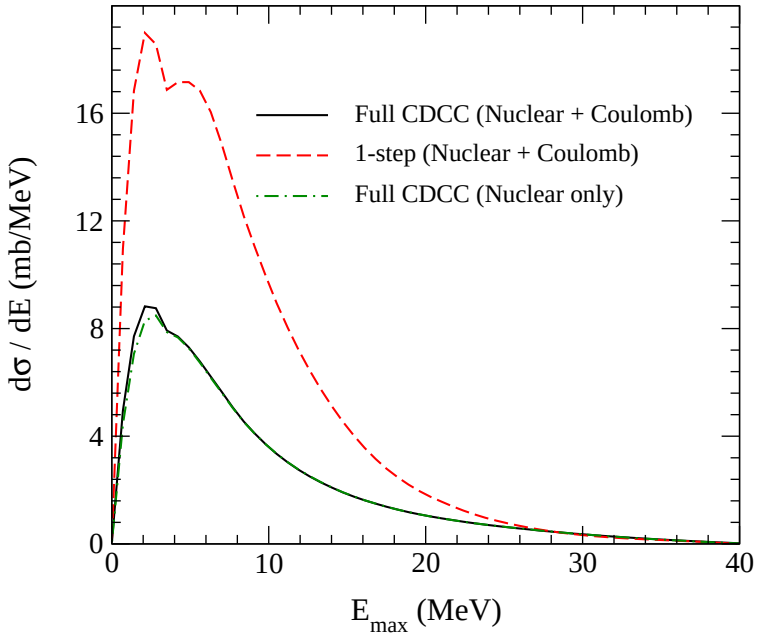

Figure 2: Breakup of deuterons on ^{10}Be at 35 MeV/u: energy distribution.

the CDCC wavefunction [17]. One then needs a reliable deuteron CDCC wavefunction.

We have applied the CDCC method to study the breakup of deuterons on ^{10}Be at 10 MeV/u and 35 MeV/u. Calculations are performed using the global parameterization CH89 [30] for the nucleons-target potentials calculated at half the deuteron energy. For now we exclude the spin-orbit interaction, although later we plan to take it into account. A single gaussian potential is used for the deuteron, reproducing its binding energy and radius.

The model space was checked for convergence. For example for the reaction at 35 MeV/u, the coupled channel equations are integrated up to a maximum radius of $R_{max} = 60$ fm, partial waves up to $l_{max} = 2$ in the relative n-p motion and $L_{max} = 80$ in the d-Be relative motion are required. The deuteron continuum is discretized up to a deuteron relative energy of $E_{max} = 40$ MeV such that for each set of channels we include 3 bins for relative energy in the range (0.1,5.0) MeV, 4 bins for (5.0,15) MeV and 5 bins for (15,40) MeV. Calculations were performed including spin (neutron, proton and deuteron) and repeated setting all spins to zero (to reproduce the work of [6]). With the discretization described above, we have in all 112 (35) channels when deuteron spin is (not) considered.

As an internal check, we compare results including spins with those neglecting it. Since the Hamiltonian is spin independent, results need to be identical. This was verified.

We also repeat the calculations including, instead of a simple gaussian, the Reid interaction [25] for V_{np} in the s- and d-waves. This means that not only do we have coupled channels in the ground state of the deuteron, but in all the discretized continuum. Our results show that the tensor interaction does not have an effect on the energy distribution, angular distribution or total cross sections for breakup. In fact, these observables are very well approximated by the simple gaussian as long as the binding energy is well reproduced.

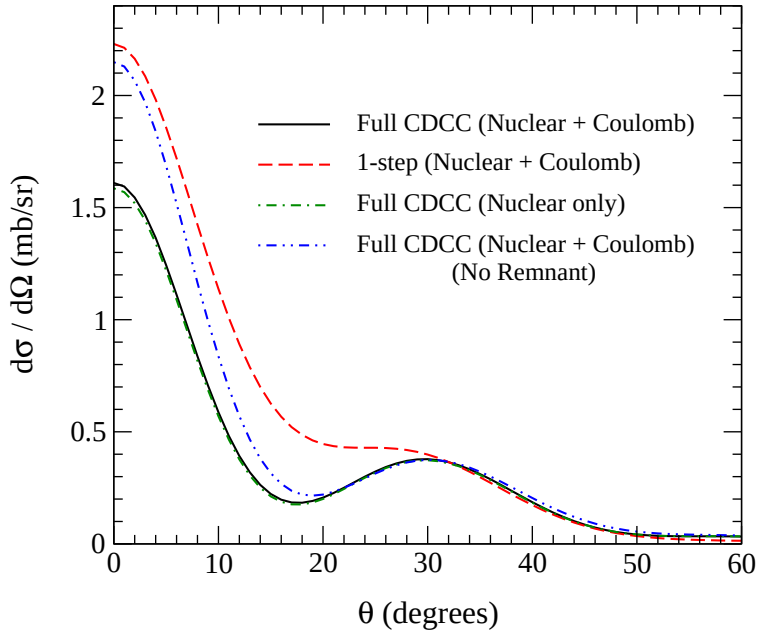

Figure 3: Angular distributions for ^{10}Be(d,p)^{11}Be at 35 MeV/u.

Shown in figures 1 and 2 are the angular distributions and the energy distributions for the breakup of deuterons on ^{10}Be at 35 MeV/u. The solid lines corresponds to the full CDCC results, where Coulomb and nuclear couplings are included. The dashed line is the 1-step calculation and the dot-dashed line corresponds to a full CDCC calculation including nuclear only. Results show that multi-step effects in the continuum are important. This is consistent with previous findings. As expected, Coulomb excitation is negligible in the process.

Transfer to weakly bound states in CDCC

Next we consider the transfer channel, writing down the T-matrix in post-form and replacing the exact deuteron 3-body wavefunction by the CDCC wavefunction determined before. This is sometimes referred to as CDCC-BA although this terminology is misleading because the calculation is not perturbative. In fact, if the CDCC wavefunction is a good representation of the deuteron 3-body wavefunction, our calculations should be exact.

In addition to the model space details defined above, attention needs to be paid to the transfer kernel. With centration of 1.8 fm, this reaction requires a non-local width of 13 fm. We also need to introduce an overlap function for $\langle^{10}\text{Be}|^{11}\text{Be}\rangle$, representing the properties of the valence neutron in the halo final state. We approximate this by a single particle state in a Woods-Saxon mean field with reduced radius $r = 1.25$ fm, diffuseness $a = 0.65$ fm and depth adjusted to provide the correct binding energy.

Angular distributions for ^{10}Be(d,p)^{11}Be at 35 MeV/u are shown in figure 3. The solid line corresponds to the inclusion of breakup effects in the transfer, while the dashed line takes only the direct process (1-step DWBA). Differences are large, demonstrating that breakup is important in the transfer reaction. The dot-dashed line has only taken into account nuclear in the breakup

excitation and agrees well with the results taking both nuclear and Coulomb. As for the breakup observables, the transfer angular distribution is not affected by Coulomb excitation. Finally, the double-dot-dashed line corresponds to the results neglecting the remnant term. Our results confirm that remnant effects for light loosely bound systems are important. In order to compare results to data, one needs to include the spin-orbit interaction for both the nucleon optical potentials and the neutron binding potential. One also has to improve upon the description of the n-p systems, particularly in relation to the p-waves which are strongly populated in the process.

We will continue CDCC calculations for the other test cases we have identified. After this training period, the other cases should come out in a short period of time. In parallel, AGS calculations are being performed in collaboration with Arnas Deltuva (Lisbon). By the end of the current year, a systematic comparison will be provided and should lead to a better understanding of the source of discrepancy between the two methods, providing critical vectors on further developments.

2.3 Generalized Faddeev Methods

Personnel involved: N. Upadhyay (postdoc), Ch. Elster, A. Mukhamedzhanov and F.M. Nunes

Deuteron stripping reactions have been a common tool to get spectroscopic information about single-particle levels, in particular, the spectroscopic factors, where the analysis of the data is based on the distorted wave Born approximation (DWBA). The FRESCO code written by Ian Thompson [29] became the worldwide tool to analyze deuteron stripping. There were a few attempts to improve on the DWBA by including higher order effects. Among the higher order effects is deuteron breakup, which can be taken into account using the continuum discretized coupled channel (CDCC) method, the adiabatic wave approximation (ADWA) [13] which is much simpler than the CDCC method, coupled reaction channel (CRC) approach, and the coupled channel Born approximation (CCBA). The advantage of the code FRESCO is that all these approaches are incorporated into the code. However, all these are still not able to reproduce the full complexity of the stripping reaction and it is the main goal of this project to deliver a new approach allowing one to calculate the deuteron stripping reactions on stable and unstable isotopes over wide energy intervals. Our approach is incorporating the coupled reaction channels to all significant orders necessary to achieve required accuracy. We use as starting point the Faddeev equations written in the commonly used Alt-Grassberger-Sandhas (AGS) formulation. The generalization to be implemented is the inclusion of target degrees of freedom. The starting point for this are two works where participants of the TORUS collaboration already were involved, namely [1]: "Deuteron elastic scattering and stripping processes off ^{12}C as a three-body problem", and [6]: "Three-body description of direct nuclear reactions: Comparison with the continuum discretized coupled channels method". We are progressing with the CDCC calculation as discussed in Section 2.2, and are in the process of setting up the codes for the Faddeev calculations.

We will be using separable representations of realistic nucleon-nucleon (NN) and nucleon-target (NA) interactions. This ansatz reduces the dimension of the integrations in the kernel, leaving the Faddeev equations as a large set of one dimensional coupled integral equations. The use of separable expansions in the AGS equations is particularly relevant to our problem, since then the parameters of bound states (their position, and their residue the ANC) can be fixed or fitted independently of the treatment of the scattering continuum. Accurate separable representations of

specific NN interactions exist [11, 12, 27], and have been generalized to treating Coulomb like interactions in the Faddeev equations [24, 23]. There is less work on separable representations of optical potentials [26], thus we will need to invest work on this aspect of the problem.

Elster has started work on the AGS code and will soon be joined by the postdoc N. Upadhyay. We will first reproduce the work of Ref. [1], and then extend the calculations to the ^{10}Be(d,p)^{11}Be reaction to compare with the CDCC calculation.

2.4 Transfers to Resonances

Personnel involved: A.M. Mukhamdezhanov, J.E. Escher, I.J. Thompson, and G. Arbanas

One-nucleon stripping reactions involving bound final states have long been used as a tool to study the spectroscopic properties of (primarily) stable isotopes. Descriptions of stripping to resonances have also been developed. Typically, they describe the reaction process by approximating the final nucleon-nucleus state as a pseudo-bound state or a continuum wave function. The former does, obviously, not have the correct width, and the latter leads to problems with poor convergence of the relevant radial integrals. In both cases, relevant nuclear-structure information is lost.

One important activity of the TORUS collaboration is the development of a theoretical description of stripping to resonances that provides valuable insights into the structure of the resonant state. The necessity for theoretical advances in this field is due to the fact that the number of the experiments leading to population of the resonance states is mounting but there is no available code for experimentalists to be used to analyze the data. Moreover, it is even unclear what kind of the spectroscopic information can be extracted from the analysis of the data. Since the resonance binary reaction amplitudes in the very popular R-matrix approach are parameterized in terms of the observable partial resonance widths, it is quite natural and convenient for experimentalists to have a theory in which the transfer cross sections are also parameterized in terms of the same observable as is in case of the binary resonance reactions.

During the first year A.M. Mukhamedzhanov began work on the R-matrix theory of deuteron stripping into resonance states. His goal is to deliver a theory which allows the experimental community to reproduce measured cross sections for one-nucleon transfer experiments, and to interpret the results in terms of the partial widths of all open channels. Then the required code will be implemented by Ian Thompson. This work is also important for planning and interpreting inverse-kinematics experiments with radioactive beams [2, 16], and for extracting the relevant nuclear-structure information from the measurements. By the end of a one-month visit to LLNL in February, A.M. Mukhamedzhanov developed the formalism and obtained necessary equations for the theory of the deuteron stripping to resonances, in which the subsystem "transferred nucleon-target" is described within a general multi-channel, multi-level R-matrix approach. The reaction amplitude is expressed in terms of the resonance partial widths, boundary conditions and channel radii, i.e. exactly the same characteristics which appear in the analysis of the resonance scattering in the R-matrix approach. It makes possible for experimentalists to use a combined analysis of deuteron stripping to resonance states and resonance binary reactions, including sub-threshold resonances. An important step in the derivation of the reaction amplitude is the split of the configuration space of the sub-system "transferred nucleon-target" into the internal and external regions, similarly to what is being done in the R-matrix approach [15]. To calculate the contribution from

the external part of the reaction amplitude, which is also expressed in terms of the partial resonance widths, we will be exploring several different techniques: continuum discretized coupled channels (CDCC), exterior complex scaling and surface formulation of the reaction theory. Extending the R-matrix approach to one-nucleon transfers will make it possible to simultaneously fit data for all available channels, including the (n,α), (p,α)and (n,γ) channel, and to determine the relevant physical parameters in a consistent manner. Possible applications were discussed and test cases were identified.

In addition to the developing the theory of the deuteron stripping to resonance states, A.M. Mukhamedzhanov has begun to work on the theory of the Trojan Horse resonance reactions. The only difference between the classical deuteron stripping and the Trojan Horse method is that in the former only the outgoing nucleon-spectator is measured while in the latter both fragments formed after the resonance decay are measured in the coincidence. The delivering of the theory of the Trojan Horse method will be important extension of the deuteron stripping reactions to resonance states as indirect tool to determine the astrophysical factors for the (n,α) and (p,α) resonant reactions.

We will incorporate the formalism developed by A.M. Mukhamedzhanov into a modified Fresco code. This will be tested by various test applications, e.g. partial widths will be extracted that can be compared with known results from (n,α), (p,α) and (n,γ) reactions. The effects of deuteron breakup in the initial channel will be considered using the CDCC approach. We will also investigate the possibility to simultaneously fit resolved resonance parameters and the smoothly varying cross section, which would be a useful development for the nuclear data community. This work will be carried out by A.M. Mukhamdezhanov, J.E. Escher, I.J. Thompson, and G. Arbanas.

2.5 Capture Reactions

Personnel involved: G. Arbanas and I.J. Thompson

A milestone of this collaboration is to incorporate semi-direct capture via the giant-dipole resonance into existing direct-reaction code FRESCO, since this is a significant contributor to the capture cross section in addition to the direct mechanism that is determined from the above transfer reactions. This implies that a full calculation should have both Direct and Semi-Direct (DSD) processes.

The first step is therefore to formally express semidirect capture processes in terms of a coupled-channel framework, while drawing upon the understanding of semidirect capture gained using the conventional single-particle optical potential models. With this goal, Goran Arbanas discussed with LLNL inverstigators about the semi-direct processes and how to implement them within the coupled-channels code Fresco. Based on these discussions, Ian Thompson outlined a method that would incorporate semidirect processes into a coupled-channel framework of FRESCO. In this method, the transition matrix amplitude is to be written as

$$T_{\rm fi}(E,E_\gamma) = \langle \Psi_{\rm f}(E,E_\gamma)|O^{\rm n}_\lambda + O^{\rm c}_\lambda|\Psi_{\rm i}(E)\rangle \tag{1}$$

where $O^{\rm n}_\lambda$ and $O^{\rm c}_\lambda$ are single-particle and core multipole electromagnetic operators of multipolarity λ. Further, the giant-dipole resonance (GDR) degree of freedom of the core is to be added to

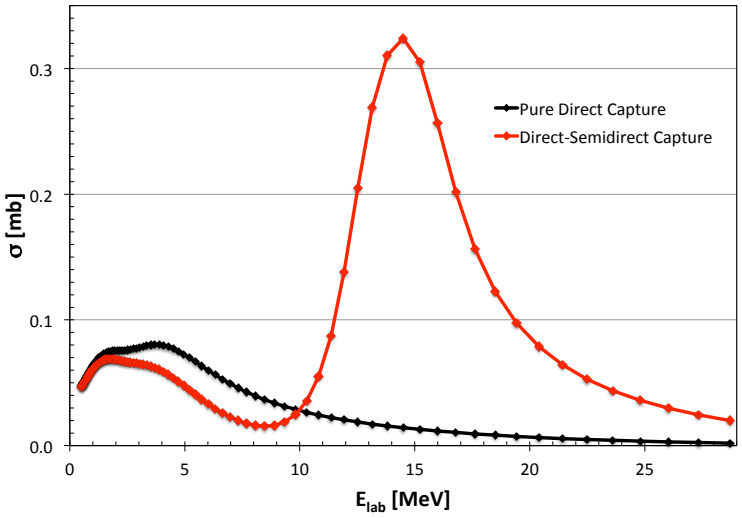

Figure 4: Comparision of pure direct vs direct-semidirect (DSD) neutron total radiative capture on ^{130}Sn using the Koning-Delaroche global optical model potential, and the Bear-Hodgson potential for the bound state wave functions. The effect of semidirect capture is relatively large above 2 MeV. The effect could be either to lower (destructive interference) or to increase (constructive interference) the DSD, relative to pure direct capture. This result is for comparison with the more-realistic model in the coupled-channel framework of Fresco.

(on-shell) initial and final states

$$\Psi_{\rm i}(E) = \chi_{\rm n}^{E}(r_{\rm n})\phi_{\rm gs}(\xi) + \chi_{\rm d}^{E-E_{\rm d}}(r_{\rm n})\phi_{\rm d}(\xi) \quad (2)$$

$$\Psi_{\rm f}(E,E_\gamma) = [\chi_{\rm b}^{E-E_\gamma}(r_{\rm n})\phi_{\rm gs}(\xi) + \chi_{\rm e}^{E-E_{\rm d}-E_\gamma}(r_{\rm n})\phi_{\rm d}(\xi)]\zeta_\gamma(r_\gamma) \quad (3)$$

where $\chi_{\rm n}^{E}(r_{\rm n})$ is the incoming neutron wave-function at energy E, E_γ is the γ-ray energy, $E_{\rm d}$ is the GDR energy, $\chi_{\rm b}^{E-E_\gamma}(r_{\rm n})$ is the neutron bound-state wave function, $\chi_{\rm d}^{E-E_\gamma}(r_{\rm n})$ is a single-particle component in the GDR, $\phi_{\rm gs}(\xi)$ is the target ground state, $\phi_{\rm d}(\xi)$ is the collective GDR state of the target nucleus. With these definitions, and after suppressing energy labels, the direct-semidirect transition matrix element becomes

$$T_{\rm fi} = \langle\chi_{\rm b}|O_\lambda^{\rm n}|\chi_{\rm n}\rangle + \langle\chi_{\rm e}|O_\lambda^{\rm n}|\chi_{\rm d}\rangle + \langle\chi_{\rm b}|\chi_{\rm d}\rangle\langle\phi_{\rm gs}|O_\lambda^{\rm c}|\phi_{\rm d}\rangle + \langle\chi_{\rm e}|\chi_{\rm n}\rangle\langle\phi_{\rm d}|O_\lambda^{\rm c}|\phi_{\rm gs}\rangle, \quad (4)$$

where the first term accounts for a conventional direct capture reaction, and the remaining three account for semidirect capture via a GDR.

To expedite the implementation of this method, it was desirable to have a simple and reliable numerical test case. Based on several prior computations of direct-semidirect capture performed by Arbanas[1] on several light- and medium-mass nuclei, ^{60}Ni was chosen as the first test case for early stages of implementing semidirect capture processes into FRESCO. The ^{60}Ni target was selected because the conventional computations showed that semidirect processes had a large effect on the direct capture at practically all incoming neutron energies up to tens of MeV's, including an unusually large 50% destructive interference effect below 100 keV. In an attempt to simplify

[1]The computations were performed in the single-particle optical model potential, using Frank Dietrich's (LLNL) capture code CUPIDO over the last several years, in support of the Nuclear Data and Nuclear Astrophysics programs.

this test case, only the ground state of ^{61}Ni will be included in computations initially. Similar comparisons between the two codes were performed successfully in the past to verify consistency between respective direct capture computations alone, in a study that aimed to quantify and understand differences between computations that use a current- vs. density-form of the EM operator. Although computations of pure direct capture performed by FRESCO and CUPIDO were found to be in agreement, differences are likely to emerge when semidirect capture is included, due to different models of semidirect capture.

As an overture into systematic computations of DSD on unstable isotopes, Arbanas has been computing DSD capture using CUPIDO on neutron-rich and nearly doubly-magic ^{130}Sn, using the information on bound levels in ^{131}Sn extracted from a very recent ^{130}Sn(d,p)^{131}Sn experimental effort lead by Raymond Kozub (TTU) and Kate Jones (UTK). The effect of the semidirect capture, relative to the pure direct capture, can be seen in Fig. 4. Accurate computation of this capture cross section below 100 keV will be a welcome input to nucleosynthesis models that have been shown to be very sensitive to this particular capture rate. This computation of this DSD capture will be repeated by Fresco, once the anticipated implementation of semidirect capture in Fresco has been tested.

In year 2, we will program the semidirect capture via giant-dipole resonances into FRESCO, and then use FRESCO (and CUPIDO for comparison) to study the effect of the semidirect across the chart of nuclides. Later we will generalize the model to semidirect capture via pygmy and isobar-analogue resonances, and compute cross sections for select nuclides.

2.6 Pair Transfers

Personnel involved: I.J. Thompson

The theory of two-nucleon transfer reactions is closely related to the above TORUS projects that examine transfers to unbound states, because leading candidates for two-nucleon reactions often involve continuum channels among the intermediate states. Two-neutron transfers by (p,t) reactions, for example, must deal with unbound singlet ($S = T = 0$) 'deuteron' d* channels. Neutron-proton transfers by (p,^{3}He) reactions require treatment not only of this d* channel, but also the similar unbound pp channel. Similar (α,^{6}Li) transfer reactions have unbound states in both the ^{5}He and ^{5}Li intermediate channels. The future TORUS work on the treatment of asymptotic boundary conditions, both for resonances and for non-resonant continua, will have direct bearing on how to obtain converged results that include all the intermediate channels in the reactions proposed by the experimentalists. A complete set of intermediate channels is needed, in order to avoid any spurious 'spin filters' in generating predictions for the cross sections for $T = 0$ and $T = 1$ pair transfers.

An initial step in our first year was participation by Ian Thompson in a workshop "Probing Neutron-Proton Pair Correlations – pairing models, cross section measurements and reaction mechanisms" that was held at RIKEN Nishina Center, Japan on November 19-20, 2010. This meeting brought together both reaction and structure theorists, as well as experimentalists, from world-wide institutions. Ian's reaction code FRESCO, already in use within the TORUS collaboration, proved to be the leading candidate for implementing reaction models for nn and np transfer reactions. It is necessary to include both simultaneous and sequential transfer mechanisms for the

two nucleons, and to interface in detail with the structure models since the routes are all coherent, and so phase and coupling conventions need to be carefully checked. A preliminary project is underway to examine the two-nucleon knockout from ^{12}C as measured at Berkeley Lab in the mid-1980s [14]. Already our knockout-reaction colleagues have examined this reaction [28], and our collaboration will examine these reactions soon, when suitable two-nucleon overlap functions have been generated from the No-core Shell Model by Petr Navratil (TRIUMF) and from the Greens Function Monte Carlo method by Ivan Brida (Argonne). The results will be compared with existing transfer measurements, and their accuracy will be compared with that of Glauber calculations of knockout cross sections using the same overlap form factors.

In Year 2 (if time permits), we will calculate two-nucleon transfers for the (p,t) and (p,^{3}He) reactions on ^{12}C using shell-model overlap form factors, and also overlaps from the No-core-Shell-Model and the Variational-Monte-Carlo method when available.

2.7 Implementing Advanced Optical Potentials

This subsection deals with the use of the more advanced optical potentials that have been recently derived in projects funded separately. We are not taking credit for the research leading to these optical potentials, only that, in our TORUS project, we are devoting a small part of our effort to *using* the results of those other projects. We are doing this because we think that important new physics may have been uncovered there, and we want to use the best optical potentials in our own work. This is especially important as we need good theories to extrapolate optical potentials from known stable nuclei to new exotic species.

Dispersive Optical Potentials (from NSF funding)

Personnel involved: F.M. Nunes

The basic idea of these direct reaction models is that we can reduce the many-body problem into a few-body problem with the introduction of effective interactions. Optical potentials and binding potentials are thus inevitable ingredients and usually a source of large uncertainty. Improving these effective interactions is important to this collaboration. A recent development of a dispersive optical model has shown promise [7]. One obvious advantage as compared to other traditional fitting procedures, is that there is a connection between the bound and scattering potential and therefore within the same framework, both interactions are determined. We have initiated a small project where these potentials are used in transfer calculations to assess their usefulness. Results from that work are being finalized and will be written up within the next few months.

L-dependent Optical Potentials from UNEDF project (from DOE SciDAC2 funding)

Personnel involved: I.J. Thompson

The UNEDF project, funded as a SciDAC2 project by the DOE/SC and NNSA, has produced optical potentials for neutron-nucleus scattering by calculating [20] the explicit couplings of elastic scattering to all the doorway channels produced by exciting or transferring one nucleon. The resulting optical potentials, calculated as two-step Feshbach operators, are non-local, energy-dependent

and L-dependent. The non-locality and energy dependence are approximately as expected, but the L-dependence is unexpectedly strong. This suggests that including similar kinds of L-dependence as an extension of existing local optical potentials may significantly improve their accuracy. This should be particularly important for non-elastic channels which depend on the elastic wave function in the surface and interior regions, and thus may well influence the (d,p) transfer reactions which are a focus of our TORUS project.

Microscopic Folding Optical Potentials (from DOE funding)

Personnel involved: Ch. Elster and S. Weppner (consultant)

Elster and collaborators have extensive experience in constructing so-called microscopic "full-folding" optical potentials in "$\tau\rho$" form, where τ contains the information about the nucleon-nucleon interaction and ρ represents the ground state density of the target [10, 9, 4, 8]. These optical potentials are based on the Watson [31] form, which guarantees that neutron and proton distributions are properly taken into account [3]. The evaluation of the full-folding potential requires a fully off-shell density matrix, given in its most general form as $\rho(\mathbf{r}', \mathbf{r}) = \Phi_A^\dagger(\mathbf{r}')\Phi_A(\mathbf{r})$, where $\Phi_A(\mathbf{r})$ is the wave function describing the nuclear ground state in position space, as well as a fully off-shell nucleon-nucleon t-matrix. Thus, the resulting optical potentials are non-local, and depend on energy as well as angular momentum.

These features exhibit similarities to the ones obtained from the coupled channel formulation described above, despite the theoretical starting points of the two formulations being quite different. We decided that these findings warrant some closer investigation of similarities and differences of the properties of those optical potentials: if non-locality and angular momentum dependence are inherently important features we will need to consider these in our description of (d,p) reactions, for which those optical potentials are one of the input quantities. Our findings may also lead to guided prescriptions of additional terms to be included into phenomenological global optical potentials, which are still extensively used as input for describing nuclear reactions. The collaboration with S.P. Weppner, who recently published a new global optical potential fit [32], will be highly beneficial in this investigation. Furthermore, Weppner's capabilities of fitting phenomenological optical potentials will be important, when we need to prepare specific potentials as input the (d,p) reactions.

During the next year we plan to complete the investigation of the non-locality and angular momentum dependence of the optical potential. Within the context of this grant we will also investigate methods of representing optical potentials with separable expansions.

For all potentials:

In Year 2, we will determine how to use the most suitable kind of modern potential within our coupled-channels and generalized-Faddeev formalisms.

3 Project Management

Coordination

- The coordinating P.I. coordinates the different sub-projects, and ensures the cohesion of the overall project.
- Monthly conference calls ensure that practical information is exchanged, and that research projects, visitors and collaborations are properly coordinated.
- Additional conference calls are set up as needed, and our website (see below) is used to deposit internal documents for discussion.
- Collaborative visits and small-group conference calls allow for detailed discussions of physics issues.

Website

We have developed a website at http://www.reactiontheory.org that is hosted at MSU. For the public, this site contains general information about our collaboration, our research papers and talks, the workshops and conferences we attend, and lists of relevant experiments.

For ourselves (protected by a password), we have information about our budget, our plans and deliverables, minutes from our meetings and conference calls, and also a place to deposit internal documents for access by the collaboration.

Collaborative visits

June 2010: the whole collaboration met at MSU for planning purposes
August 2010: Elster and Mukhamedzhanov visited MSU for discussions with Nunes and Upadhyay.
October 2010: Mukhamedzhanov visited LLNL to define the resonance problem.
November 2010: We all attended the DNP10 Fall Meeting at Santa Fe, where our monthly meeting was held.
November 2010: Arbanas visited LLNL to discuss methods for semi-direct captures.
December 2010: Thompson visited MSU to discuss breakup calculations.
December 2010: Elster visited LLNL to discuss L-dependence of optical potentials.
February 2011: Mukhamedzhanov visited LLNL to work on transfers to resonances.
February 2011: Thompson visited OU for work on L-dependent optical potentials.

4 Postdoctoral Staff and Visits

TORUS Postdoctoral researcher

Neelam Upadhyay was hired as the postdoctoral staff in this project. She was hired from a different field (few-body reactions with eta mesons). Neelam arrived at MSU on the 15th July 2010 and has since been actively learning the relevant methods and the interesting physics questions we are addressing. Since September 2010 she has been focusing on learning CDCC and has performed the calculations reported in section 2.2. She participated in a winter school at MSU in January 2010 which broadened her understanding of low energy nuclear physics in particular in connection to FRIB. She will present her work on the deuteron breakup in a contributed session at the APS April meeting. At that meeting she will also participate in a professional skills workshop sponsored by APS.

External Visitors in Year 1

- Antonio Fonseca (University of Lisbon): expert in few-body methods and in particular the AGS method. Visited in November 2010.
- Seth Waldeck (Washington University in St Louis): student of Wim Dickhoff and working on the dispersion optical model. Visited in January 2011.

Other Collaborators in Year 1

These collaborations contributed to our project, but were not funded by this grant:

- Frank Dietrich (LLNL)
- Arthur Kerman (MIT emeritus, now University of Tennessee at Knoxville).
- Raymond Kozub (Tennessee Technological University)
- Kate Jones (University of Tennessee at Knoxville)
- Steve Weppner (Eckerd College, FL)
- Azamat Orazbayev (Ph.D. student at OU)
- Walter Glöckle (Ruhr-Universität Bochum, Germany)
- N.B. Nguyen (Ph.D student at MSU)
- Wim Dickhoff and Seth Waldecker (Washington University, Missouri)

Planned Visitors in Year 2

We plan to support the visits of the following people in Year 2 as visitors or consultants:

- Peter C. Tandy (Kent State U., OH) visit to OU
- Erwin Alt (Johannes Gutenberg U., Mainz, Germany) to visit OU
- Steve Weppner (Eckerd College, FL) visit to OU
- Antonio Fonseca (Lisbon) to visit MSU

5 Plans for Year 2

- Publish the theory of transfers to bound states defined by R-matrix parameters, and numerically examine the accuracy of this approach.
- Continue CDCC calculations to study breakup effects in further transfer reactions.
- Perform AGS calculations in collaboration with Deltuva (Lisbon). Provide systematic comparisons with CDCC results, and gain a better understanding of the source of discrepancy between the two methods.
- Adopt and extend an AGS code for generalized Faddeev calculations. Adapt realistic potentials NN and N-target potentials to separable forms.
- Extend the above R-matrix theory for transfers to multi-channel, multi-level resonances and publish the results, and incorporated into a coupled-channels code. Test the theory, e.g. by extracting partial widths that can be compared with known results from (n,γ) reactions. The effects of deuteron breakup in the initial channel will be considered using the CDCC approach.
- Investigate the simultaneous fit of resolved resonance parameters and the smoothly varying cross section, which would be a useful development for the nuclear data community.
- Implement semidirect capture via giant-dipole resonances into coupled-channels methods, to study the effect of the semidirect across the chart of nuclides. Generalize the model to semidirect capture via pygmy and isobar-analogue resonances.

6 Deliverables

6.1 Publications

1. Published paper [18]: Physical Review C 82, 051601(R) (2010)
Unitary correlation in nuclear reaction theory: Separation of nuclear reactions and spectroscopic factors. A. M. Mukhamedzhanov[1] and A. S. Kadyrov[2]
[1]Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA; [2]ARC Centre for Antimatter-Matter Studies, Curtin University, GPO Box U1987, Perth, WA 6845, Australia. published 3 November 2010

   > Future exact many-body theory will allow us to calculate nuclear reactions based on the adopted NN and many-body nuclear potentials. But NN potentials are not observable and there are an infinite number of the phase equivalent NN potentials related via finite-range unitary transformations.We show that asymptotic normalization coefficients, which are the amplitudes of the asymptotic tails of the overlap functions, are invariant under finite range unitary transformations but spectroscopic factors are not. We prove also that the exact amplitudes for the (d,p), (d,pn), and (e,e′p) reactions determining the asymptotic behavior of the exact scattering wave functions in the corresponding channels, in contrast to spectroscopic factors, are invariant under finite-range unitary transformations. Moreover, the exact reaction amplitudes are not parameterized in terms of the spectroscopic factors and nuclear reactions in the exact approach cannot provide a tool to determine spectroscopic factors which are not observable.

   The work was supported by the US Department of Energy under Grant Nos. DE-FG02-93ER40773 and DE-SC0004958 (topical collaboration TORUS), NSF under Grant No. PHY-0852653 which supported the visit of Dr. A. Kadyrov.

6.2 Preprints and Reports

1. Submitted to Phys. Rev. C
Improved description of ^{34,36,46}Ar(p,d) transfer reactions
F. M. Nunes,[1] A. Deltuva[2] and June Hong[1]
[1]National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, Michigan 48824, USA [2] Centro de Física Nuclear da Universidade de Lisboa, P-1649-003 Lisboa, Portugal

   > An improved description of single neutron stripping from ^{34,36,46}Ar beams at 33 MeV/nucleon by a hydrogen target is presented and the dependence on the neutron-proton asymmetry of the spectroscopic factors is further investigated. A finite range adiabatic model is used in the analysis and compared to previous zero range and local energy approximations. Full three-body Faddeev calculations are performed to estimate the error in the reaction theory. In addition, errors from

the optical potentials are also evaluated. From our new spectroscopic factors extracted from transfer, it is possible to corroborate the neutron-proton asymmetry dependence reported from knockout measurements.

2. Submitted to Phys. Rev. C (Rapid Communication)
Once more about astrophysical S factor for the $\alpha + d \to {}^6\mathrm{Li} + \gamma$ reaction
A. M. Mukhamedzhanov, Cyclotron Institute, Texas A&M University, TX 77843;
B. F. Irgaziev, 2GIK Inst. of Engineering Sciences and Technology, Topi, Pakistan.

   Recently to study the radiative capture $\alpha + d \to {}^6\mathrm{Li} + \gamma$ process new measurements of the ${}^6\mathrm{Li}(\mathrm{A}\,150\,\mathrm{MeV})$ dissociation in the field of ${}^{208}\mathrm{Pb}$ has been reported in [F. Hammache *et al.* Phys. Rev **C82**, 065803 (2010)]. However, the dominance of the nuclear breakup over the Coulomb one prevented from obtaining the information about the $\alpha + d \to {}^6\mathrm{Li} + \gamma$ process from the breakup data. The astrophysical $S_{24}(E)$ factor has been calculated within the $\alpha - d$ two-body potential model with potentials determined from the fits to the $\alpha - d$ elastic scattering phase shifts. However, the scattering phase shift itself doesn't provide a unique $\alpha - d$ bound state potential, which is the most crucial input when calculating the $S_{24}(E)$ astrophysical factor at astrophysical energies. In this work we emphasize an important role of the asymptotic normalization coefficient (ANC) for ${}^6\mathrm{Li} \to \alpha + d$, which controls the overall normalization of the peripheral $\alpha + d \to {}^6\mathrm{Li} + \gamma$ process and is determined by the adopted $\alpha - d$ bound state potential. We demonstrate that the ANC previously determined from the $\alpha - d$ elastic scattering s-wave phase shift in [Blokhintsev *et. al* Phys. Rev. **C 48**, 2390 (19930] gives $S_{24}(E)$, which is at low energies about 38% lower than the one reported in [F. Hammache *et al.* Phys. Rev **C82**, 065803 (2010)]. We recalculate also the reaction rates, which are also lower than the those obtained in [F. Hammache *et al.* Phys. Rev **C82**, 065803 (2010)]. This paper discusses a very important point for nuclear reaction theory: how to determine the two-body potential from the elastic scattering phase shifts. This procedure can be used in application of the Faddeev formalism to deuteron stripping reactions on composite nuclei.

   Acknowledgment of the DOE support through TORUS collaboration is indicated.

3. Internal report
Transfer reactions using the Dispersive Optical Model
N.B. Nguyen,[1] S. Waldercker,[2] F. M. Nunes,[1]
[1]National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, Michigan 48824, USA [2] Washington University in St. Louis, St. Louis, MO U.S.A.

6.3 Proposals

1. Workshop Proposal
The status and future of (d,p) reactions, J. E. Escher (Lawrence Livermore National Laboratory), B. B. Back (Argonne National Laboratory), A. C. Fonseca (Universidade de Lisboa). Submitted to

the Institute for Nuclear Theory, University of Washington, Seattle, February 2011. See Section 6.7 for more details.

2. Experimental Proposal
Systematic studies of neutron-proton pairing in sd-shell nuclei using (p,^{3}He) and (^{3}He,p) transfer reactions, J. Lee (spokesperson)[1] , N. Aoi[1] , A. O. Macchiavelli[2], P. Fallon[2], D. Beaumel[3], I. J. Thompson[4], A. Tamii[5], K. Hatanaka[5], Y. Fujita[5], H. J. Ong[5], T. Suzuki[5], Y. Yasuda[5], J. Zenihiro[5], H. Fujita[6], H. Matsubara[7], T. Kawabata[8], N. Yokota[8], E. Ganioglu[9] and G. Susoy[9].
[1] RIKEN, Nishina Center, [2] Lawrence Berkeley National Laboratory [3] IPN Orsay [4] Lawrence Livermore National Laboratory, [5] RCNP, Osaka University [6] Dep. of Physics, Osaka University, [7] CNS, Univ. of Tokyo [8] Dep. of Physics, Kyoto University, [9] Science Faculty, Istanbul University.

> Pairing correlations, influencing almost every feature of ground and low-lying states in nuclei, lie at the heart of nuclear physics. Understanding the mechanism of neutron-proton (np) pairing in N=Z nuclei has been a long-sought goal in nuclear structure since the early sixties. Despite large efforts in both theoretical and experimental studies, the fundamental nature and the interplay between T=0 and T=1 pairs are still the subject of debate. Cross section measurement of np-pair transfer is considered as a sensitive probe for the dynamical implications of T=0 and T=1 pairing correlations. We propose a series of (p,^{3}He) and (^{3}He,p) transfer reaction measurements in normal kinematics on N=Z nuclei in the 2s-1d shell. The consistent set of accurate cross sections from the proposed systematic measurements spanning the sd-shell region are expected to provide insight into T=0 and T=1 np pairing collectivity and the mechanism of np pairing in these light nuclear systems. In addition, by comparing the cross sections from the proposed measurements to the predictions from the reaction framework coupled with structure model, we are able to evaluate the microscopic descriptions of np pairing correlations in this region. The results would serve as the foundation of the systematic studies of np pairing for heavier N=Z nuclei.

6.4 Presentations

1. *Improving the theory for transfer reactions*, Invited talk by F.M. Nunes, INPC July 2011, Vancouver, Canada.

2. *Where did matter come from?*, Colloquium by F.M. Nunes, University of Michigan Dearborn, Dearborn, U.S.A.

3. *Reaction theory for studying rare isotopes: the missing piece of the puzzle*, Colloquium by F.M. Nunes, University of Notre Dame, South Bend, U.S.A.

4. (d, p) *reactions. Simple or complicated*, Invited talk by A.M. Mukhamedzhanov, 7 April 2010 at the ECT* "Reactions and Nucleon Properties in Rare Isotopes", Trento, Italy, April 6-10, 2010. A new combined method of analysis of the deuteron stripping reactions was addressed. In this method to extract the spectroscopic factor the information about the ANC is added. It allows to fix correctly the normalization of the external part of the reaction amplitude. Extracted in such a way spectroscopic factors disagree with the shell-model predictions. It underscores the flaw in the existing DWBA approach and calls for delivery a new theory of the deuteron stripping.

5. *Unitary correlations in nuclear reaction theory: Separation of nuclear reactions and spectroscopic factors*, Invited talk by A.M. Mukhamedzhanov, 22 September 2010 at ATOMKI, Debrecen, Hungary.

6. *Unitary correlations in nuclear reaction theory: Separation of nuclear reactions and spectroscopic factors*, Invited talk by A.M. Mukhamedzhanov, 26 October 2010 at the ECT* "Workshop on Limits of existence of Light Nuclei", Trento, Italy, October 25-30, 2010

   All trips to Hungary and Italy were supported by DOE, and the last two talks had the common abstract:

   > Future exact many-body theory will allow us to calculate nuclear reactions based on the adopted NN and many-body nuclear potentials. But NN potentials are not observable and there are an infinite number of the phase equivalent NN potentials related via finite-range unitary transformations. We show that asymptotic normalization coefficients, which are the amplitudes of the asymptotic tails of the overlap functions, are invariant under finite range unitary transformations but spectroscopic factors are not. We prove also that the exact amplitudes for the (d,p), (d,pn), and (e,e$'$p) reactions determining the asymptotic behavior of the exact scattering wave functions in the corresponding channels, in contrast to spectroscopic factors, are invariant under finite-range unitary transformations. Moreover, the exact reaction amplitudes are not parameterized in terms of the spectroscopic factors and nuclear reactions in the exact approach cannot provide a tool to determine spectroscopic factors which are not observable.

7. Goran Arbanas participated in the FUSTIPEN Inauguration and gave the talk "Neutron Matter as a Composite Bose-Fermi Superfluid" the first FUSTIPEN workshop: "Bridging the Atlantic with Exotic Isotope Physics", GANIL, Caen, France (January 18-19, 2011). While at GANIL, Arbanas discussed ways of collaborating with Marek Ploszajczak (GANIL) and Witek Nazarewicz (University of Tennessee/ORNL) in a promising initiative to compute reactions on unstable isotopes by building on the framework on the Gamow Shell Model. The synergy of goals with the TORUS collaboration is apparent, but due to being quite different otherwise, this work will not be covered by TORUS funds. $1,250 of the TORUS funds were used to pay for one half of the travel expenses, while UNEDF SciDAC funds were used to pay for the other.

8. *Simultaneous and Sequential Contributions to Two-nucleon Transfer Reactions*, Invited talk by I.J. Thompson, November 20, 2010 at the RIKEN workshop "Probing Neutron-Proton Pair Correlations – pairing models, cross section measurements and reaction mechanisms", RIKEN Nishina Center, Japan on November 19-20, 2010:

   > To probe the details of nucleon pairing in heavy nuclei by means of two-nucleon transfer reactions, detailed structure and reaction theories are both needed, and both tested by the experiments. Structure theories are needed to calculate two-nucleon overlap form factors, making sure to include the best treatment of pairing correlations. Reaction theories use these form factors to calculate both simultaneous and sequential mechanisms to the observed cross sections. These mechanisms, which require some complete set of intermediate channels, give contributions which all add coherently, stressing the need for careful treatment of phase conventions and bound-state signs.

9. *Nuclear Reactions - a Challenge for Few- and Many-Body Theory* Invited talk by Ch. Elster, November 6, 2010 at the "2010 Fall Meeting of the APS Division of Nuclear Physics", Santa Fe, NM, Bulletin of the American Physics Society, Vol. 55, No 14, BAPS.2010.DNP.MC.1

It is a particular exciting time for rare isotope science. As the engineering and construction issues for the new facility for rare isotopes (FRIB) are tackled, the physics community prepares to address the challenging science. A large fraction of the FRIB program will involve direct reactions with rare isotope beams, reactions, which leave a good part of the beam nuclei intact. Thus, the theory of nuclear reactions is central to understanding experiments at FRIB. The reliable prediction of reactions with rare isotopes will be major piece in the theory effort for FRIB. Over the last decade tremendous progress has been in made in exact descriptions of nuclear few-body systems as well as in nuclear structure calculations. The expertise gained in both of these areas will be essential to face the challenge in describing nuclear reactions with rare isotopes. This presentation will use a few examples to illustrate, where the synergy of few- and many-body theory will be able to address the challenges nuclear reactions with rare isotopes faces.

10. *A Nucleon-Nucleus Optical Potential for Rare Isotope Beam Facilities* Contributed talk by Stephen Weppner, November 6, 2010 at the "2010 Fall Meeting of the APS Division of Nuclear Physics", Santa Fe, NM, Bulletin of the American Physics Society, Vol. 55, No 14, BAPS.2010.DNP.MC.6

    A global nucleon-nucleus optical potential for elastic scattering has been produced (see Weppner et. al.; Phys. Rev. C 80, 034608 (2009)) which replicates experimental data to high accuracy and compares well with other recently formulated global optical potentials. The calculation that has been developed describes proton and neutron scattering from target nuclei ranging from carbon to nickel and is applicable for projectile energies from 30 MeV to 160 MeV. With these ranges it is suitable for calculations associated with recent and future experiments performed by rare isotope beam accelerators. Elastic cross section and spin observables from this phenemological potential will be compared to other optical potentials results and experimental data. Deficiencies in the theoretical models and experimental reaction database will be discussed.

11. *Some remarks on reaction theory for Rare Isotopes*, Contribution by F.M. Nunes, 19 January at FUSTIPEN inauguration, Caen, France.

12. *Reaction theory for studying rare isotopes: the missing piece of the puzzle*, Colloquium by F.M. Nunes, 24 Feb at Michigan State University, East Lansing, U.S.A.

13. *Cross sections for astrophysics and other applications,* Invited talk by J. E. Escher, LLNL, at the XXXIV Symposium on Nuclear Physics in Cocoyoc, Mexico, January 2011.

14. *Coupled-channels Neutron Reactions on Nuclei*, Invited Seminar by Ian Thompson at the Institute of Nuclear and Particle Physics, Ohio University, Feb 2011.

6.5 Posters

1. *Reactions of deuteron on* ^{10}*Be*, by N. Upadhyay and the TORUS collaboration, 25th November at Theory group meeting, Michigan State University, U.S.A.

6.6 In Preparation

1. To be submitted to Phys. Rev. C
   Asymptotic Normalization Coefficients From the $^{14}\mathrm{C}(\mathrm{d},\mathrm{p})^{15}\mathrm{C}$ **Reaction.**

A.M. Mukhamedzhanov,[1] V. Burjan,[2] M. Gulino,[3] Z. Hons,[2] V. Kroha,[2] M. McCleskey,[1] J. Mrazek,[2] N. Nguyen,[4] J. Novvak,[2] F. M. Nunes,[4] S. Piskor,[2] S. Romano,[3] M.L. Sergi,[3] C. Spitaleri,[3] L. Trache,[1] and R.E. Tribble[1]
[1]Cyclotron Institute, Texas A&M University, College Station, TX 77843 [2]Nuclear Physics Institute, Czech Academy of Sciences, 250 68 ?Re?z near Prague, Czech Republic [3]Universita di Catania and INFN Laboratori Nazionali del Sud, Catania, Italy [4]National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, Michigan 48824, USA

The $^{14}\mathrm{C}(n,\gamma)^{15}\mathrm{C}$ reaction plays an important role in inhomogeneous big bang models. In [N. K. Timofeyuk *et al.*, Phys. Rev. Lett. **96**, 162501 (2006)] it was shown that the ^{14}C(n,γ)^{15}C radiative capture at astrophysically relevant energies is peripheral reaction, i.e. the overall normalization of its cross section is determined by the asymptotic normalization coefficient (ANC) for ^{15}C $\rightarrow^{14}$C + n. Here we present new measurements of the ^{14}C(d,p)^{15}C differential cross sections at deuteron incident energy of 17.06 MeV and the analysis to determine the ANCs for neutron removal from the ground and first excited states of ^{15}C. The results are compared with the previous estimations.

The acknowledgment to the DOE support through TORUS grant is indicated.

2. Two papers are in preparation by Mukhamedzhanov: (a) The theory of Trojan Horse reaction model, and (b) New approach to deuteron stripping reactions populating resonance states. These papers will be submitted during the first half of 2011.

3. F. Nunes and A. Deltuva, *Comparing the adiabatic wave approximation with exact three-body in (d,p) reactions*, in preparation ([21]).

4. A.M. Mukhamedzhanov has been invited to give a talk about the ANC and spectroscopic factors and recent advances in transfer reaction theory on the workshop "Recent Developments in Transfer and Knockout Reactions" at the European Center for theoretical studies (ECT*) in Trento, Italy, 8-13 April. This talk will be related with the work done on the project within the TORUS collaboration.

5. *Indirect cross section measurements for astrophysics and other applications;* Invited seminar by J. E. Escher, LLNL, at the University of Notre Dame, South Bend, IN, U.S.A., in preparation.

6. *Cross sections for neutron-induced reactions from transfer and inelastic scattering measurements;* Invited seminar by J. E. Escher, LLNL, at Argonne National Laboratory, Argonne, IL, U.S.A., in preparation.

6.7 Proposed TORUS/INT workshop

Personnel involved: J.E. Escher

The TORUS collaboration focuses on basic science issues that are essential for the success of experiments at existing and upcoming radioactive beam facilities, such as ORNLs HRIBF, the Texas A&M Reaccelerated Exotics facility T-REX, and the DOE's Facility for Rare Isotopes Beams. Specifically, to extract relevant structure information from one-nucleon transfer reactions, and advance methods for determining important reaction cross sections from indirect measurements, new theory developments are required. This includes advanced treatments of breakup channels during transfer reactions, especially for transfers of nucleons to weakly-bound or unbound (continuum) states, revised descriptions of transfer reactions that populate resonances and accurate descriptions of reactions that involve both the disintegration of the projectile and the subsequent fusion of one or both fragments with the target nucleus.

For a successful implementation and tests of the theories that are being developed, a close connection to experimental efforts is crucial. Of similar importance is a constructive exchange with reaction theorists working on related issues. In order to increase the interactions between these communities and to highlight the work of the Topical Collaboration in the basic science community, a one-week workshop on (d,p) reactions is planned for the summer of 2012. Jutta Escher has developed the requisite workshop proposal and formed an organizing committee consisting of Birger Back (Argonne National Laboratory), Antonio Fonseca (University of Lisbon), and herself.

The planned workshop will bring together theorists and experimentalists to review recent progress in the description of one-nucleon transfer reactions, to identify issues to be addressed and experiments that can test the theory, and to map out strategies for further theory developments. The focus will be on (d,p) and (d,n) reactions. One important goal of the workshop is to provide the theorists and the experimentalists with a clearer picture of each side's capabilities and challenges. Another important objective is for the theorists to critically examine the presently-used techniques, to identify areas that most urgently need improvements, and to determine appropriate theoretical benchmarks that make it possible to compare different theoretical methods and to test their reliability.

The main topics of the workshop will be closely related to issues investigated by the TORUS collaboration: 1. few-body descriptions of transfer reactions, 2. spectroscopic factors for weakly-bound states and resonances, 3. interplay of direct and statistical reaction mechanisms in one-nucleon transfer reactions, 4. radiative-capture cross sections from transfer measurements. Additional topics will be determined based on the interests of the participants.

The plan has been submitted to the Institute for Nuclear Theory at the University of Washington in Seattle and is presently under consideration.

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