Lawrence Livermore National Laboratory

TORUS Topical Collaboration
Year 1 Overview

Ian Thompson

Structure of Overview

- Purpose of TORUS Topical Collaboration
- Projects and Deliverables
- People and activities: expertise & skills
- Particular Projects:
  - Theory for (d,p) reactions: connecting new and old
  - Capture reactions
  - Preparatory for later years:
    - Transfers to resonances
    - Interior & Exterior in reaction theory
    - Pair Transfers
    - Using advanced optical potentials

Theory Opportunities with FRIB

DOE Nuclear Physics Mission is to understand the fundamental forces and particles of nature as manifested in nuclear matter, and provide the necessary expertise and tools from nuclear science to meet national needs

DOE Nuclear Physics Mission is accomplished by supporting scientists who answer overarching questions in major scientific thrusts of basic nuclear physics research

Science Drivers (Thrusts) from NRC RISAC

Nuclear Structure	Nuclear Astrophysics	Tests of Fundamental Symmetries	Applications of Isotopes
Overarching Questions from NSAC 2007 LRP			
What is the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotopes? What is the origin of simple patterns in complex nuclei?	What is the nature of neutron stars and dense nuclear matter? What is the origin of the elements in the cosmos? What are the nuclear reactions that drive stars and stellar explosions?	Why is there now more matter than antimatter in the universe?	What are new applications of isotopes to meet the needs of society?

Overarching questions are answered by rare isotope research

17 Benchmarks from NSAC RIB TF measure capability to perform rare isotope research

1. Shell structure 2. Superheavies 3. Skins 4. Pairing 5. Symmetries 6. Limits of stability 7. Weakly bound nuclei 15. Mass surface	6. Equation of State (EOS) 7. r-Process 8. $^{15}O(\alpha,\gamma)$ 9. ^{59}Fe supernovae 15. Mass surface 16. rp-Process 17. Weak interactions	12. Atomic electric dipole moment	10. Medical 11. Stewardship

FRIB-CDR, 2010

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Purpose of TORUS Topical Collaboration

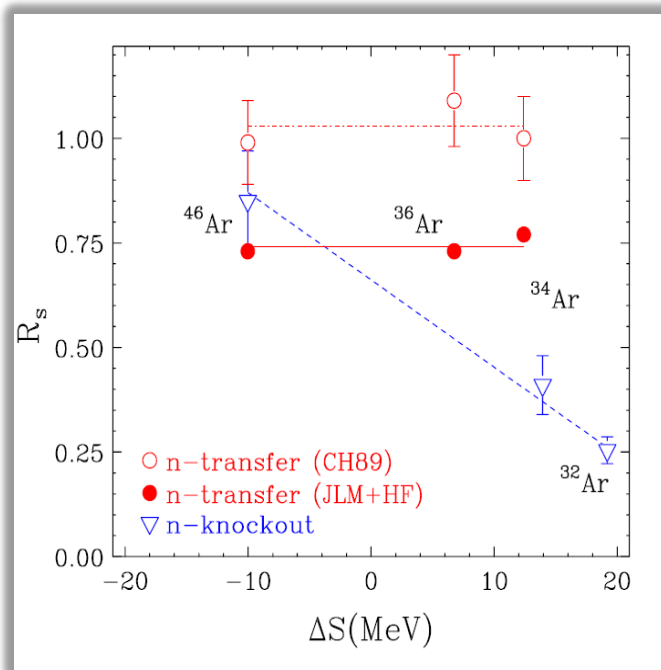**Theory Of Reactions for Unstable iSotopes:**

- Develop new methods to advance nuclear reaction theory for unstable isotopes
  - Theory for (d,p) transfer reactions
  - Build on Faddeev techniques for 3-body systems
  - Treat projectile & target continuum states
  - Apply to capture reactions

Need for Accurate Theories

transfer versus knockout

[Jenny Lee et al, PRL 2009]

[Gade et al, Phys. Rev. Lett. 93, 042501]

o shell structure
o correlations
o pairing
o weakly bound systems
o role of continuum
O ...

**FRIB needs
accurate reaction models!**
Need expertise in
Transfer reactions, 3-body models,
resonances, capture reactions, ...

Projects and Deliverables

Year 1	Year 2	Year 3	Year 4	Year 5
Testing and Extending Direct Reaction Methods				
Application of CDCC-BA to (d,p) and (d,n) reactions populating bound states of rare isotopes with mass A > 40 at energies from 3 MeV/u to 20 MeV/u to identify the role of the continuum	Upgrade an existing code of the momentum-space Faddeev integral equations to include optical potentials and perform tests	Application of the CDCC-BA method to (d,p) and (d,n) reactions populating unbound states and exploring the technical limitations for both resonant and non-resonant continua	Implementation of extended complex-scaling or Gamow-state method	Integration with the compound nuclear part and extraction of the neutron/proton capture cross section and evaluation of uncertainties
Completion of a full comparative study between CDCC-BA and Faddeev integral equations	Calculation of direct transfer 130,131, 132Sn(d,p) reactions within CDCC-BA; identification of the role of the continuum in this reaction and others of relevance for astrophysics	Establish the limits of validity of the CDCC approach for direct reactions from the comparison with full Faddeev calculations in momentum space with full Faddeev calculations in momentum space	Calculation of transfer to unbound states through (d,n) and (d,p) using CDCC-BA, and complex scaling and/or the Gamow method	A robust procedure for extracting the neutron/proton capture cross sections from reaction data
Integrating Direct and Compound-Nucleus Reactions				
Incorporate semi-direct capture via the giant-dipole resonance into existing direct-reaction code	Extend semi-direct formalism to treat pygmy and isobaric-analogue resonances; incorporate into codes	Calculate partial-fusion contributions to (d,p) and (d,n) measurements in the literature and from new measurements	Exploring limits of statistical descriptions, and implement new method for decays of nuclei near the drip lines	Systematic study of direct, semidirect, and statistical contributions to capture reactions for increasingly neutron-rich nuclei
Systematic calculation of semi-direct contributions in capture reactions	Assessment of the relative importance of the extensions (pygmy and IAR resonances) for calculations of astrophysically-relevant cross sections	Calculation of relative probability of compound-nucleus formation and nucleon escape (and resulting CN spin-parity distributions) for various possible (d,p) and (d,n) surrogate experiments, along with prediction of γ-ray transitions for CN decays	New method for description of statistical decay of dripline nuclei	Calculation of cross sections for direct, semidirect, and statistical capture for a range of isotopes; assessment of the behavior and relative importance of the different contributions to the total cross section.

Milestones and Deliverables (year 1)

Testing and Extending Direct Reaction Methods

- <u>Project</u>: Application of T-matrix-CDCC to (d,p) and (d,n) reactions populating bound states of rare isotopes with mass A > 40 at energies from 3 MeV/u to 20 MeV/u to identify the role of the continuum
- <u>Milestone</u>: Completion of a full comparative study between CDCC and Faddeev integral equation

Integrating Direct and Compound-Nucleus Reactions

- <u>Project</u>: Incorporate semi-direct capture via the giant-dipole resonance into existing direct-reaction codes
- <u>Milestone</u>: Systematic calculation of semi-direct contributions in capture reactions

People involved: expertise & skills

- Ian Thompson (LLNL)
  - Coupled-channels methods & reactions
- Filomena Nunes (MSU)
  - (d,p) transfer theory including deuteron breakup
- Akram Mukhamedzhanov (TAMU)
  - General reaction theory & astrophysics, three-body methods
- Charlotte Elster (OU)
  - Three-body systems and microscopic optical potentials
- Jutta Escher (LLNL)
  - Continuum states and compound-nucleus reactions
- Goran Arbanas (ORNL)
  - Capture reactions and nuclear-data applications
- Neelam Upadhyay (the project postdoc at MSU)
  - Implementation & testing of reaction models

Activities

- Monthly conference calls for administration & planning
  - or meetings at INT / DNP conferences
- Additional 'physics conference calls' on specific topics
- Website http://www.reactiontheory.org
  - Public area for papers, talks, etc.
  - Internal area for minutes of meetings, research notes, etc.
- The postdoc has own homepage for showing results.
- Visits between sites
  - (only MSU has funds for postdoc employment.)
- External visitors
  - (usually to MSU)

Website: http://www.reactiontheory.org

ReactionTheory.org

TORUS: Theory of Reactions for Unstable iSotopes
A Topical Collaboration for Nuclear Theory

Collaboration

Research Proposal

Research Papers

Research Talks

TORUS internal

Workshops

Laboratories

Experiments

Site Details

Theory of Reactions for Unstable iSotopes

A Topical Collaboration 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 developing 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 identified in the solicitation: (b) properties of nuclei far from stability; (c) microscopic studies of nuclear input parameters for astrophysics and (e) microscopic nuclear reaction theory.

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TORUS transfer theory topics
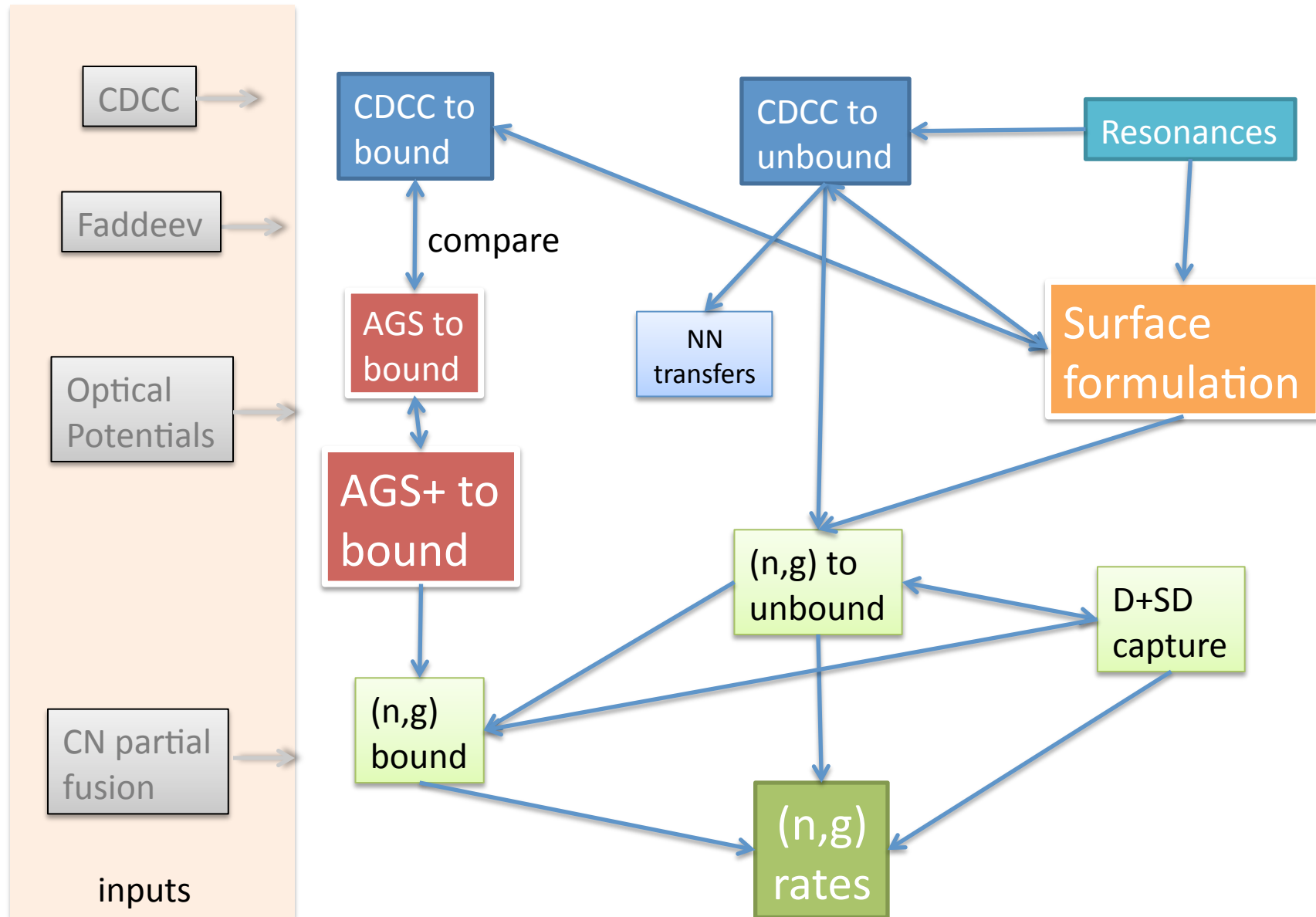
Theory for (d,p) reactions

Led by Filomena Nunes and Neelam Upadhyay
- in collaboration with A. Deltuva (Lisbon)

- Define 3-body model of   (d=n+p) + target
- Solve 'exactly' using AGS eqns in momentum space
  - Includes all intermediate deuteron breakup channels
- Compare with simpler approximations for breakup
  1. Adiabatic model of Johnson & Tandy
  2. Continuum discretized coupled channel (CDCC) method
- Determine accuracy and limits of validity of AD & CDCC methods.

Theory for (d,p) reactions: next steps in Year 2

Nunes and Upadhyay, further collaborating with
Charlotte Elster and Akram Mukhamedzhanov:

- Extending a new AGS code for nuclear reactions
  - start code development

- Include capability of including target excitation
  - show effects of complex nucleon-target potentials

- Use separable optical potentials
  - examining advantages/disadvantages

Capture Reactions

Led by Goran Arbanas and Ian Thompson

- Analysis of transfer reactions will give properties of novel neutron bound states:
  - Use to calculate <u>direct</u> (n,γ) capture cross sections.

- But also need <u>semi-direct</u> captures:
  - Two-step coherent contributions via Giant Dipole Resonances
  - At present, this is only calculated separately, and not within a general coupled-channels framework

- Goran will show new unified method for D+SD capture

Surface Formulation of reaction theory

Led by Akram Mukhamedzhanov

- Only the <u>tails</u> of wave functions are 'observable';
  that is: the same for all phase-equivalent models.

  - Interior part necessarily linked to tail properties
  - How?

- Akram will demonstrate a new transfer theory:

  - Use R-matrix theory for nucleon+target states
  - Find how the interior and exterior parts of transfer matrix elements depend on the tail properties
  - See then the remaining dependence on the interior integrals

- To be suggested as method for analyzing experiments.

  - Method tested for bound states and resonances.

Links between Theories

Generalized Faddeev equations (AGS), target degrees of freedom are included

Equations from
Alt, Mukhamedzhanov et al,
Phys. Rev. C **75**, 054003 (2007).
Starting code is available

Collaboration with C. Elster and N. Upadhyay

Year 2: beginning code

Theory of deuteron stripping into bound and resonance states

Equations: completed

Year 2: code and test of the theory, application for nuclear astrophysics

Collaboration with I. Thompson, F. Nunes and J. Escher

Important: both theories provide ANCs:
the residues in the S-matrix poles
(for both bound states and resonances).
No Spectroscopic Factors!

Describing resonances

- Reactions involve bound and resonance states: resonances prominent for weakly-bound systems
- Shape and position of resonances part of the structure of unstable nuclei,
- and determine astrophysical reaction rates
- CDCC approach:
  - OK with breakup & narrow resonances ✓
  - Wide resonance ??

- We study limitations and possible improvements of the 'discretized continuum'

- Relevant for application of CDCC-BA (see TORUS year 3) and identification of improvements (year 4)

^{14}O+p resonance scattering

Testing N=8 shell closure

PRC 69 (2005) 024309

Astrophysical reaction rates:
- narrow resonances: exponential dependence on E_{Res}
- broad resonances: E_{Res} and E-dependence of width needed

Rolfs & Rodney (1988)
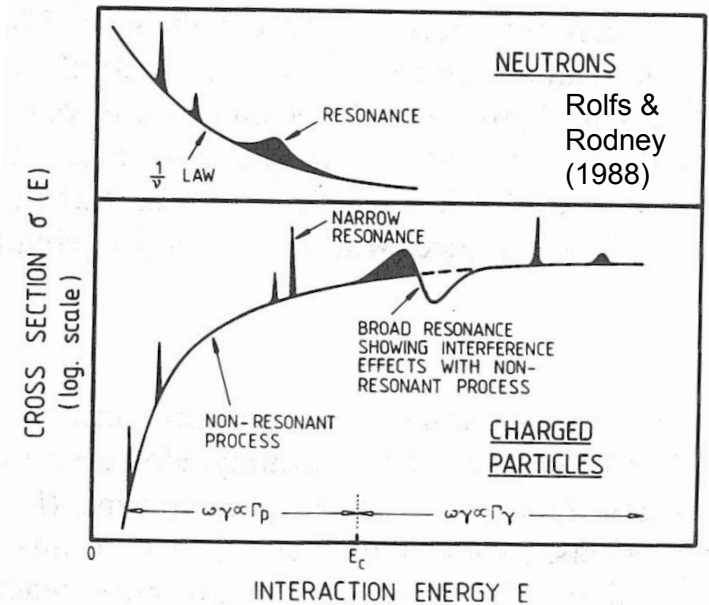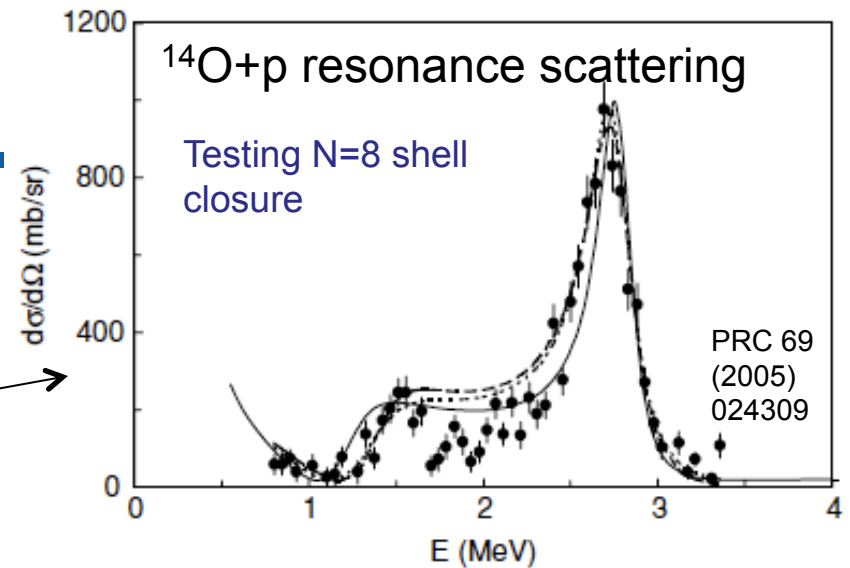
Led by Jutta Escher and Ian Thompson

Verify or Improve CDCC treatment of broad resonances

Discretized Continuum states

ε_{max}

$s_{1/2}$ $p_{1/2}$ $p_{3/2}$ . . . .
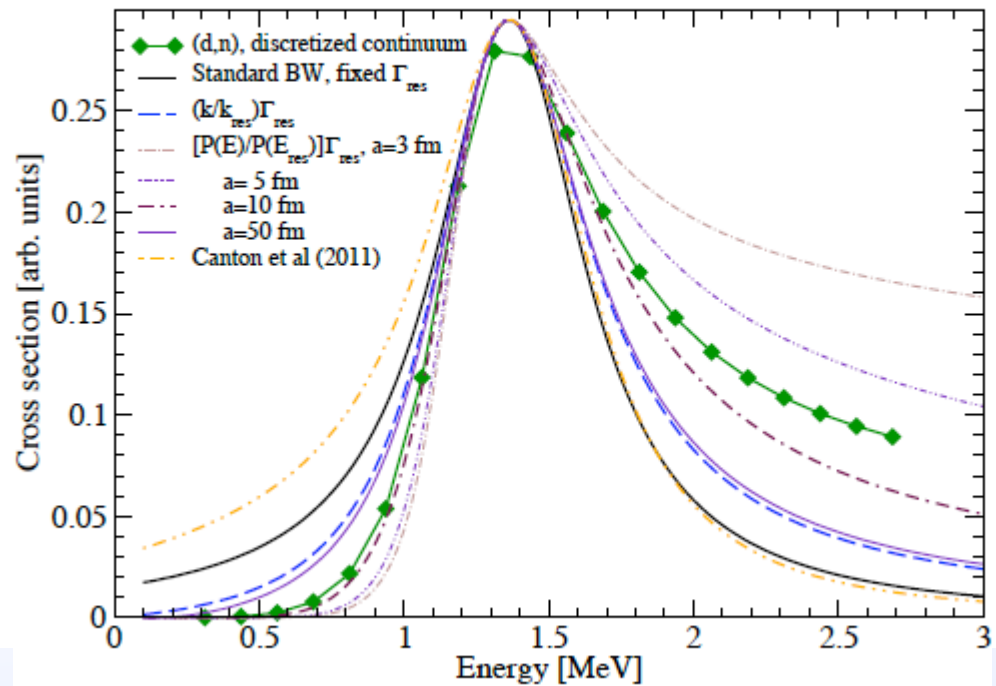
Threshold

. . . .

(Ground state)
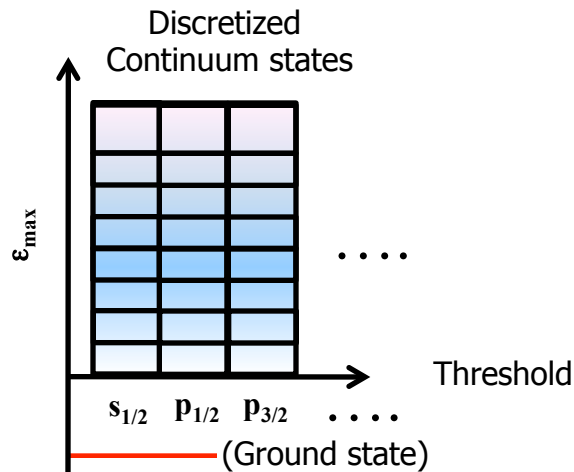
Status:

- Current formalism can treat nonresonant continuum and narrow resonances
- Can we extend this to broad resonances or do we need complex scaling or Gamow states?
- Treatment of overlapping resonances?

Objectives:

- Develop and test new prescriptions for sampling of continuum in 'bins'
- Provide practical tool and guidance to experimentalists: extract resonance parameters from scattering, (d,p) and (d,n)
- Investigate implications for new R-matrix theory of stripping to resonances
- Determine limitations of 'bin' approach

Legend:
- (d,n), discretized continuum
- Standard BW, fixed Γ_{res}
- $(k/k_{res})\Gamma_{res}$
- $[P(E)/P(E_{res})]\Gamma_{res}$, a=3 fm
- a= 5 fm
- a=10 fm
- a=50 fm
- Canton et al (2011)

Cross section [arb. units] vs Energy [MeV]

Using Advanced Optical Potentials

Lead by Charlotte Elster (with S.P. Weppner)

- All previous methods require optical potentials as input

- Here: ab initio approach for microscopic optical potentials:
  - folding the NN t-matrix with the nuclear density matrix

- Testing results by explicit consideration of the cluster dynamics for a 2-neutron halo nucleus.
  - Motivation: A_y problem in reaction ^{6}He+p @ 71 MeV
  - Insight: Ay is sensitive to the cluster dynamic, $d\sigma/d\Omega$ not

- Future: Explicit consideration of open shells in the folding approach
  - Motivation: A_y in reactions ^{6}He+p and ^{8}He+p @ 71 MeV
  - Expectation: well defined additional terms to central and spin-orbit parts

- Also use optical potentials from UNEDF results.

A secondary TORUS priority

Two-nucleon Transfer Reactions

Lead by Ian Thompson

- Two-nucleon transfer reactions probe <u>pairing</u> in nuclei.
  - Neutron-proton pairing for N≅Z nuclei.
  - Neutron-neutron pairing elsewhere.

- Reactions (p,t), (t,p), (p,^{3}He), (^{6}Li,α), ….

- Needs to be future expertise in two-nucleon transfers
  - Include simultaneous and sequential transfer amplitudes
  - They add coherently
  - Possible continuum intermediate states, for example d*, ^{5}Li*

A secondary TORUS priority

Review of Year 1

- Funded from June 1, 2010,

- Postdoc employed at MSU from July 15, 2010.
  - Background was PhD: meson production reactions at Mumbai
  - Learning deuteron-nucleus reactions since September

- This 'half TC' had the LLNL postdoc removed
  - So initially more work for MSU, OU and TAMU investigators, in comparison with those from LLNL and ORNL.

- Milestone 1 (extending direction reaction methods)
  - Done

- Milestone 2 (semidirect methods)
  - New method on track, and applications underway

- Additional works