The **TORUS** collaboration

Filomena Nunes
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topical collaborations in nuclear theory

- **JET**: Quantitative Jet and eletromagnetic tomography of extreme phases of matter in heavy-ion collisions
- Neutrinos and Nucleosynthesis in hot and dense matter
- **TORUS**: Theory Of Reactions of Unstable iSotopes

Topical collaboration in nuclear theory

Theory Of Reactions for Unstable iSotopes:

- overarching theme: connect (d,p) with (n,γ)

- develop new methods to advance nuclear reaction theory for unstable isotopes, building on Faddeev techniques
- treat projectile & target continuum states
- investigate treatment of capture reactions (n,γ)

- output to be used in FRIB reactions & related experiments!

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

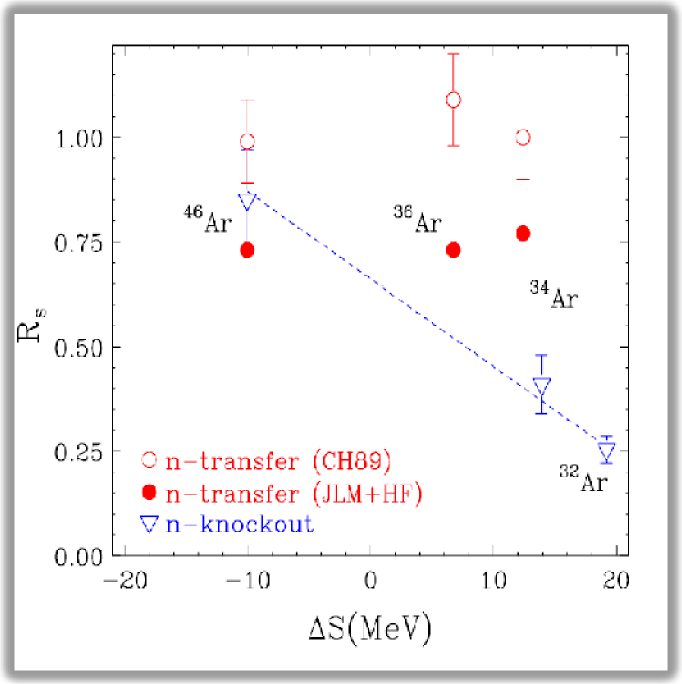
Science Drivers (Thrusts) from NRC RISAC

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			
Shell structure 2. Superheavies 3. Skins Pairing 5. Symmetries Limits of stability Weakly bound nuclei 15. Mass surface	6. Equation of State (EOS) 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

opportunities with FRIB

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!

Topical collaboration in nuclear theory

Theory Of Reactions for Unstable iSotopes:

- overarching theme: connect (d,p) with (n,γ)

- develop new methods to advance nuclear reaction theory for unstable isotopes, building on Faddeev techniques
- treat projectile & target continuum states
- apply to capture reactions (n,g)

  - **need expertise in: transfer reactions, 3-body models, resonances, capture reactions, …**

People and skills

- Ian Thompson (LLNL)
  - Coupled-channels methods
- Filomena Nunes (MSU)
  - (d,p) transfer theory including deuteron breakup
- Akram Mukhamedzhanov (TAMU)
  - General reaction theory & astrophysics applications
- Charlotte Elster (OU)
  - Three-body models and 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

Milestones (1st year)

Testing and Extending Direct Reaction Methods

- Project: Application of Tmatrix-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
- Milestone: Completion of a full comparative study between T-matrix CDCC and Faddeev integral equations

Integrating Direct and Compound-Nucleus Reactions

- Project**:** Incorporate semi-direct capture via the giant-dipole resonance into existing direct-reaction code
- Milestone**:** Systematic calculation of semi-direct contributions in capture reactions

what sort of reaction are we interested in?

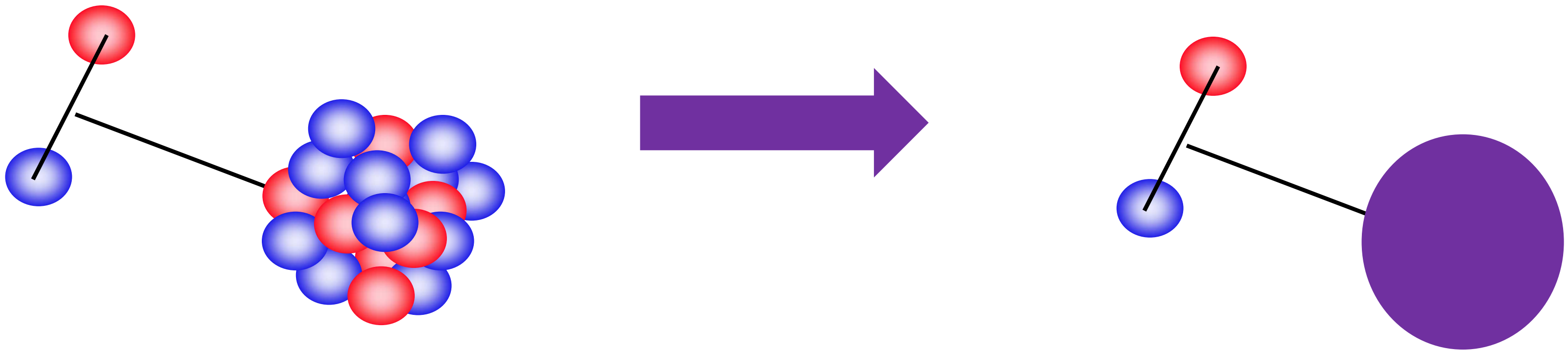
$^{3}He(d,p)^{4}He$

$^{140}Sn(d,p)^{141}Sn$

or anything in between and beyond

?

reducing the many body to a few body problem



- ❑ isolating the important degrees of freedom in a reaction (keeping track of all relevant channels)
- ❑ connecting back to the many-body problem

uncertainties in reaction models

- many-body to few-body
  - overlap function
  - effective interactions (optical potentials)

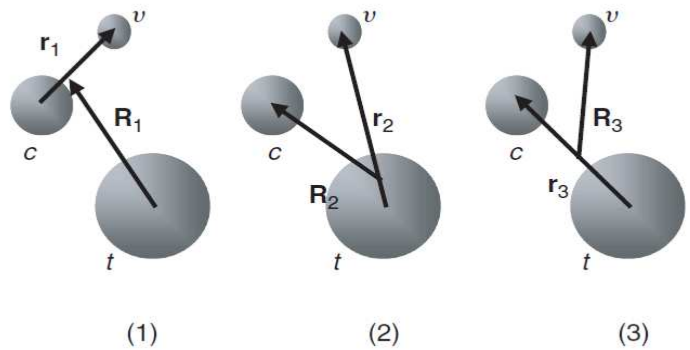
- solving the few-body problem

differences between three-body methods

Faddeev AGS:

- all three Jacobi components are included
- elastic, breakup and rearrangement channels are fully coupled
- computationally expensive

Deltuva and Fonseca, Phys. Rev. C**79**, 014606 (2009).



3 jacobi coordinate sets

CDCC:

- only one Jacobi component
- elastic and breakup fully coupled (no rearrangement)
- computationally expensive

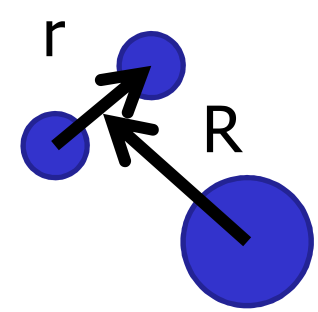
ADWA:

- only one Jacobi component
- elastic and breakup fully coupled (no rearrangement)
- adiabatic approximation for breakup
- runs on desktop – practical for experimentalists

what do we learn from these comparisons?

- o importance of fully coupling to rearrangement channels
- o possible problems with optical potentials
- o quantify accuracy of approximations

(d,p) reactions: three body model



Start from a 3B Hamiltonian

$$\mathcal{H}_{3B} = T_{\mathbf{r}} + T_{\mathbf{R}} + U_{nA} + U_{pA} + V_{np}$$

Solve for 3B wfn and use in exact T-matrix

$$T = < \phi_{nA} \chi_{pB}^{(-)} | V_{np} + \Delta_{rem} | \Psi^{(+)} >$$

ADWA: Johnson and Tandy theory

Expand 3-body wfn in deuteron Weinberg states

$$(T_r + \alpha_i V_{np})\phi_i(\vec{r}) = -\varepsilon_i \phi_i(\vec{r}) \qquad \Psi^{(+)}(\vec{r},\vec{R}) = \sum_{i=1}^{\infty} \phi_i(\vec{r})\chi_i(\vec{R})$$

- set of scattering coupled channel equations

Johnson and Tandy potential

$$U_{ij}(\vec{R}) = -\langle \phi_i | V_{np}(U_{nA} + U_{pA}) | \phi_j \rangle$$

If only first term of the expansion is included:
coupled equations reduce to single channel!

[Johnson and Tandy, NPA 235, 56(1974)]

Systematic comparison: FR-ADWA vs Faddeev

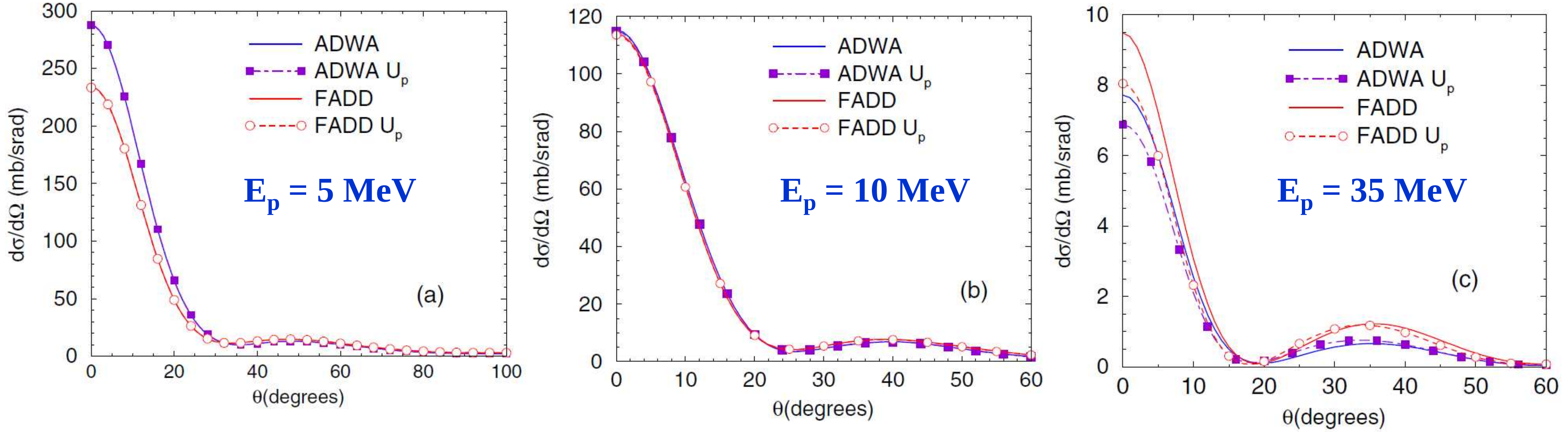


FIG. 1: Angular distributions for ^{11}Be(p,d)^{10}Be: (a) $E_p = 5$ MeV, (b) $E_p = 10$ MeV, and (c) $E_p = 35$ MeV.

Systematic comparison: FR-ADWA vs Faddeev

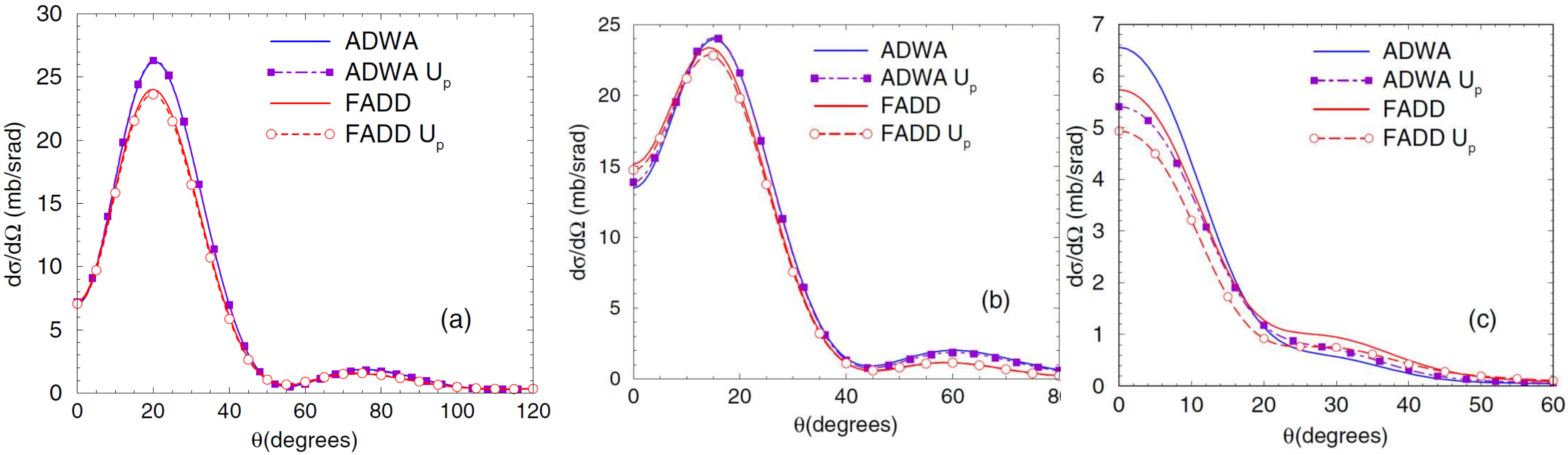


FIG. 2: Angular distributions for ^{12}C(d,p)^{13}C: (a) $E_d = 7.15$ MeV, (b) $E_d = 12$ MeV and (c) $E_d = 56$ MeV

[FN and Deltuva, submitted PRC]

Systematic comparison: FR-ADWA vs Faddeev

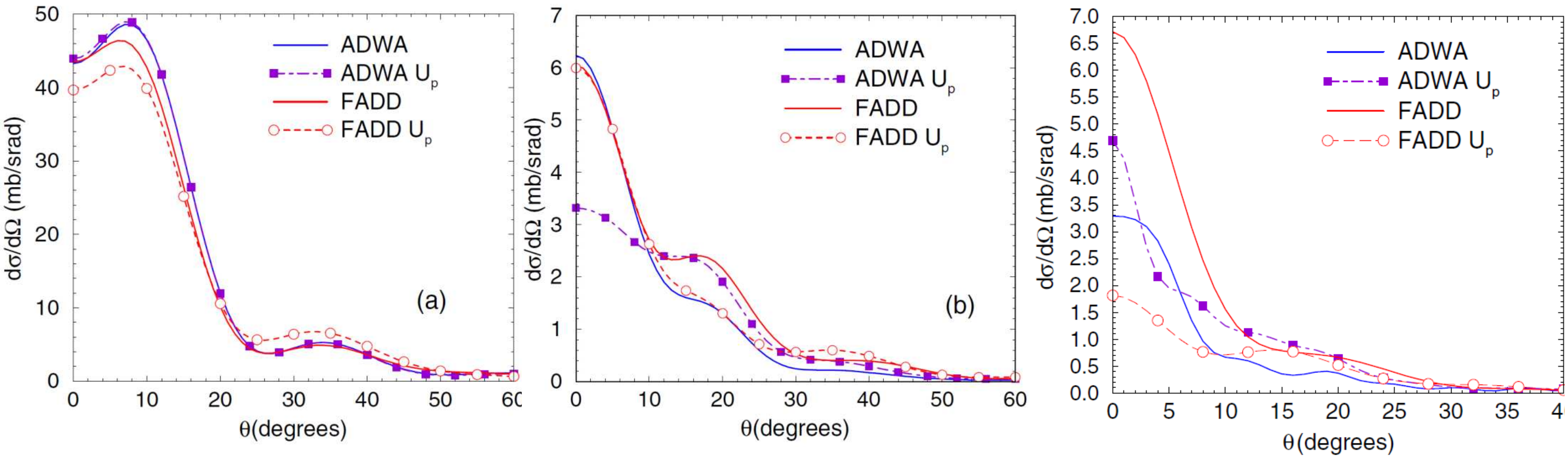


FIG. 3: Angular distributions for ^{48}Ca(d,p)^{49}Ca: (a) E_d = 19.3 MeV, (b) $E_d = 56$ MeV and (c) $E_d = 100$ MeV.

[FN and Deltuva, submitted PRC]

systematic comparison: FR-ADWA vs Faddeev

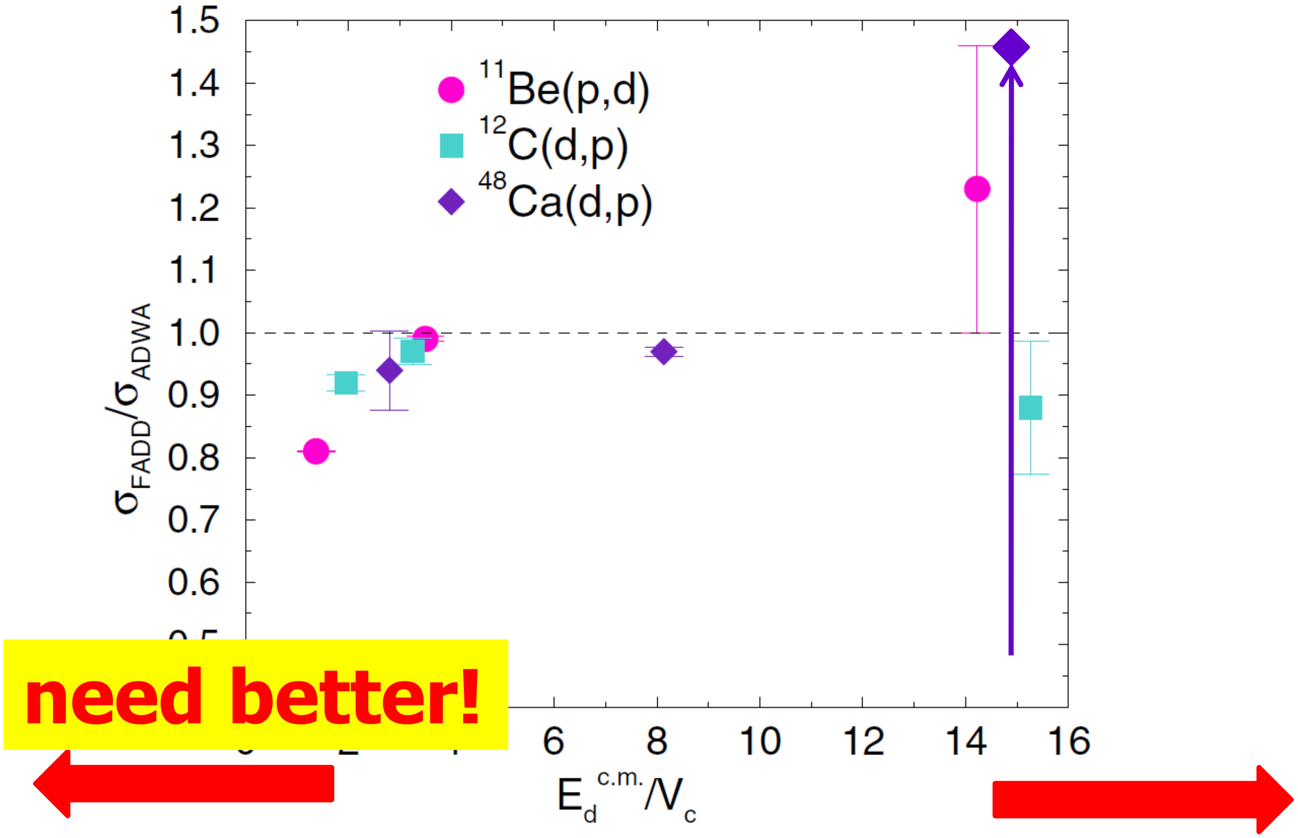


FIG. 4: Ratio of Faddeev prediction for the cross section at the peak of the angular distribution versus the Adiabatic counterpart plotted in term of the deuteron energy in the c.m. over the Coulomb Barrier.

[FN and Deltuva, submitted PRC]

(d,p) reactions: beyond FR-ADWA

FR-ADWA: deuteron breakup plus finite-range

[Nguyen, Nunes, Johnson, Phys. Rev. C **82**, 014611(2010)]

If only first term of the expansion is included:
coupled equations reduce to single channel!

Continuum discretized coupled channel does not make this approximation

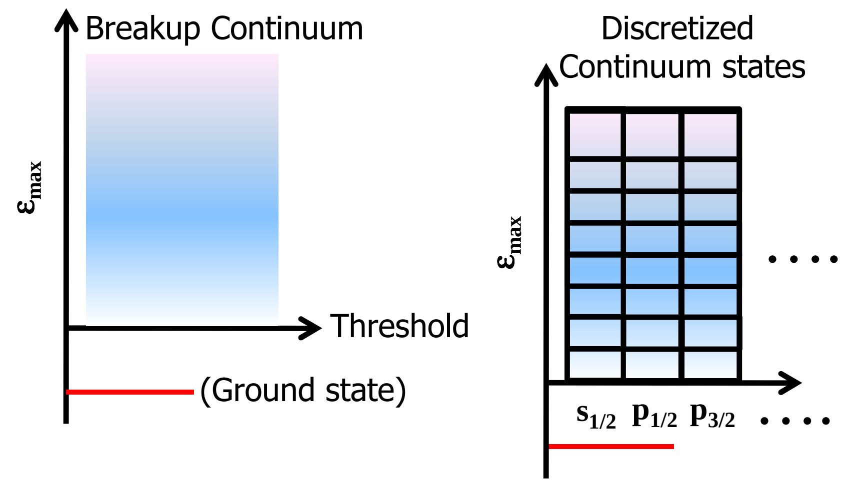
Milestone for yr 1: comparison CDCC vs Faddeev

(d,p) reactions: CDCC

Expand 3-body wfn in deuteron eigenstates

$$\mathrm{H}_{\mathrm{int}}(\mathbf{r}) = T_r + V_{\mathrm{pn}}(\mathbf{r}) \qquad \Psi^{(+)}(\vec{r},\vec{R}) = \sum_{i=1}^{\infty} \phi_i(\vec{r})\chi_i(\vec{R})$$

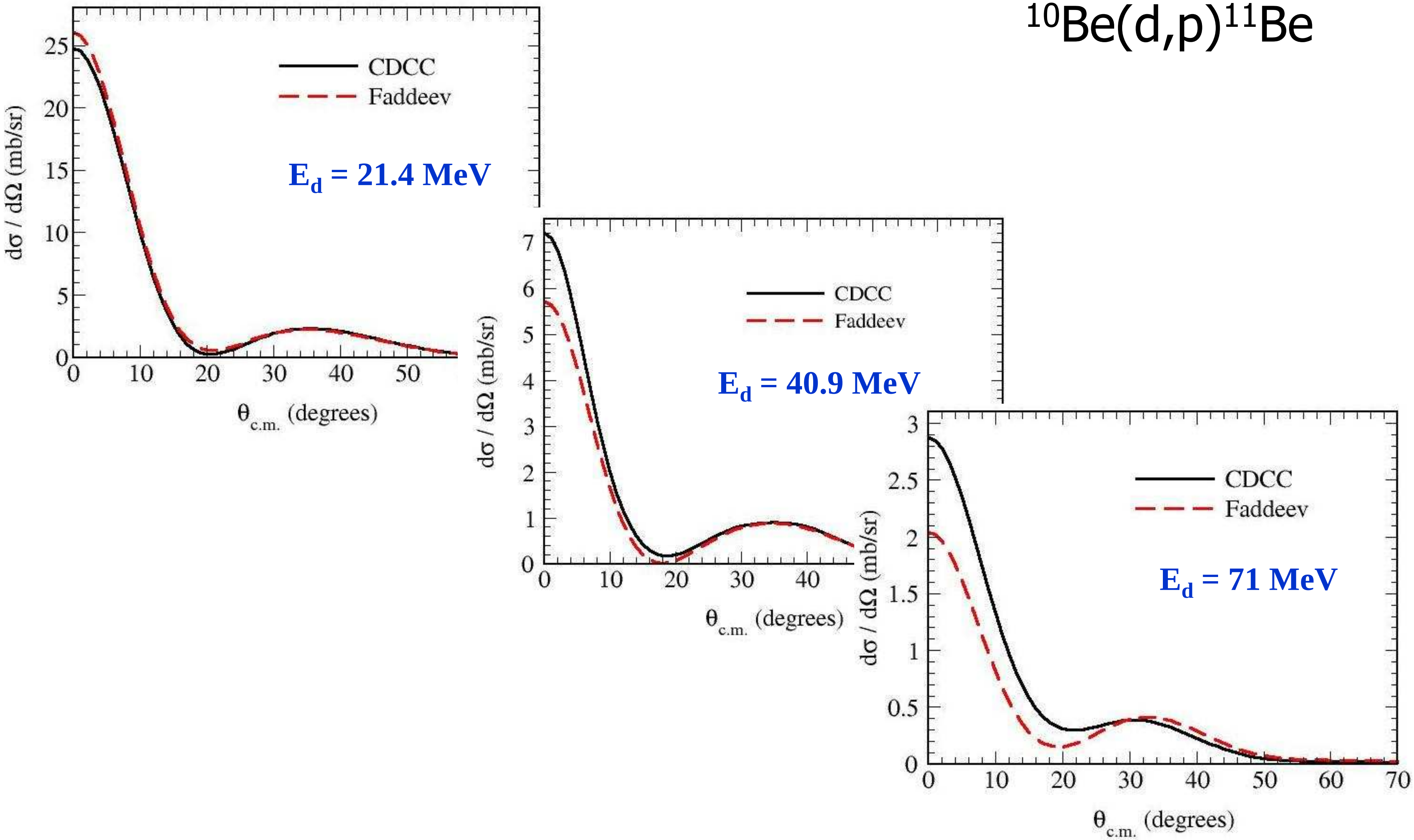
➢ Discretize the continuum



➢ continuum discretized coupled channel (CDCC) equations

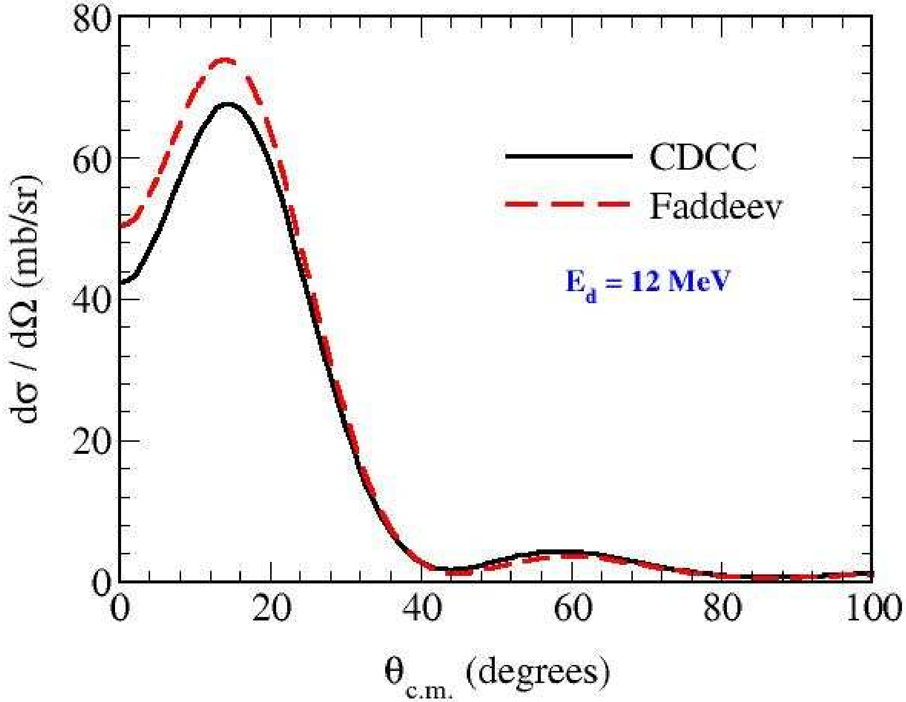
systematic comparison: CDCC vs Faddeev

$^{10}Be(d,p)^{11}Be$

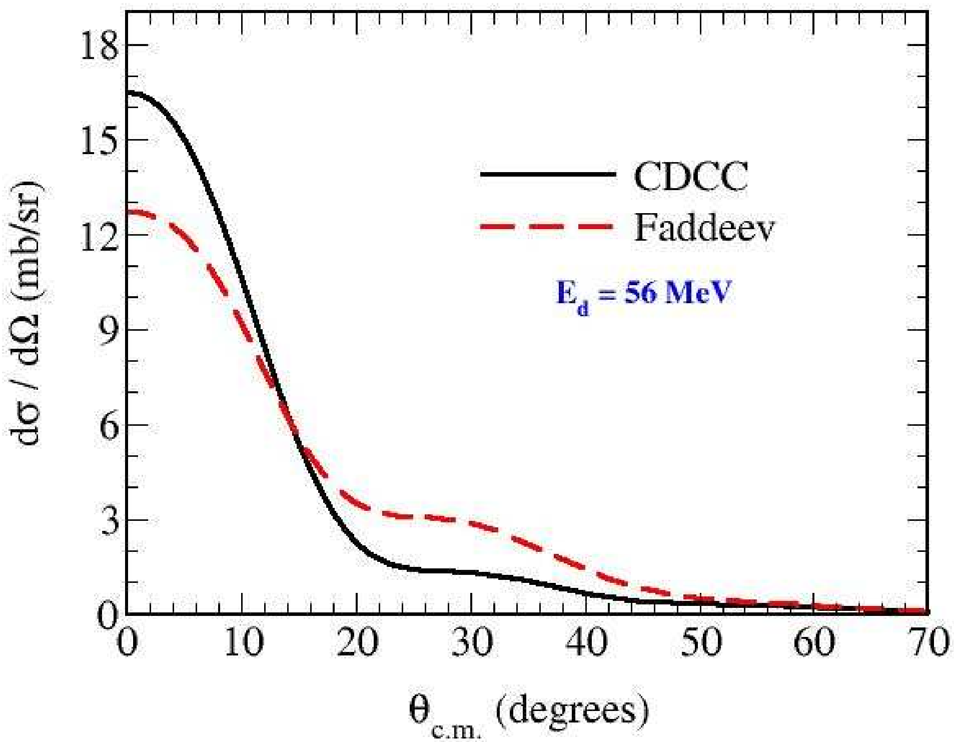


Upadhyay, Deltuva and Nunes, in preparation

systematic comparison: CDCC vs Faddeev



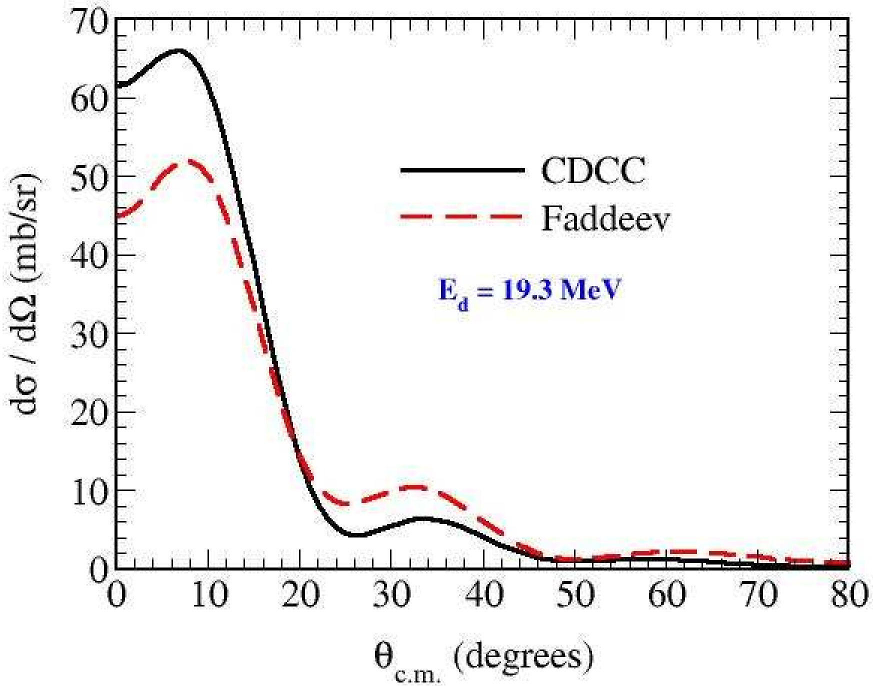
$^{12}C(d,p)^{13}C$

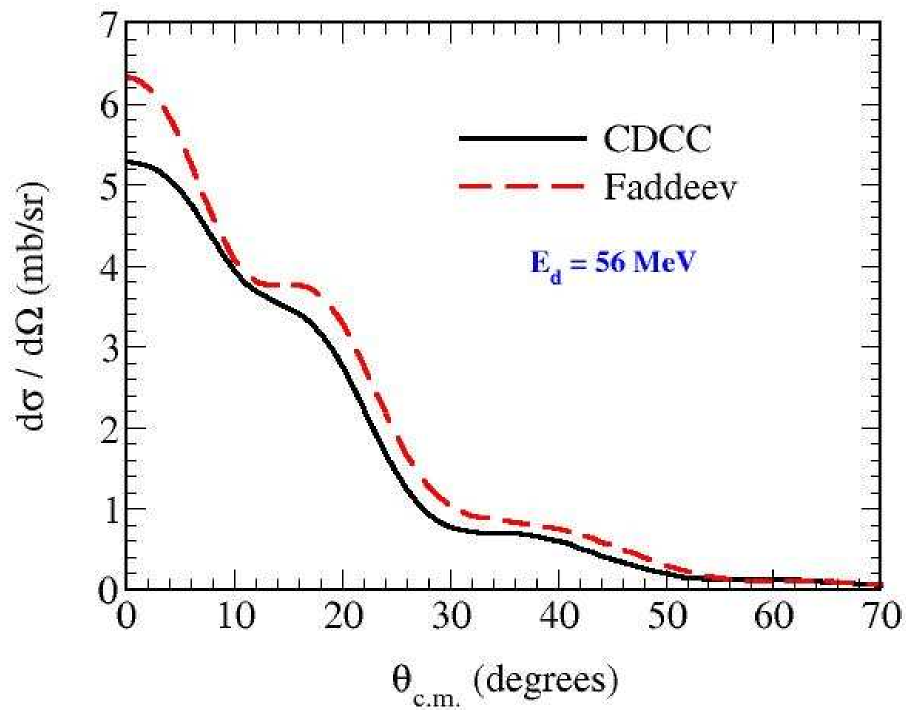


Upadhyay, Deltuva and Nunes, in preparation

systematic comparison: CDCC vs Faddeev

$^{48}Ca(d,p)^{49}Ca$



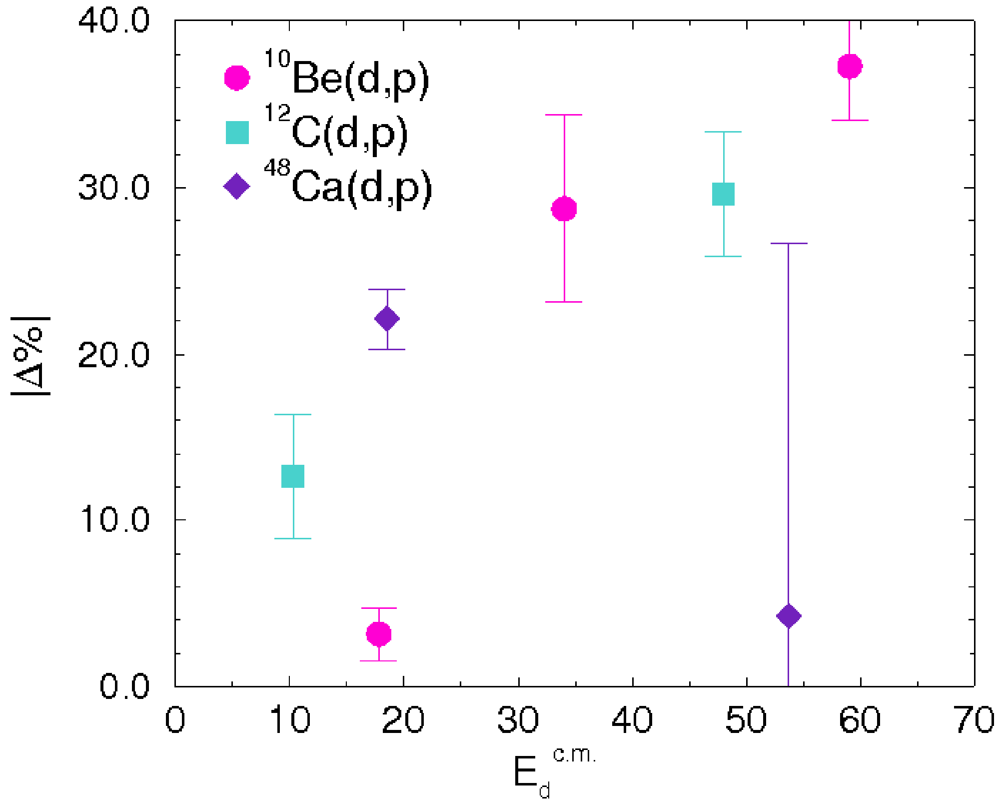


Upadhyay, Deltuva and Nunes, in preparation

Systematic comparison: CDCC vs Faddeev

NSCL

Comparative differences CDCC/FADD



(errors analysis ongoing…)

Upadhyay, Deltuva and Nunes, in preparation

summary and conclusions

o preliminary project

comparisons Faddeev and Adiabatic **(completed)**

o 1st yr milestone

comparisons Faddeev and CDCC **(nearly completed)**

Conclusions:

o agreement around 10 MeV/u

o agreement deteriorates with increasing beam energy

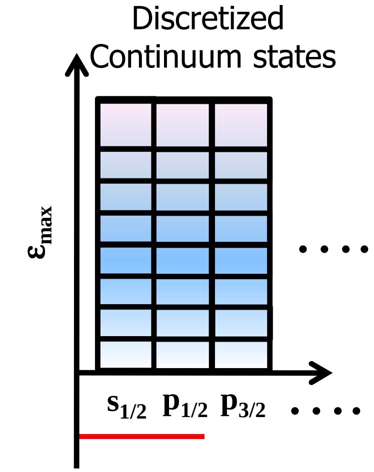
o ambiguities in optical potentials have higher impact at higher E

next steps

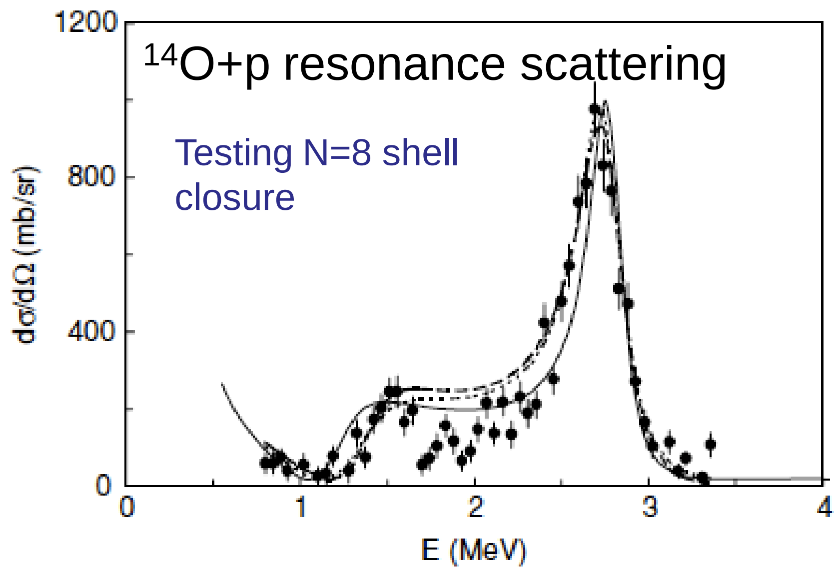
- o extending new AGS code for nuclear reactions
  - o starting code development
- o capability of including target excitation
- o separable optical potentials
  - o examining advantages/disadvantages

additional project: continuum bins

- need to characterize resonances for two purposes:
  - narrow resonances can be treated like bound states, but
  - broad resonances are more difficult.



- to verify CDCC method for discretizing the continuum
  - generalize to wide resonances
  - generalize to overlapping resonances
  - try to produce a new 'bin' prescription



additional project: surface formulation

- only asymptotic parts of wave functions are 'observable'
  (same for all phase-equivalent Hamiltonians)
  - tails of bound states measured by 'ANC':
    - for resonances ANC ~ 'Reduced Width'
  - interior part necessarily linked to ANC
    (relation to 'Spectroscopic Factors')

- new theory under construction:
  - interior and exterior parts of transfer matrix elements expressed in terms of ANCs,
  - to test for transfer to bound states, and also to resonances.

Milestones and deliverables (1st year)

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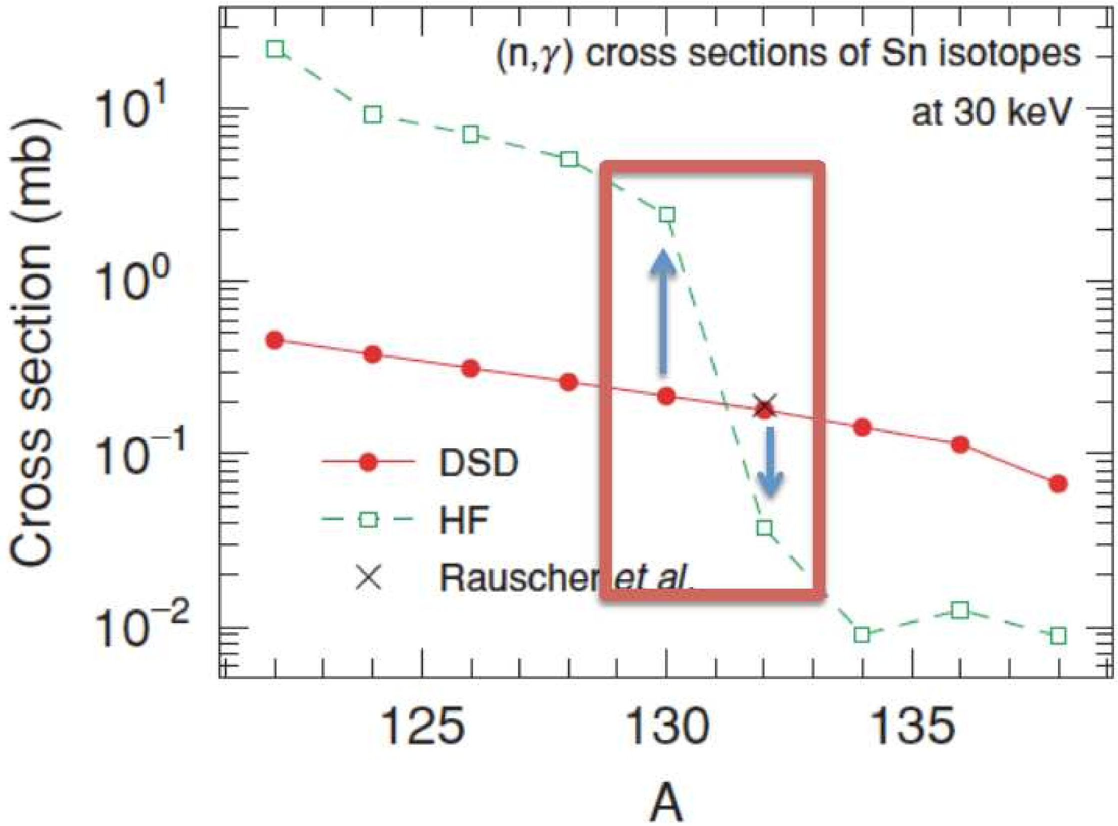
Integrating Direct and Compound-Nucleus Reactions

- Project**:** Incorporate semi-direct capture via the giant-dipole resonance into existing direct-reaction code
- Milestone**:** Systematic calculation of semi-direct contributions in capture reactions

main contributions to captures

- o direct capture (D)
  - o important at low energies on light or neutron rich nuclei
  - o potential model needs ANC from (d,p) reaction
- o semidirect (SD) 2-step
  - o via GDR, GQR and around, $E_b + E_{GDR}$
  - o D+SD contributions interfere
- o compound capture (many-steps)
  - o via complex compound nuclear states
  - o can dominate for low energy

capture reactions: direct and semi-direct



Chiba et al, PRC 77, 015809

include semi-direct in fresco

- o CUPIDO
  - o 1^{st} order perturbation (F Dietrich)
  - o one-pole approx for inelastic neutron Green's function

- o FRESCO
  - o coupled channel code
  - o included D+DSD for comparison with cupido
  - o more accurate away from GDR peaks

- o two tests so far
  - o $^{60}Ni(n,g)^{61}Ni_{gs}$
  - o $^{130}Sn(n,g)^{131}Sn_{gs}$

next steps

- o investigate GDR green’s functions and coupling form factors to understand differences CUPIDO/FRESCO
- o include coupled channel effects beyond DWBA 2-step
- o systematic study in addition to the 2 current test cases of experimental interest

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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Muslema Pervin (post doc at MSU)

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Anissa Bey (exp post doc at UT)
Arnas Deltuva (Lisbon)