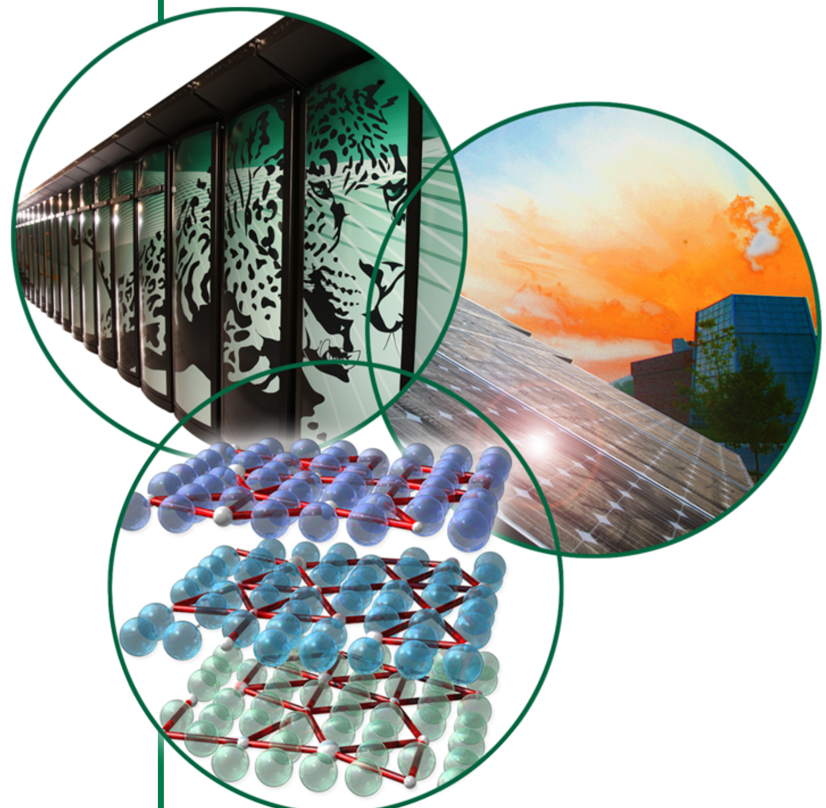
The TORUS
Theory of Reactions for Unstable Isotopes

Topical Collaboration in Nuclear Theory



Collaborators:
LLNL: Ian Thompson, Jutta Escher
MSU: Filomena Nunes
TAMU: Akram Mukhamedzhanov
OU: Charlotte Elster
ORNL: Goran Arbanas (presenter)

CSEWG/USNDP Meeting, BNL, November 5-9

U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

DOE has made big investment in unstable beams for nuclear science

- Goals of RIB investments:
  - find how elements formed (r-process, etc)
  - test nuclear forces (isospin dependence, etc)
  - limits of stability (halo nuclei at the dripline)
  - applications (e.g. fission fragments)
- FRIB allows answers to overarching science questions from the NSAC 2007 LR Plan

http://science.energy.gov/np/nsac

Reaction theory contributions

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?

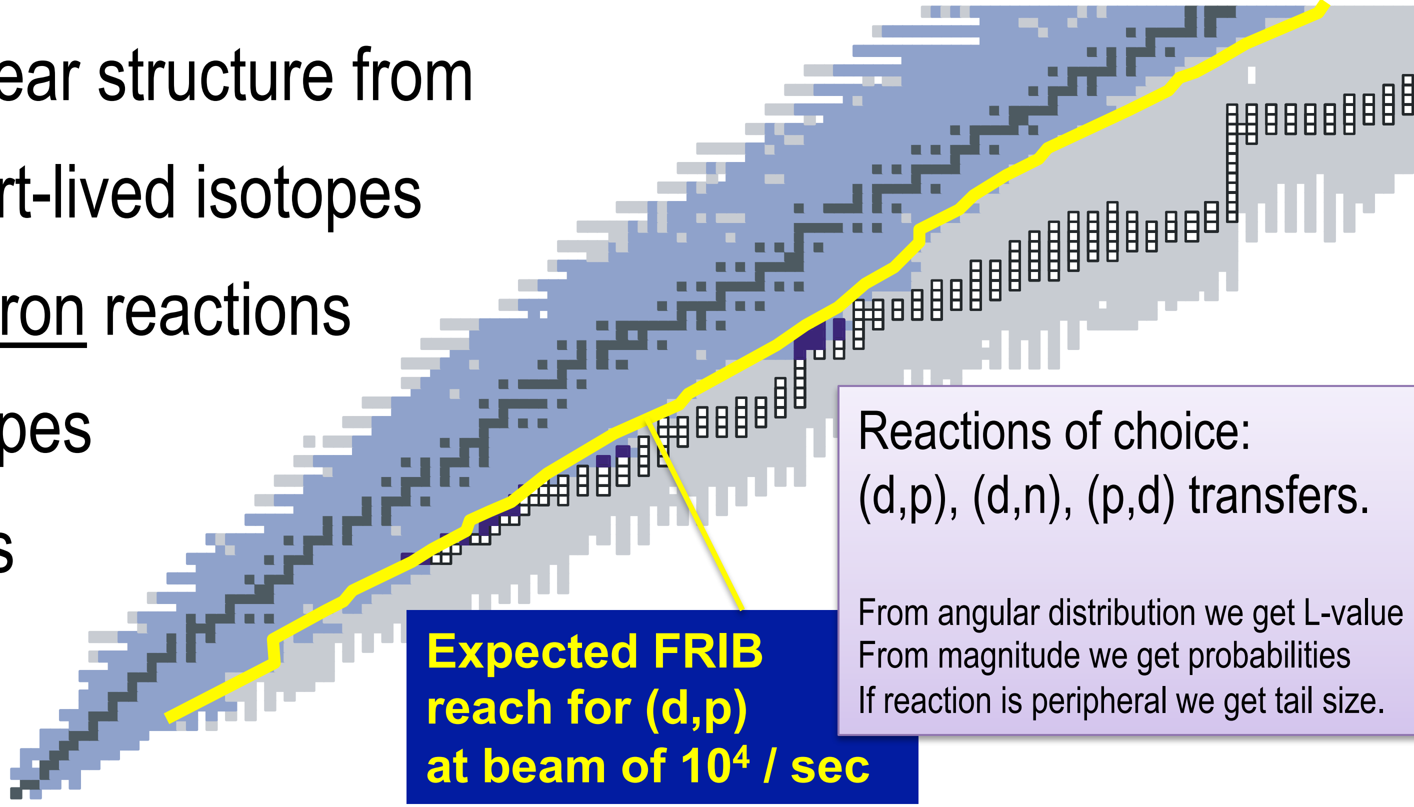
Overarching questions are answered by rare isotope research

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

Nuclear Structure	Nuclear Astrophysics	Tests of Fundamental Symmetries	Applications of Isotopes
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 rp-Process 17. Weak interactions	12. Atomic electric dipole moment	10. Medical 11. Stewardship

Need Reaction Theory to interpret experiments and extract physics

- FRIB collides nuclei to study them.
- to extract nuclear structure from reactions of short-lived isotopes
- to predict <u>neutron</u> reactions on these isotopes
- Level densities
- initial & final (n,γ) states



Reactions of choice:
(d,p), (d,n), (p,d) transfers.

From angular distribution we get L-value
From magnitude we get probabilities
If reaction is peripheral we get tail size.

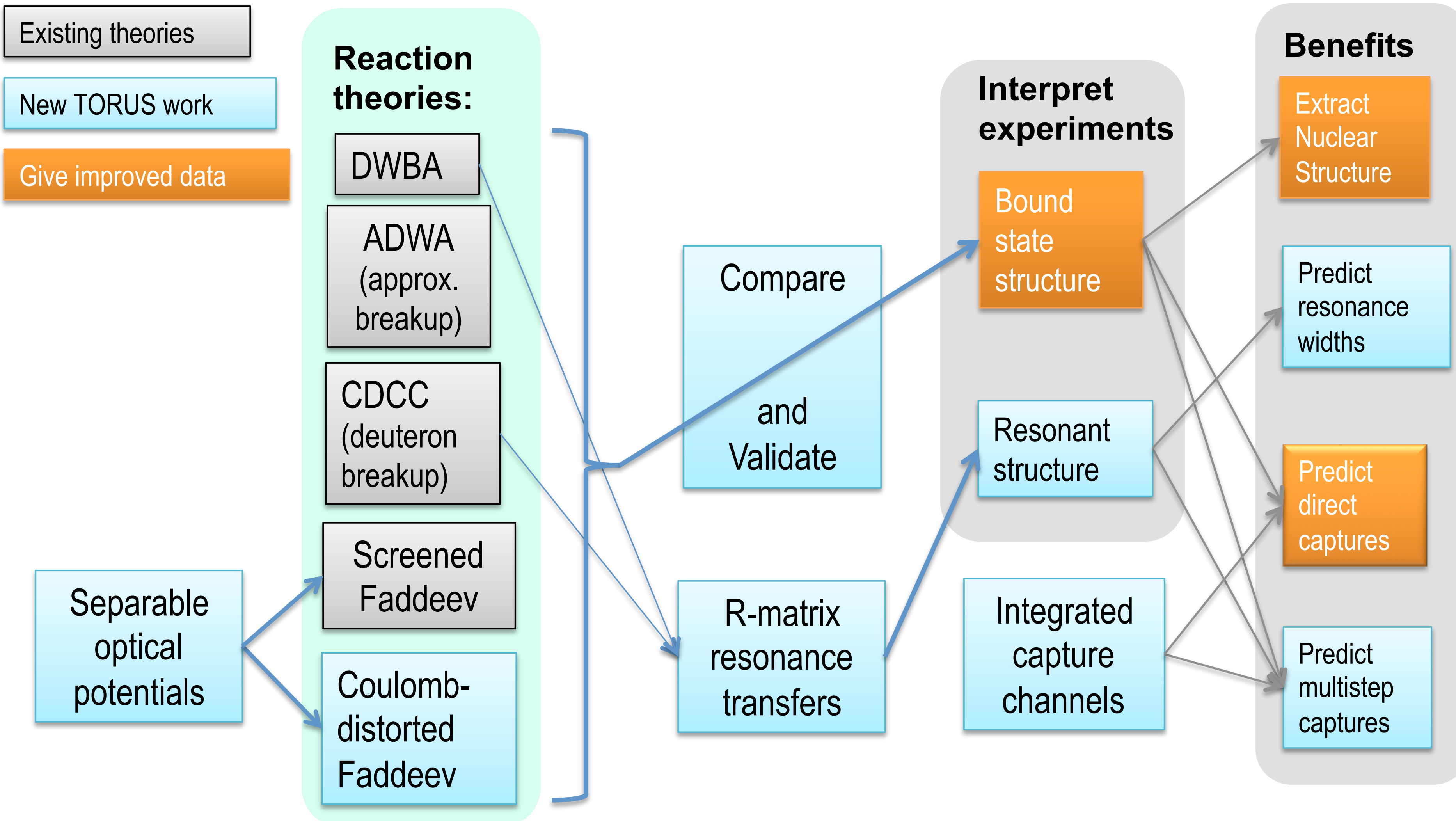
- But reaction theory has been neglected in the last 30 years

TORUS brings together a significant fraction of US workforce & provides training for future

Current reaction theories have deficiencies

- The 'Distorted Wave Born Approximation'
  - old tool still used extensively by experimentalists
- Higher-order paths neglected (except in optical parameters)
  - deuteron breakup,
  - core excitation,
  - multistep transfers at low beam energies
- Current reaction theories
  - include some of these higher-order processes, but not all.
  - hard for transfers to resonances & only single-particle so far
  - do not clarify what structure is actually measured
    - Interior spectroscopic factor, or
    - Surface ANC, or partial width, or pole residue?

Our Collaborative Work in Context



TORUS goals:
Develop new reaction theory for RIBs

1. Demonstrate need for full three-body models
2. New Coulomb-distorted Faddeev equations
   to include all orders of breakup, core-excitation and transfers
3. New theory of transfers to R-matrix states
   to measure partial widths of resonance

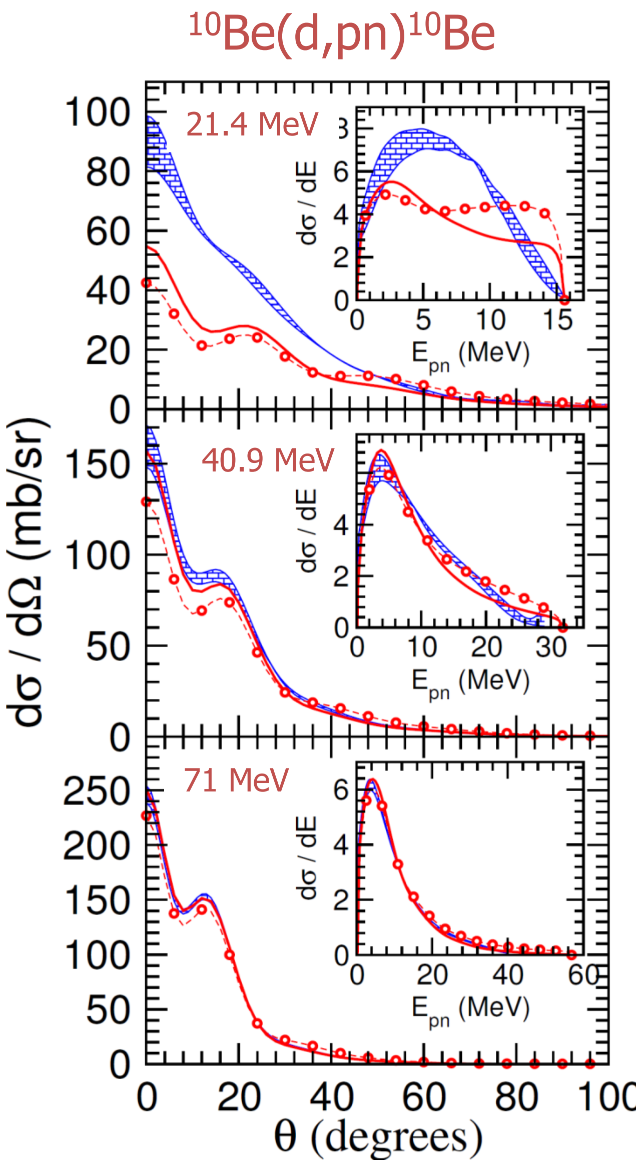
then: Extensions to capture reactions

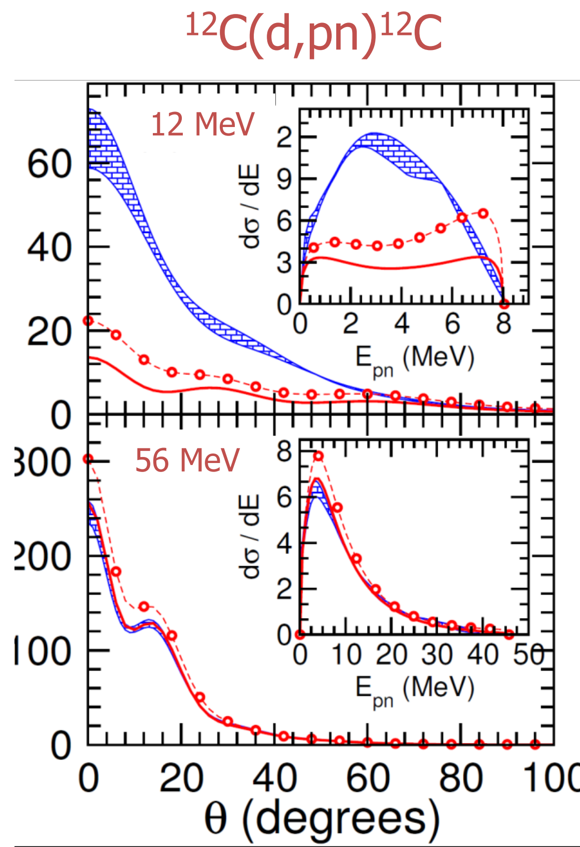
These new breakthroughs 1, 2 and 3 made possible
through the TORUS collaboration:
We combine theory + computation + validation + links to experiments

Better 3-body models needed

- CDCC does not reproduce Faddeev for:
  - transfer at high energies (~20 MeV/u)
  - breakup at low energies <10 MeV/u
- disagreement can be large
- – need better approach

- Faddeev implementation is limited
  - in many cases cannot obtain stable results for low energy
  - Coulomb screening cannot be used for Z>20
- most cases of interest at FRIB Z>20 – need better approach





Upadhyay, Deltuva and Nunes, PRC 85, 054621 (2012)

- AGS formalism with new technique for Coulomb (Texas A&M)
- Critical to include good optical potential information (Ohio)

New Coulomb-distorted Faddeev Equations with Target Excitations

- **d+A scattering needs Faddeev Equations:**
  - When rearrangement and breakup channels are open, <u>many</u> final channels:

$d + A \rightarrow$

- $d + A$ elastic
- $p + (nA)$ transfer
- $n + (pA)$ transfer
- $p + n + A$ breakup

All strongly coupled together.

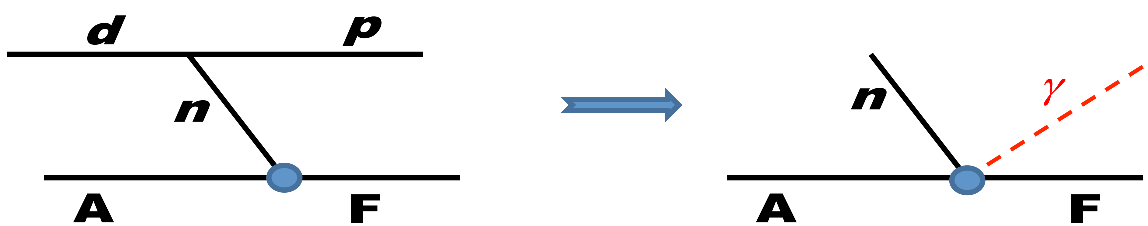
- Shortcomings of the original Faddeev equations
  - Designed for 3→3 processes for the 3-body problem,
    - **but** no target excitation and no Coulomb
  - Modification of Faddeev eqs to 2→2 gives Alt-Grassberger-Sandhas (AGS)
- Faddeev equations in the AGS form are formulated,
  - inclusion of target excitations and Coulomb interaction: PRC 09/2012

R-matrix method for (d,p) to reson.'s

- Binary resonant reactions are best given by R-matrix parameters:
  - observable partial widths, resonance energies, channel radii
  - the main tool for experimentalists

Now extended to low-energy deuteron stripping

A(d,p)F



- both for stripping to bound and resonance states.
- many-level and many-channel cases are included
- both narrow and broad resonances.

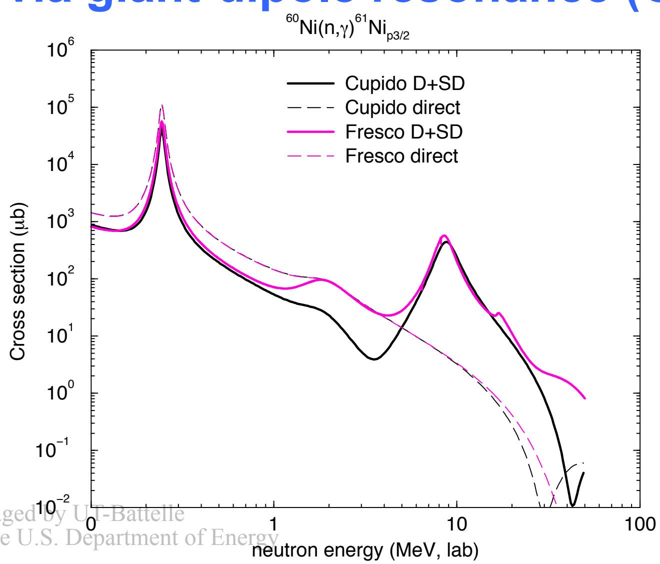
Provides a consistent tool to analyze both resonance binary reactions and deuteron stripping reactions in terms of the same parameters.

A. M. Mukhamedzhanov, Phys. Rev C 84, 044616 (2011)

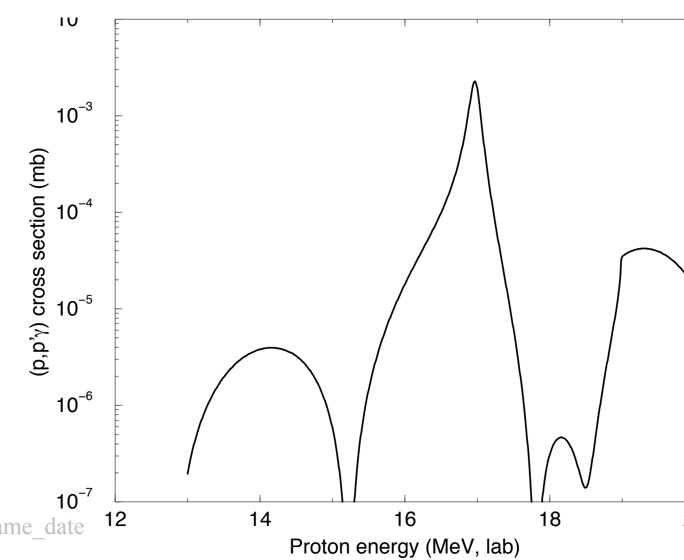
Integrated Capture Reactions

- **Needed for astrophysics and other applications**
- Use structure information derived from our reaction theories to predict capture reactions for neutrons.
- Must include higher-order contributions, some give resonances.
- Some early calculations:

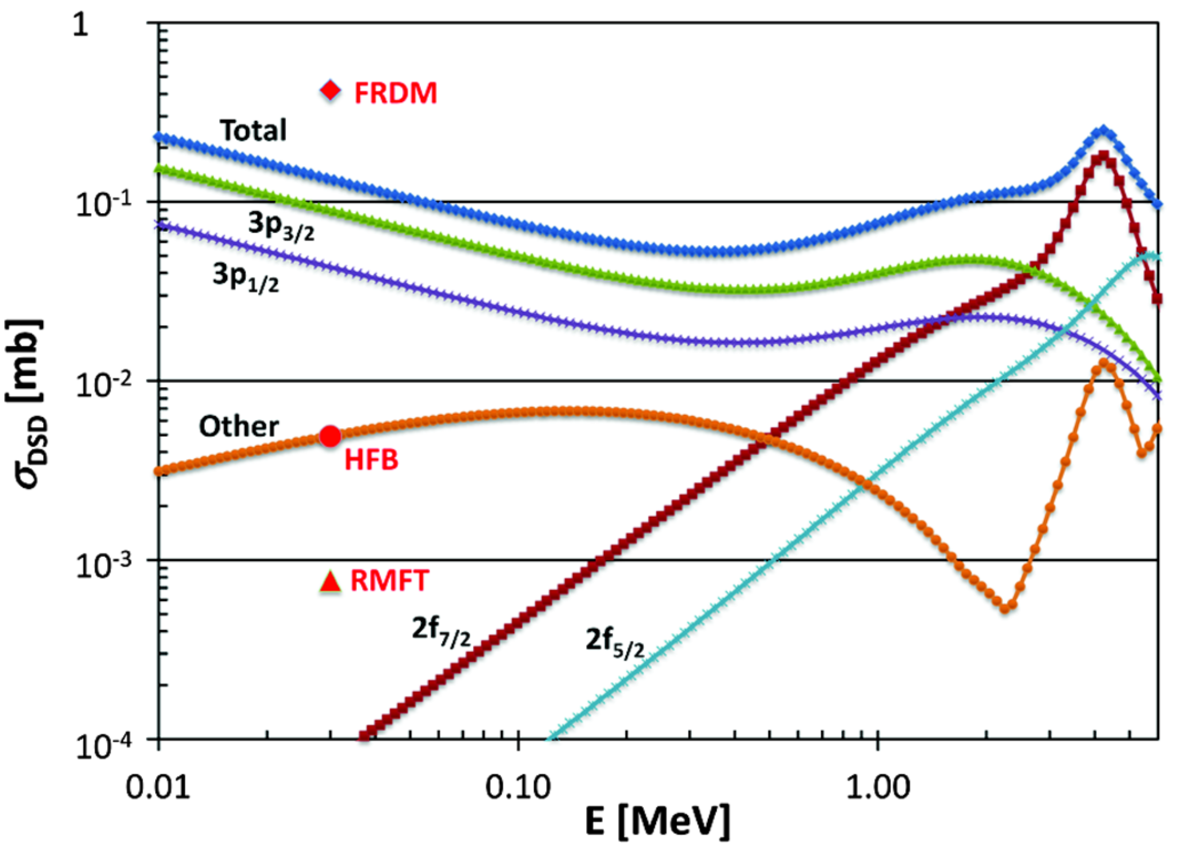
Calculation of capture ^{60}Ni(n,γ) via giant-dipole resonance (GDR)



Calculation of inelastic ^{208}Pb(p,p′γ) via Isobaric Analog Resonances



Direct-semidirect capture $^{130}Sn(n,\gamma)$



from: Phys. Rev. Lett. 109, 172501 (2012)

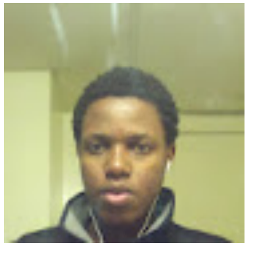
Theory Workforce

- PIs: bring together 6 reaction theorists
  - Livermore Laboratory (2)
  - Michigan State University (1)
  - Texas A&M University (1)
  - Ohio University (1)
  - Oak Ridge Laboratory (1)
- Training new Reaction Theorists:
  - 1 postdoc at MSU
  - 1 postdoc at TAMU
  - 1 student at OU
  - collaborate with 2 students at MSU and OU
- New national cooperative of reaction theorists

Neelam Upadhyay
at MSU

Vasily Eremenko
at TAMU

Linda Hlophe
at OU



We often work with experimental groups

In Collaborations:

- with formulating their proposals
- with improving their understanding of their results

Specific Experiments:

- INFN: (p,α) reactions
- NSCL: ^{34,36,46}Ar(p,d) reactions
- TAMU + Rez: ^{14}C(d,p) reaction
- LLNL + Richmond: (p,d) and (p,t) surrogate reactions on actinides
- RIKEN: ^{6}He polarized scattering
- LLNL + Richmond: (p,t) and (p,d) on rare earths
- ORNL: ^{10}Be(d,p) in inverse kinematics
- ORNL: ^{130,132}Sn(d,p) in inverse kinematics
- Rutgers + LLNL: ^{96}Mo(d,pγ) surrogate for ^{96}Mo(n,γ)
- INFN: ^{17}O+d$\rightarrow$^{14}C+p+α as Trojan horse for ^{17}O+n $\rightarrow$ ^{14}C+α

Publications and Presentations

in the first 27 months. Plus 13 conference talks & 25 other presentations.

- A.M. Mukhamedzhanov and A.S. Kadyrov, *Unitary correlation in nuclear reaction theory: divorce of reaction theory and spectroscopic factors*. Phys. Rev. C **82**, 051601(R), 2011
- F.M. Nunes, A. Deltuva, and June Hong, *Improved description of$^{34;36;46}$Ar(p,d) transfer reactions*, Phys. Rev. C **83**, 034610 (2011)
- A.M. Mukhamedzhanov, L. D. Blokhintsev, B.F. Irgaziev, *Reexamination of the astrophysical S factor for the α+ d -> ^{6}Li +g reaction*, PRC **83**, 055805, 2011
- M. La Cognata, A.M. Mukhamedzhanov, C. Spitaleri, et al., *The Fluorine Destruction In Stars: First Experimental Study Of The ^{19}F (p,a_0)^{16}O Reaction at Astrophysical Energies,* Ap. J. Letts, **738**, L54, 2011
- F.M. Nunes and A. Deltuva, *Adiabatic versus Faddeev for (d,p) and (p,d) reactions*, Phys. Rev. C **84**, 034607 (2011)
- L.J. Titus, P. Capel, F.M. Nunes, *Asymptotic normalization of mirror states and the effect of couplings*, Phys. Rev. C 85, 035805, 2011
- N.B.Nguyen, S.J.Waldecker, F.M.Nunes, R.J.Charity, W.H.Dickhoff, *Transfer reactions and the dispersive optical-model*, Phys. Rev. C **84**, 044611 (2011)
- A.M. Mukhamedzhanov, *Theory of deuteron stripping. From surface integrals to generalized R-matrix approach*, Phys. Rev. C **84**, 044616 (2011)
- R. O. Hughes, C. W. Beausang, T. J. Ross, J. T. Burke, N. D. Scielzo, M. S. Basunia, C. M. Campbell, R. J. Casperson, H. L. Crawford, J. E. Escher, J. Munson, L. W. Phair, and J. J. Ressler, *Utilizing (p,d) and (p,t) reactions to obtain (n,f) cross sections in uranium nuclei via the surrogate-ratio method,* Phys. Rev. C **84**, 024613 (2012)
- S.P. Weppner, Ch. Elster, *Elastic Scattering of ^{6}He based on a Cluster Description*, Phys. Rev. C 85, 044617 (2012)

- S.P. Weppner, Ch. Elster, *Elastic Scattering of ^{6}He based on a Cluster Description*, Phys. Rev. C 85, 044617 (2012)

- T. J. Ross, C.W. Beausang, .., J.E. Escher,…,I.J. Thompson *et al*., *Measurement of the entry-spin distribution imparted to the high excitation continuum region of gadolinium nuclei via (p,d) and (p,t) reactions,* Phys. Rev. C 85, 051304(R), (2012)
- N. J. Upadhyay, A. Deltuva, F. M. Nunes, *Testing the continuum discretized coupled channel method for deuteron induced reactions*, PRC **85**, 054621, 2012)
- K. T. Schmitt, K. L. Jones, A. Bey, S. H. Ahn, D.W. Bardayan, J.C. Blackmon, S.M. Brown, K.Y. Chae, K. A. Chipps, J.A. Cizewski, K.I. Hahn, J.J. Kolata, R.L. Kozub, J.F. Liang, C.Matei, M. Matoš, D. Matyas, B. Moazen, C. Nesaraja, F.M. Nunes, P.D. O'Malley, S.D. Pain, W.A. Peters, S.T. Pittman, A. Roberts, D. Shapir, J.F. Shriner, Jr., M.S. Smith, I. Spassova, D.W. Stracener, A.N. Villano, and G.L. Wilson, *Halo Nucleus 11Be: A Spectroscopic Study via Neutron Transfer*. Phys. Rev. Letts, **108**, 192701 (2012)
- A.M. Mukhamedzhanov, V. Eremenko, A.I. Sattarov, *Generalized Faddeev equations in the AGS form for deuteron stripping with explicit inclusion of target excitations and Coulomb interaction,* Phys. Rev. C 86, 034001 (2012)
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- R. L. Kozub, G. Arbanas*, et al*, *Neutron single particle structure in ^{131}Sn and direct neutron capture cross sections*, Phys. Rev. Lett., 109, 172501 (2012)

Conclusion

- TORUS builds the reaction-theory community
  - brings together several reaction theorists in the US
- Enables collaborations not otherwise feasible
- New applications of exact three-body methods
- New codes useful to experimentalists
- Training young reaction theorists with futures in nuclear physics
- Website: http://www.reactiontheory.org/