Advancing the theory of transfer reactions: a report from the TORUS collaboration

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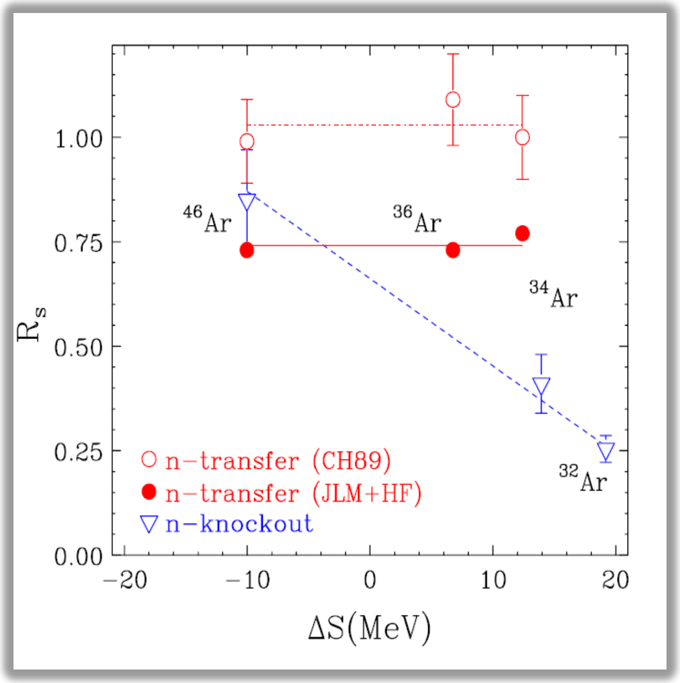
Topical collaborations in nuclear theory

- **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

opportunities with FRIB

transfer versus knockout



[Jenny Lee et al, PRL 2009]

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

- shell structure
- correlations
- pairing
- weakly bound systems
- role of continuum
- ...

FRIB needs accurate reaction models!

Topical collaboration in nuclear theory

Theory Of Reactions for Unstable iSotopes:

- Develop new methods to advance nuclear reaction theory for unstable isotopes
- Build on Faddeev techniques for 3-body models
- Treat projectile & target continuum states
- Apply to capture reactions

Output to be used in FRIB reactions & related experiments!

- 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

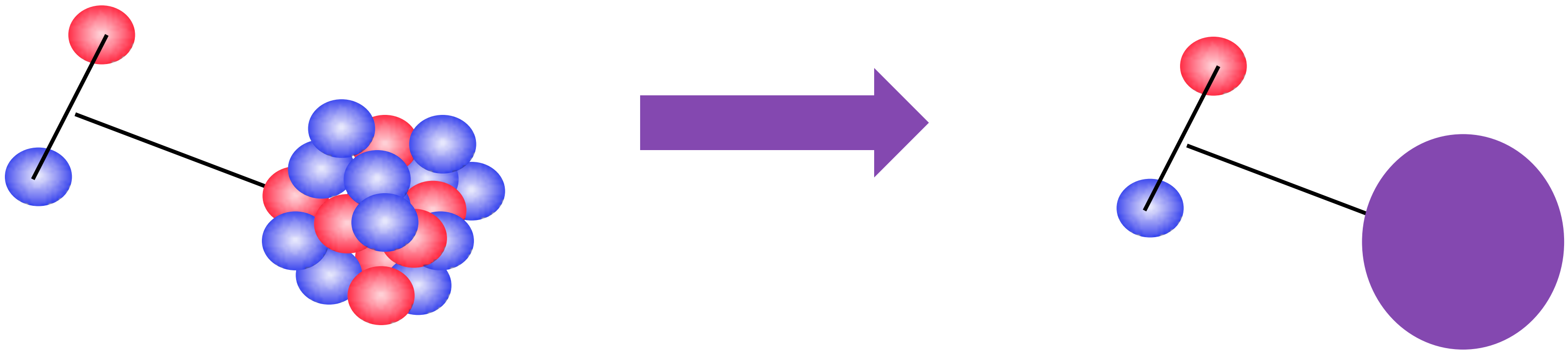
what sort of reaction are we interested in?

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

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

?

reducing the many body to a few body problem



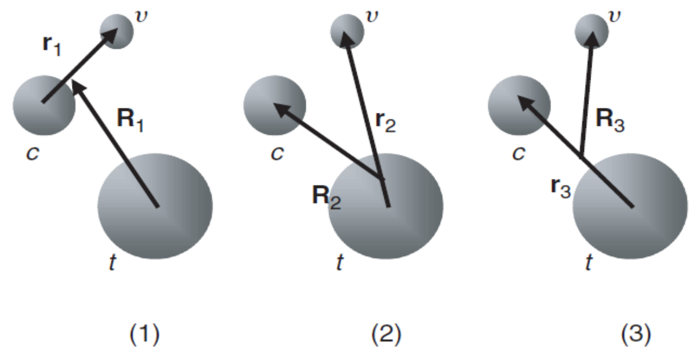
- isolating the important degrees of freedom in a reaction
  (keeping track of all relevant channels)
- connecting back to the many-body problem

uncertainties in reaction models

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

three body problem: exact solution

$$\Psi = \sum_{n=1}^{3} \Psi^{(n)}(\mathbf{r}_n, \mathbf{R}_n)$$



3 jacobi coordinate sets

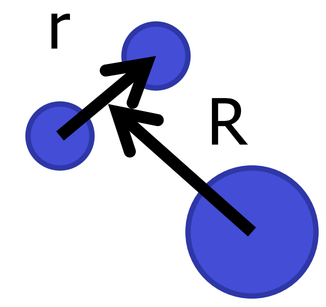
Faddeev Equations:

$$(E - T_1 - V_{vc})\Psi^{(1)} = V_{vc}(\Psi^{(2)} + \Psi^{(3)})$$
$$(E - T_2 - V_{ct})\Psi^{(2)} = V_{ct}(\Psi^{(3)} + \Psi^{(1)})$$
$$(E - T_3 - V_{tv})\Psi^{(3)} = V_{tv}(\Psi^{(1)} + \Psi^{(2)})$$

AGS: T-matrix version and momentum space

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

(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

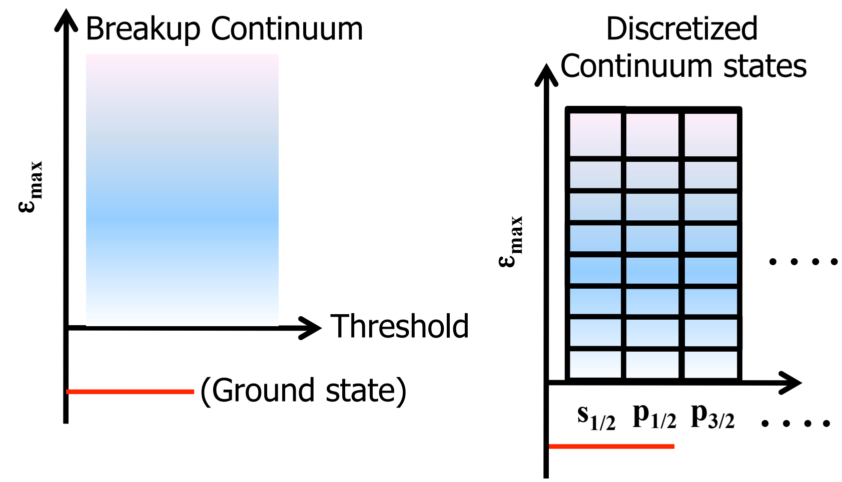
$$T = < \phi_{nA} \chi^{(-)}_{pB} | V_{np} + \Delta_{rem} | \Psi^{(+)} >$$

(d,p) reactions: CDCC

Expand 3-body wfn in deuteron eigenstates

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

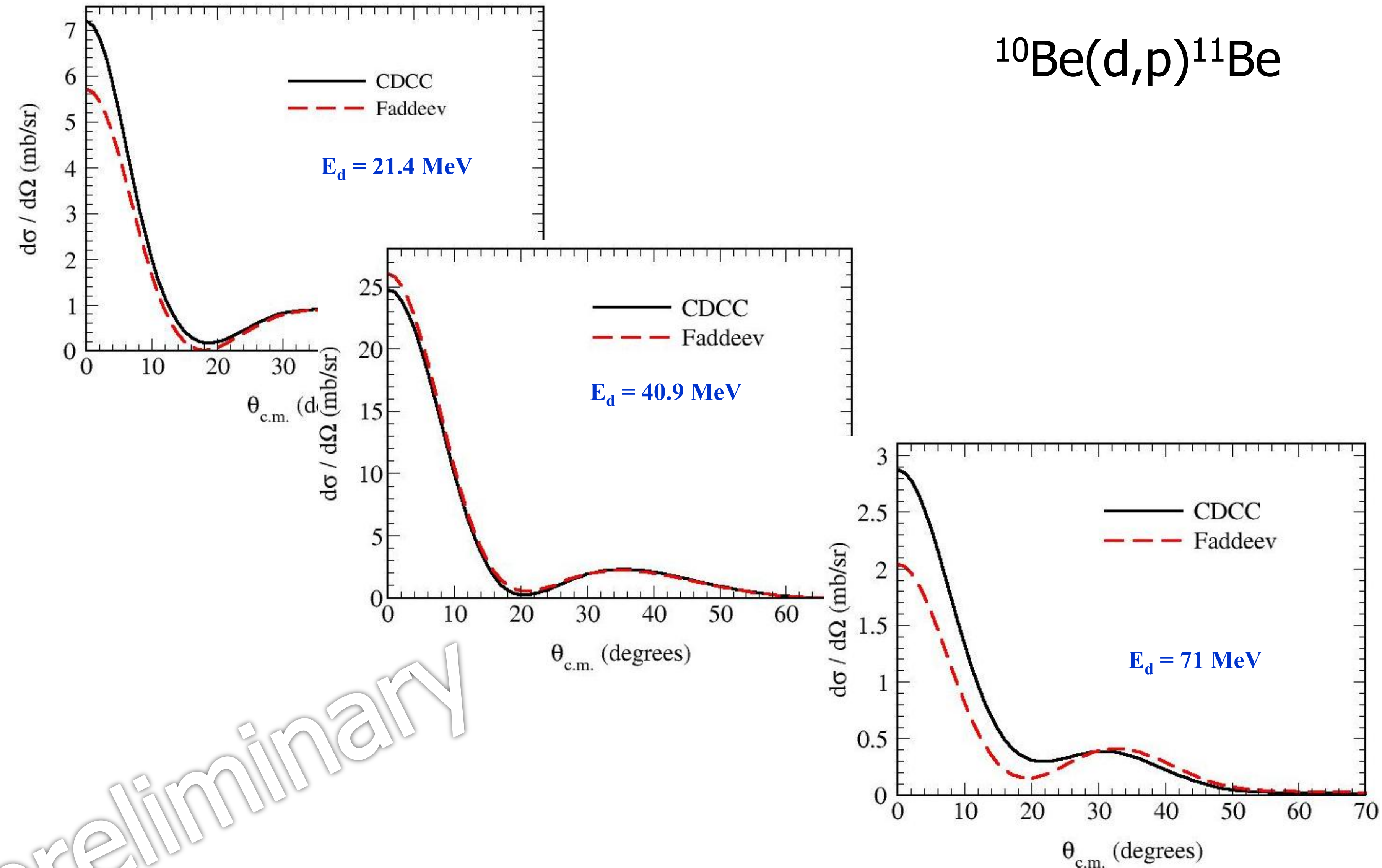
- Discretize the continuum



- continuum discretized coupled channel (CDCC) equations

systematic comparison: CDCC vs Faddeev

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

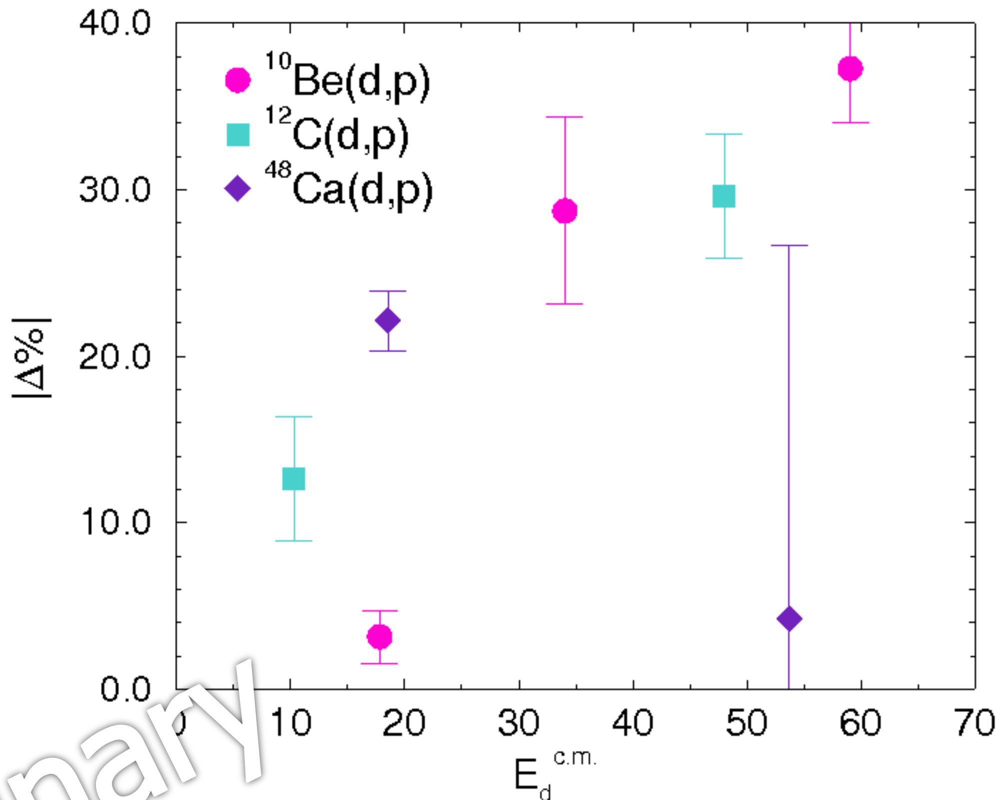


preliminary

Upadhyay, Deltuva and Nunes, in preparation

Systematic comparison: CDCC vs Faddeev

Comparative differences CDCC/FADD



(errors based on remnant)

preliminary

Upadhyay, Deltuva and Nunes, in preparation

next steps

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

Transfer to continuum?

- 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

ANC vs SF: surface formulation

- only asymptotic parts of wave functions are ‘observable’: same for all phase-equivalent models.
  - Tails of bound states measured by ‘ANC’:
    - ‘Asymptotic Normalization Coefficient’ ~ ‘Reduced Width’
  - Interior part necessarily linked to ANC
  - Discussion of 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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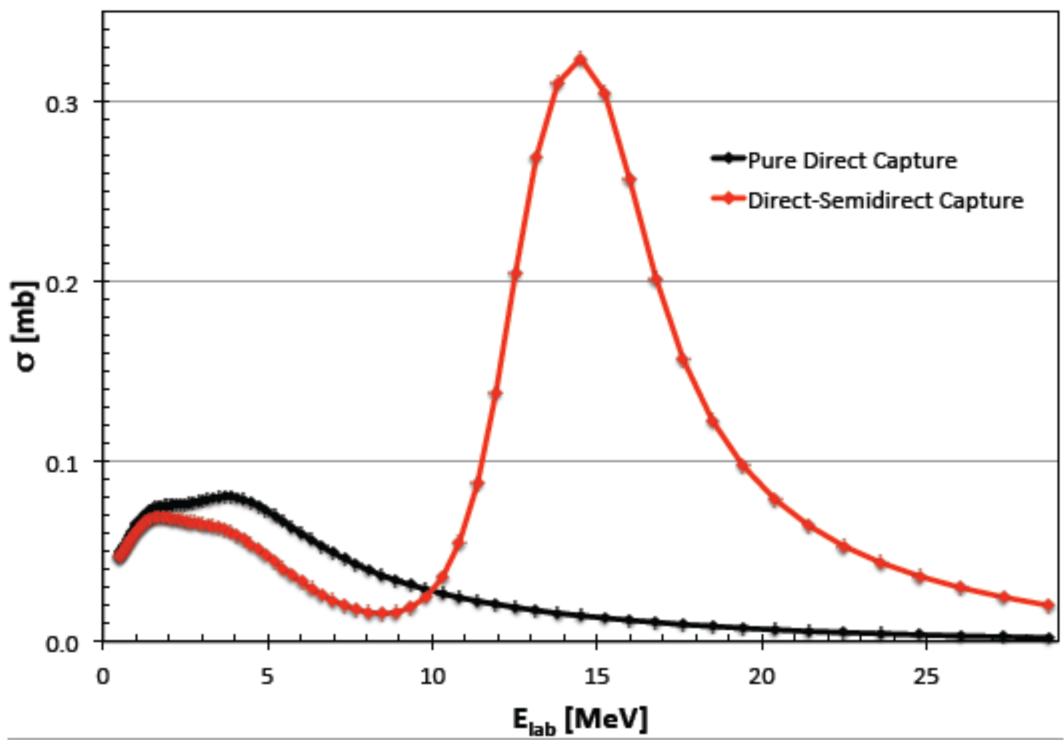
– Milestone**:** Systematic calculation of semi-direct contributions in capture reactions

Capture reactions: direct and semi-direct

- Analysis of transfer reactions will give ANC, reduced width or Spectroscopic Factor of final n bound state.
  - From which we calculate direct (n,γ) capture cross sections.
- But also need semi-direct captures:
  - Two-step coherent contributions through Giant Dipole Resonances
  - At present, this is only calculated separately, and not within a general coupled-channels framework
- TORUS is developing a new unified method for

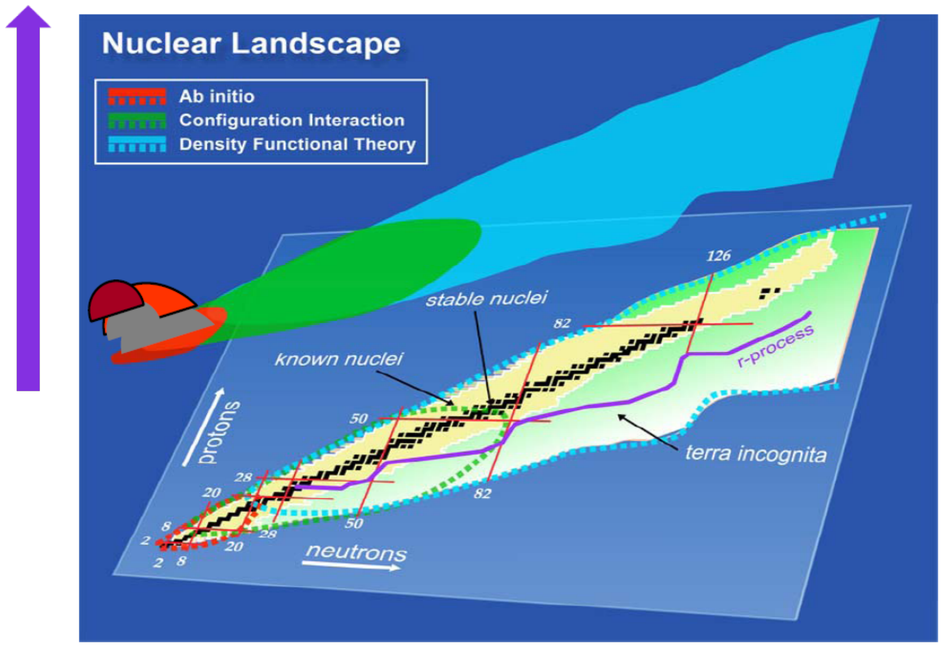
  direct+semi-direct capture

Capture reactions: direct and semi-direct



$^{130}Sn(n,g)^{131}Sn$

TORUS


Nuclear Landscape
Ab initio
Configuration Interaction
Density Functional Theory
stable nuclei
known nuclei
r-process
terra incognita
protons
neutrons
126
82
50
28
20
8
2

thankyou