INPP @OHIO UNIVERSITY
INSTITUTE OF NUCLEAR & PARTICLE PHYSICS

Nuclear Reaction Challenge and Opportunity for Few- and Many-Body Theory

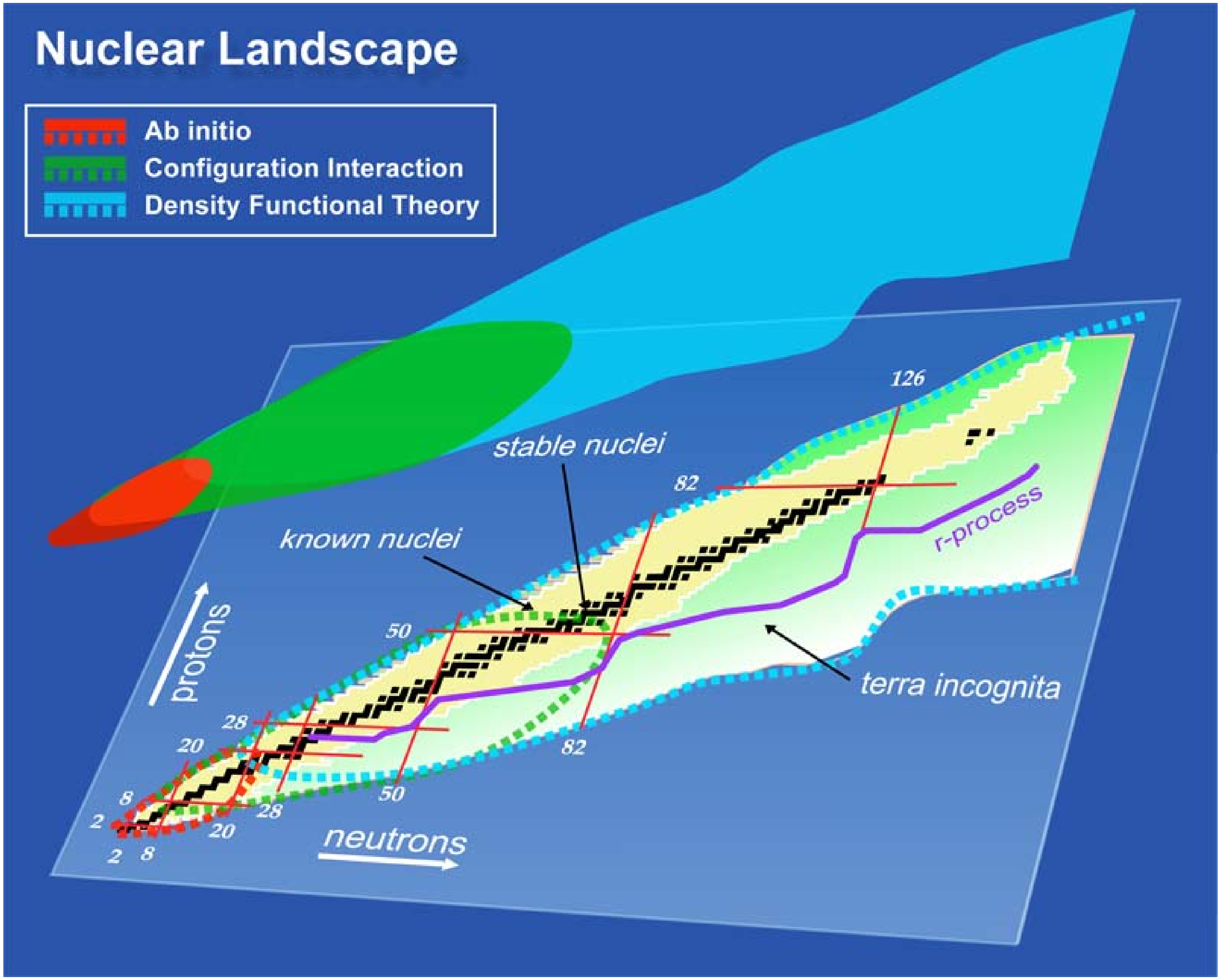
Ch. Elster

TORUS collaboration

11/7/2010

Supported by: U.S. DOE

Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

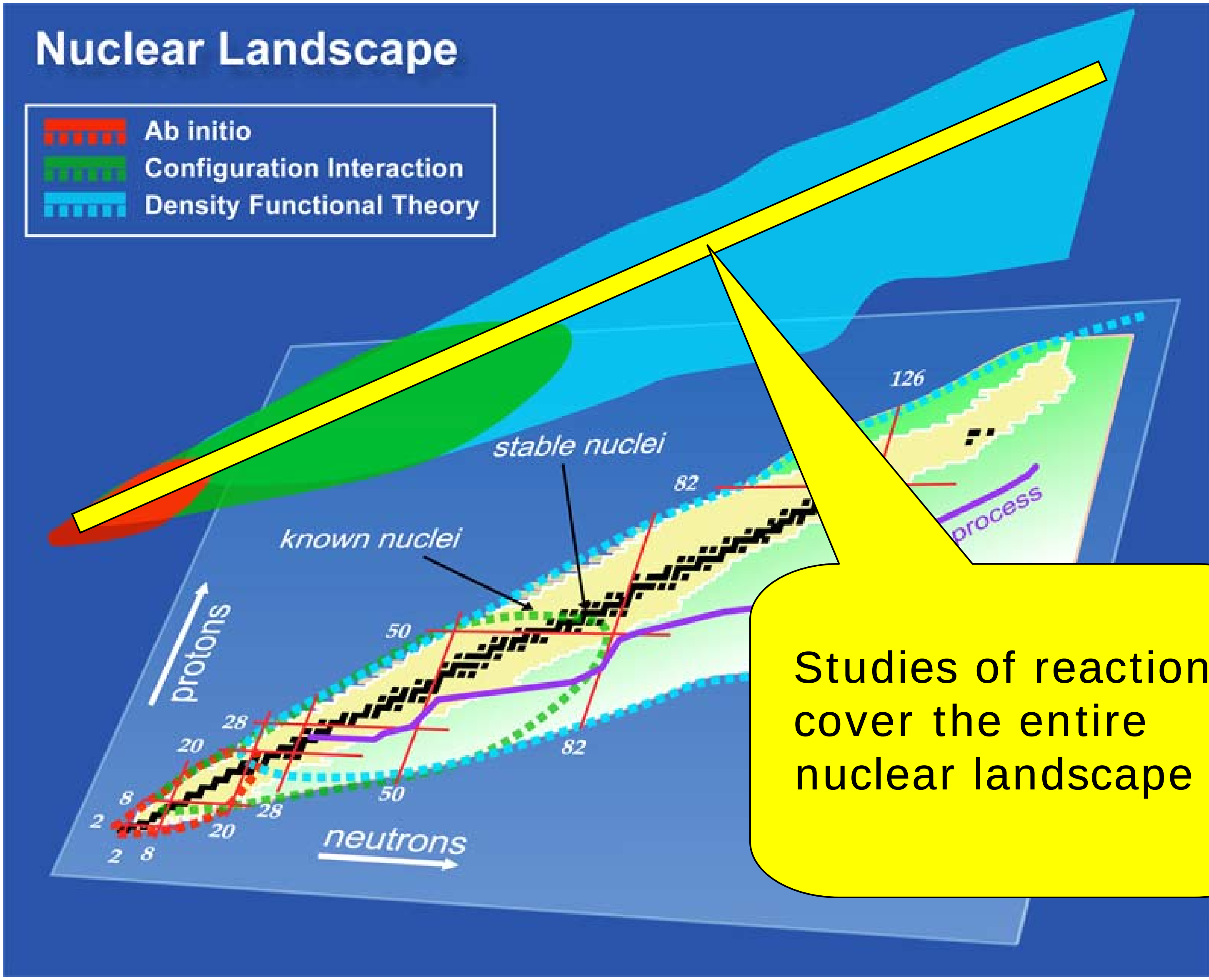


Witold Nazarewicz

Reactions at FRIB

- High energy beams
  - Knock-out reactions (one or two nucleons)
  - Break up
  - Charge exchange
- Reaccelerated beams
  - Transfer reactions (one or two nucleons)
  - Transfer to the continuum
  - Excitations
  - Elastic
  - Fusion

		Separation energy
Important: Projectile can be		
- close to dripline	←	~100 keV
- heavy neutron rich system	←	~ 6 MeV



Studies of reactions cover the entire nuclear landscape

Example: Transfer reactions

traditionally used to extract spin,parity and spectroscopic factors

$^{132}Sn(d,p)^{133}Sn$

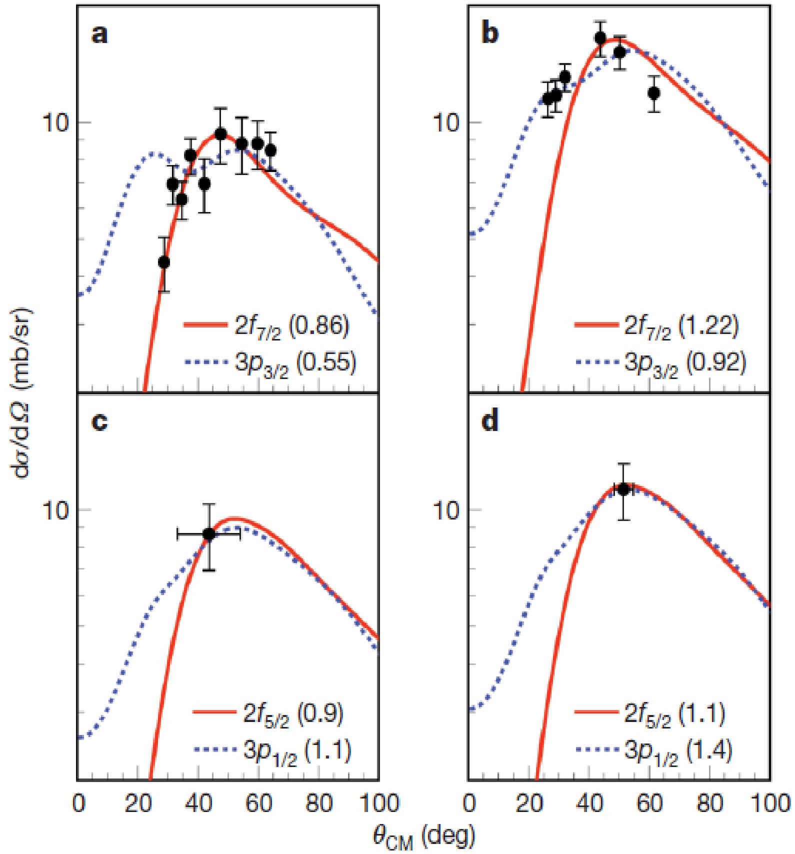


Table 1 | Properties of the four single-particle states populated by the ^{132}Sn(d,p)^{133}Sn reaction

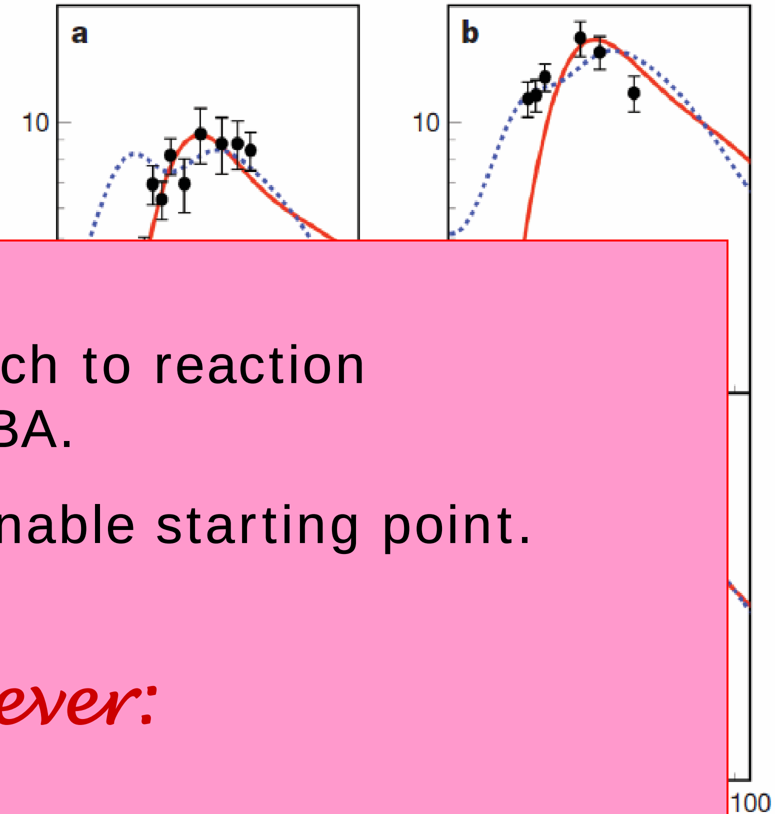
E_x (keV)	J^π	Configuration	S	C^2 (fm^{-1})
0	$7/2^-$	$^{132}Sn_{gs} \otimes \nu_{f7/2}$	0.86 ± 0.16	0.64 ± 0.10
854	$3/2^-$	$^{132}Sn_{gs} \otimes \nu_{p3/2}$	0.92 ± 0.18	5.61 ± 0.86
$1,363 \pm 31$	$(1/2^-)$	$^{132}Sn_{gs} \otimes \nu_{p1/2}$	1.1 ± 0.3	2.63 ± 0.43
2,005	$(5/2^-)$	$^{132}Sn_{gs} \otimes \nu_{f5/2}$	1.1 ± 0.2	$(9 \pm 2) \times 10^{-4}$

[K. Jones et al, to appear in Nature 2010]

Example: Transfer reactions

traditionally used to extract spin,parity and spe... fa...

^{132}Sn...



A historical approach to reaction calculations is DWBA.

In its time a reasonable starting point.

However:

In order to understand the richness of information obtained in FRIB experiments, theory needs to jump forward

Table 1 | Properties o...
^{132}Sn(d,p)^{133}Sn reacti...

E_x (keV)	J^{π}			
0	7/2$^-$			
854	3/2$^-$			
1,363 ± 31	(1/2$^-$)	^{132}Sn$_{gs}$ ⊗ $\nu_{p1/2}$	1.1 ± 0.3	2.63 ± 0.43
2,005	(5/2$^-$)	^{132}Sn$_{gs}$ ⊗ $\nu_{f5/2}$	1.1 ± 0.2	(9 ± 2) × 10^{-4}

[K. Jones et al, to appear in Nature 2010]

Reactions:

Projectile	Target
p n	p
d	d
^{3}H ^{3}He	^{3}He ^{3}H
$^{4, 6, 8}$ He	$^{4, 6, 8}$ He
^{56}Ni ^{78}Ni	^{56}Ni ^{78}Ni
^{132}Sn	^{132}Sn
…	…

Long Tradition

Determination of NN forces

Three Nucleon Physics – Reactions: low energy to GeV regime
Development of Faddeev Formulations & Calculations, 3NF's

Reactions:

Projectile | **Target**

p n → p

d → d

^3H ^3He | ^3He ^3H

4, 6, 8 He | 4, 6, 8 He

^{56}Ni ^{78}Ni | ^{56}Ni ^{78}Ni

^{132}Sn | ^{132}Sn

… | …

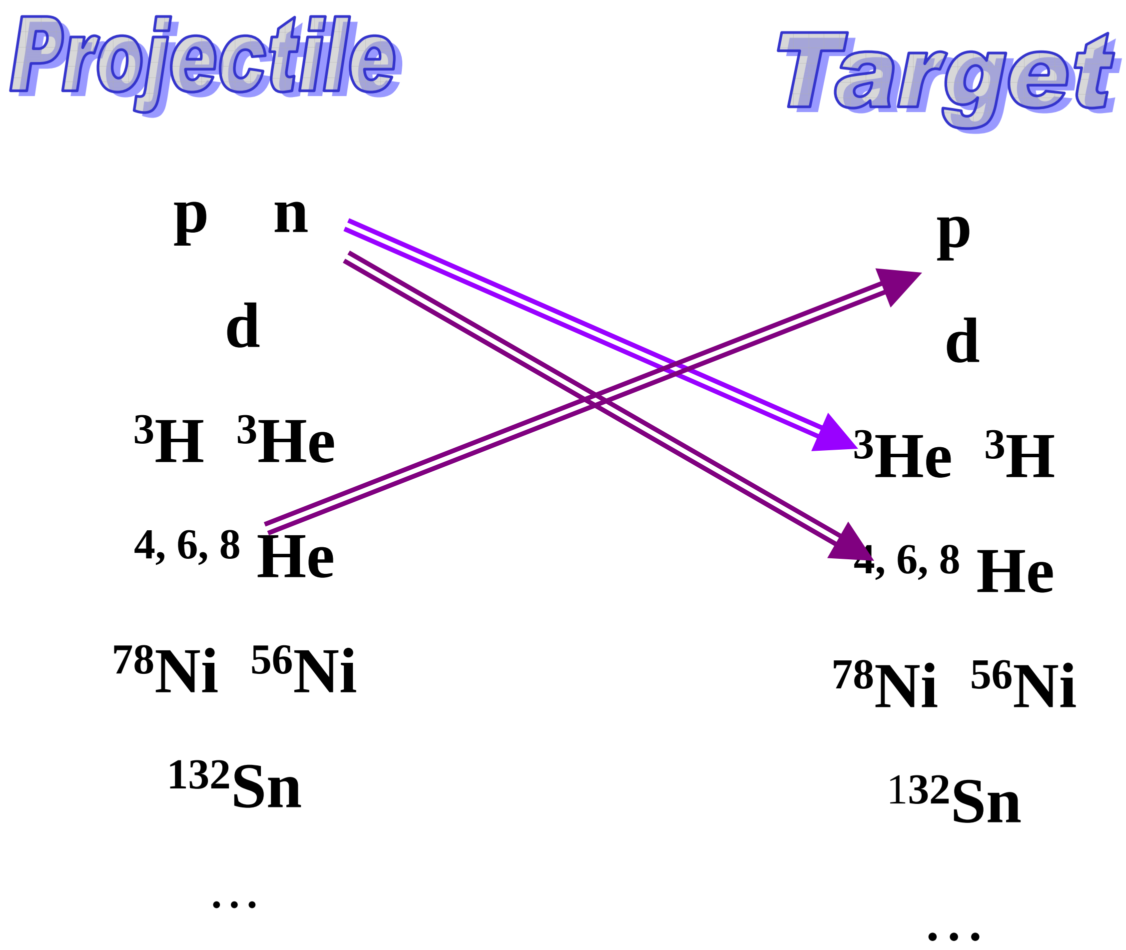
- **Los Alamos – Iowa**
- **Mainz - Bonn**
- **Bochum – Cracow**
- **Hannover**
- **Lisbon**
- **Pisa**

Determination of NN forces

Long Tradition

Three Nucleon Physics – Reactions: low energy to GeV regime

Development of Faddeev Formulations & Calculations, 3NF's



Exact Few-Body Methods:

Faddeev-Yakubovski /

GFMC / Resonating Group / Hyperspherical Harmonics

Projectile

p n

d

^{3}H ^{3}He

$^{4,6,8}He$

^{78}Ni ^{56}Ni

^{132}Sn

…

Target

p

d

^{3}He ^{3}H

$^{4,6,8}He$

^{78}Ni ^{56}Ni

^{132}Sn

…

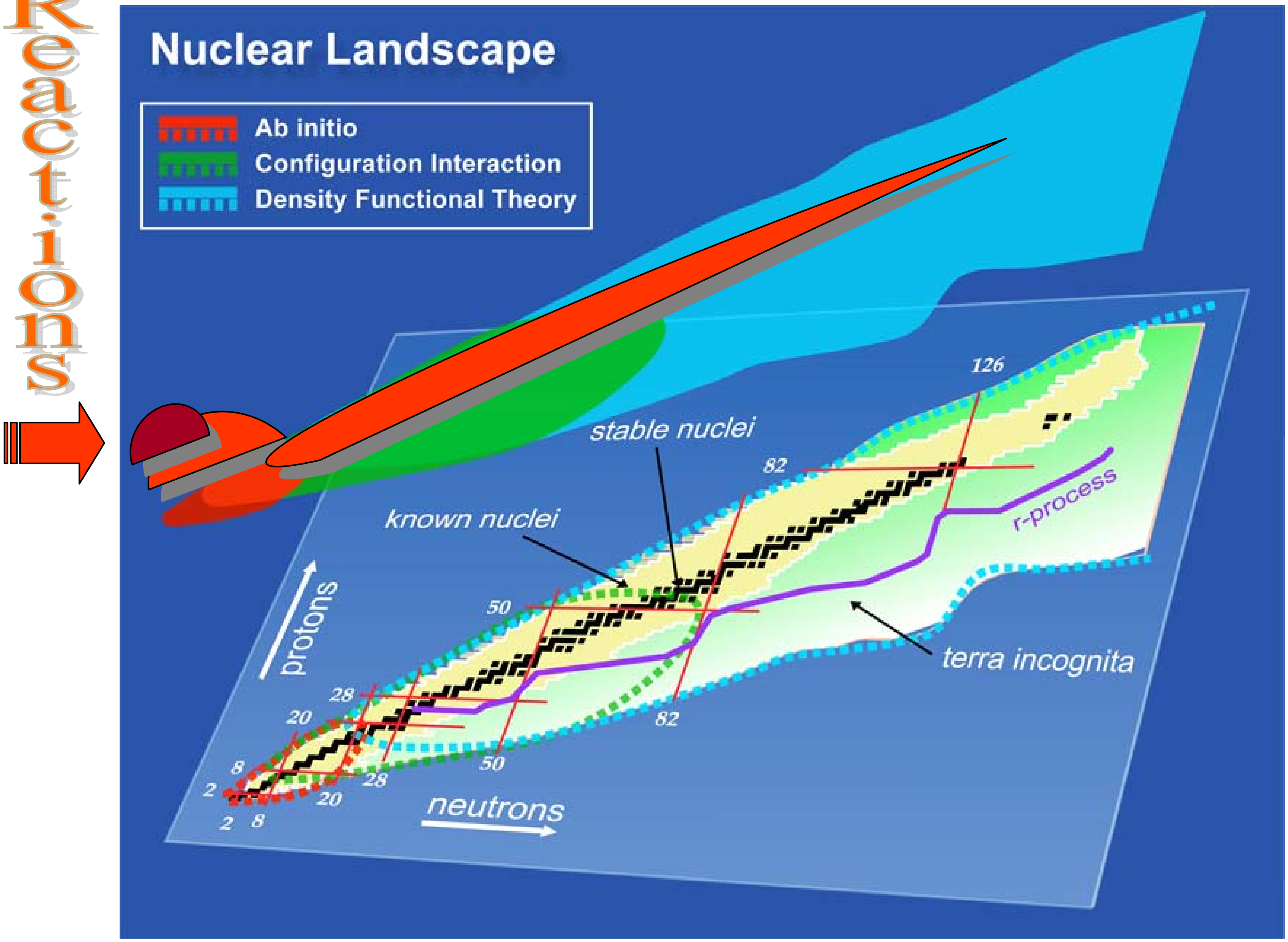
- Grenoble
- Lisbon
- ANL
- Los Alamos – Erlangen
- Kyoto
- LLNL - TRIUMF
- Pisa

Exact Few-Body Methods:

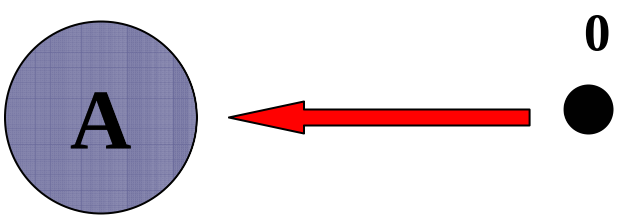
Faddeev-Yakubovski /

GFMC / Resonating Group / Hyperspherical Harmonics

Reactions


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

Scattering Problem :
Simplest: p $\rightarrow$ A

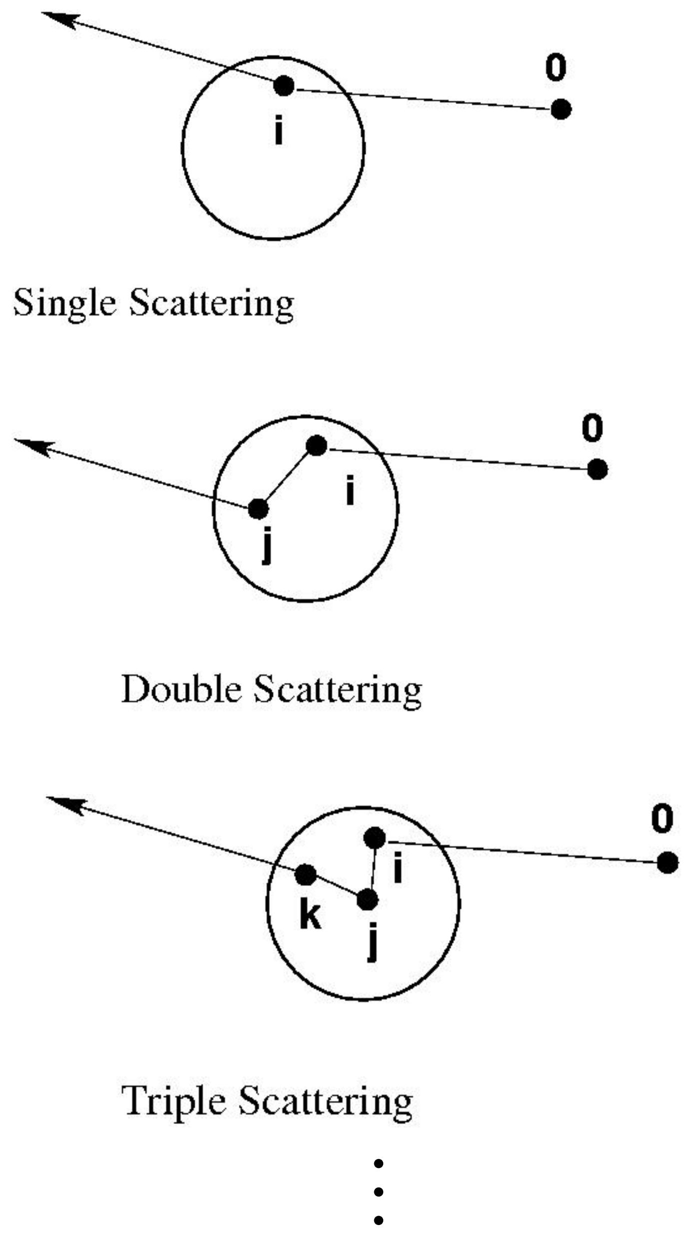


- Hamiltonian: $H = H_0 + V$
- Free Hamiltonian: $H_0 = h_0 + H_A$
- Assume: two-body interactions dominant
  - V: interactions between projectile '0' and target nucleons 'i'
    $V = \Sigma^A_{i=0}\, v_{0i}$
- Transition Amplitude: $\mathbf{T = V + V\, G_0\, T}$
- **Multiple Scattering Expansion**

Spectator Expansion:

Siciliano, Thaler (1977)

Picklesimer, Thaler (1981)



Elastic Scattering

- In- and Out-States have the target in ground state Φ_0
- Projector on ground state $P = |\Phi_0\rangle\langle\Phi_0|$
  - With 1=P+Q and $[P,G_0]=0$
- For elastic scattering one needs
- $P\ T\ P = P\ U\ P + P\ U\ P\ G0(E)\ P\ T\ P$
- Or
  - $\mathbf{T = U + U\ G_0(E)\ P\ T}$
  - $\mathbf{U = V + V\ G_0(E)\ Q\ U}$ $\Leftarrow$ **optical potential**

Optical Potential – phenomenological:

- Nucleus opaque ⇒ complex potential (removes flux)
- Most general form of optical potential
  - $\sum_i$ [$V_{A,Z,N,E}(r)$ + i $W_{A,Z,N,E}(r)$] $Operator_{(i)}$
- Best fit of elastic scattering data for a wide range of nuclei and energies
  - Cross sections, angular distributions, polarizations
- E.g.
  - Becchetti – Greenlees, Phys. Rev. 182, 1190 (1969)
  - Global: E.D. Cooper et al, PRC47, 297 (1993)
  - Koning – Delaroche, NP A713, 231 (2003)

Koning – Delaroche (2003)

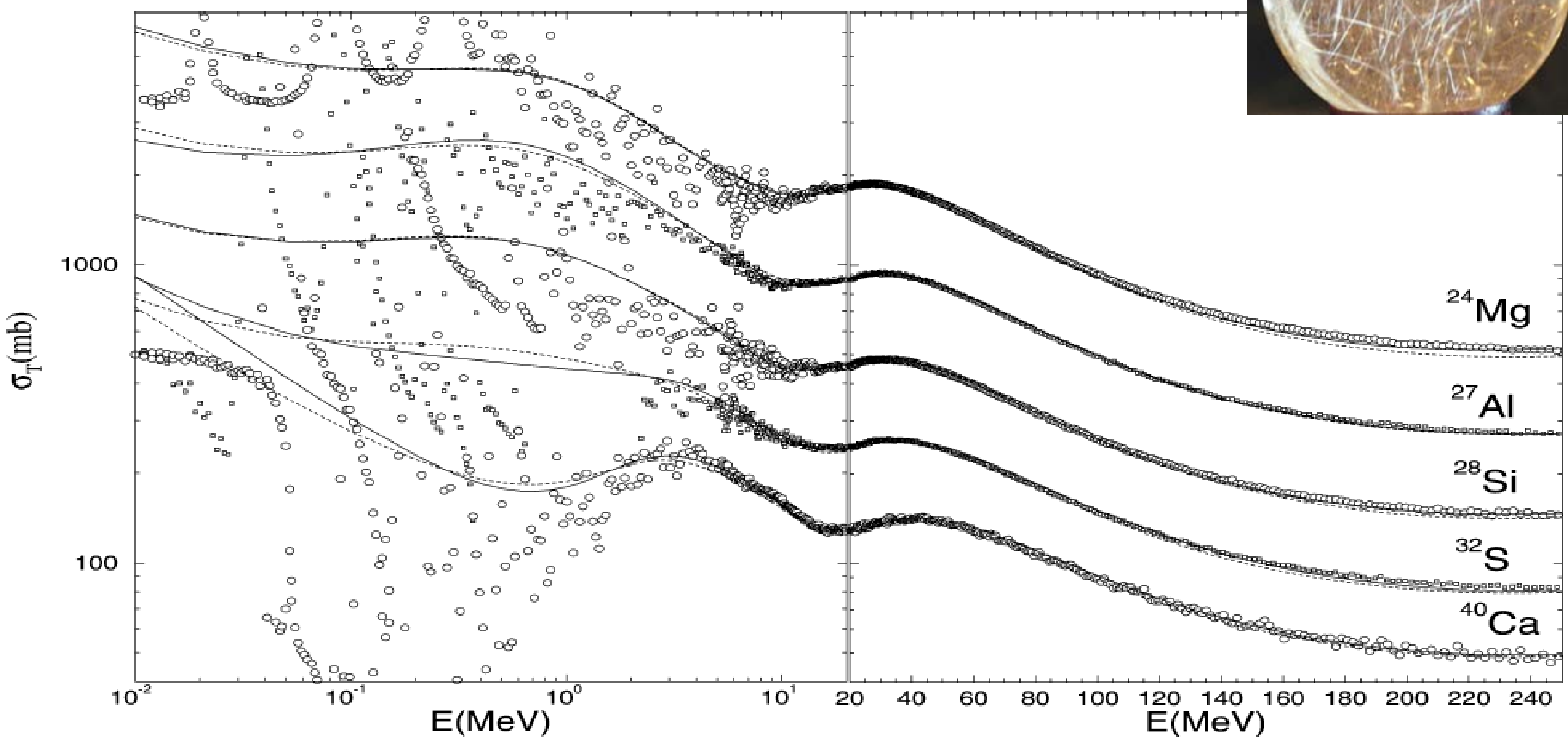


Fig. 2. Comparison of predicted neutron total cross sections and experimental data, for nuclides in the Mg–Ca mass region, for the energy range 10 keV–250 MeV.

Remark: Same importance as NN phase shift analysis

Talk: Steven Weppner

Elastic Scattering

- In- and Out-States have the target in ground state Φ_0
- Projector on ground state $P = |\Phi_0\rangle\langle\Phi_0|$
  - With $1=P+Q$ and $[P,G_0]=0$
- For elastic scattering one needs
- $P\,T\,P = P\,U\,P + P\,U\,P\,G0(E)\,P\,T\,P$
- Or
  - $T = U + U\,G_0(E)\,P\,T$
  - $U = V + V\,G_0(E)\,Q\,U$ $\Leftarrow$ optical potential

Low Energies:

Q-space contains e.g. coupling to resonances

$\Rightarrow$ Take nuclear structure information explicitly into account

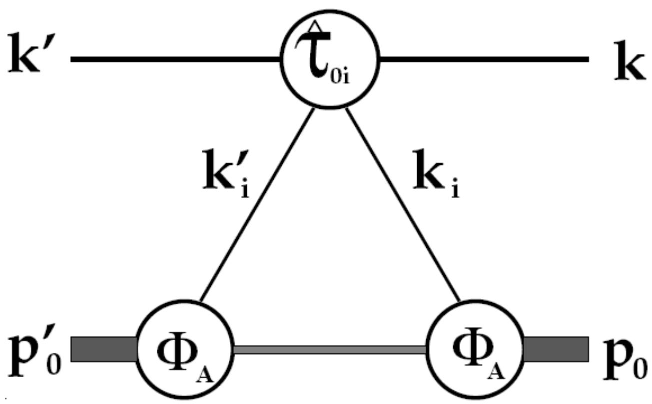
Talk: Ian Thompson

Microscopic :

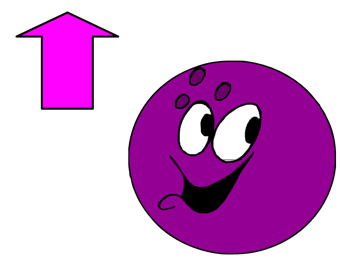
Chinn,Elster,Tandy, Redish, Thaler
Crespo, Johnson, Tostevin
Arrellano, Love

- **First order Optical Potential --- Full Folding**

$$\langle \mathbf{k}'|\langle\phi_A|PUP|\phi_A\rangle\mathbf{k}\rangle \equiv U_{el}(\mathbf{k}',\mathbf{k}) = \sum_{i=n,p} \langle \mathbf{k}'|\langle\phi_A|\hat{\tau}_{0i}(\mathcal{E})|\phi_A\rangle\mathbf{k}\rangle$$



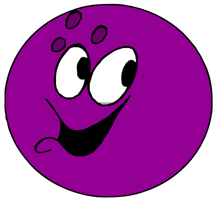
$$\langle\hat{\tau}_{01}\rangle \equiv \langle \mathbf{k}'|\langle\phi_A|\hat{\tau}_{01}(\mathcal{E})|\phi_A\rangle\mathbf{k}\rangle$$



Proton scattering: $U_{el}(\mathbf{k}',\mathbf{k}) = Z\langle\hat{\tau}_{01}^{pp}\rangle + N\langle\hat{\tau}_{01}^{np}\rangle$

Optical Potential is non-local and depends on energy

Off-shell NN t-matrix and nuclear density matrix



- Via $\langle \Phi_A | \Phi_A \rangle$ results from nuclear structure calculations enter

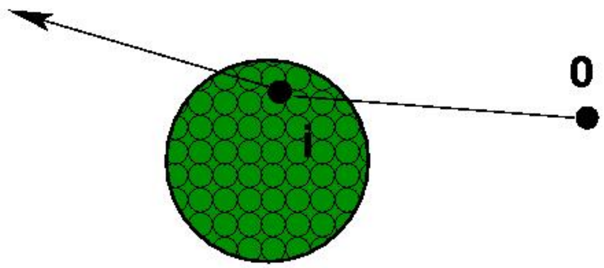
  $\Rightarrow$ **Structure and Reaction calculations can be treated with similar sophistication**

  Older microscopic calculations concentrated on closed shell spin-0 nuclei (ground state wave functions were not available)

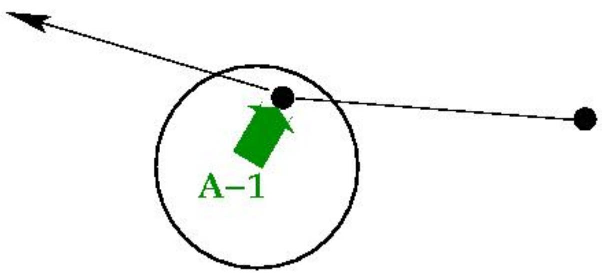
- Today one can start to explore **importance of open-shells in light exotic nuclei** (full complexity of the NN interactions enters) [Surrey group started work along this line]

  Experimental relevance: Polarization measurements for ^{6}He $\rightarrow$ p at RIKEN

"Nuclear Medium"



Single Scattering



Propagator is (A+1) body operator:
$G_0(E) = (E - h_0 - H_A + i\varepsilon)^{-1}$

H_A in a mean field view

$$H_A = h_i + \sum_{j \neq i}^{A} v_{ij} + H^i$$

$$\langle \Sigma_{j\neq i}{}^{A} v_{ij} \rangle \equiv U_i \equiv \text{mean field}$$

Single scattering is an implicit three-body problem:

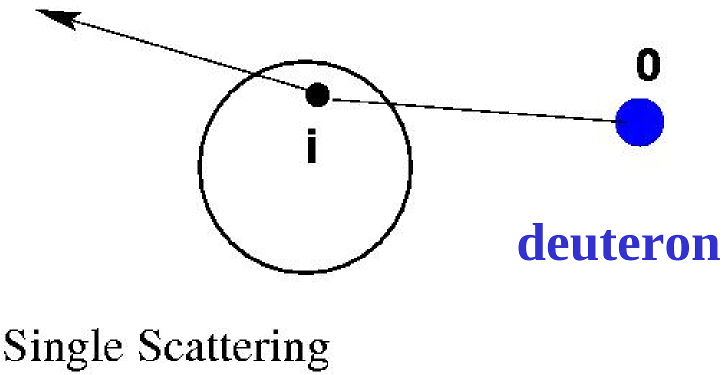
Projectile + struck nucleon + (A-1) core

Chinn, Elster, Thaler PRC 48, 2956 (1993)

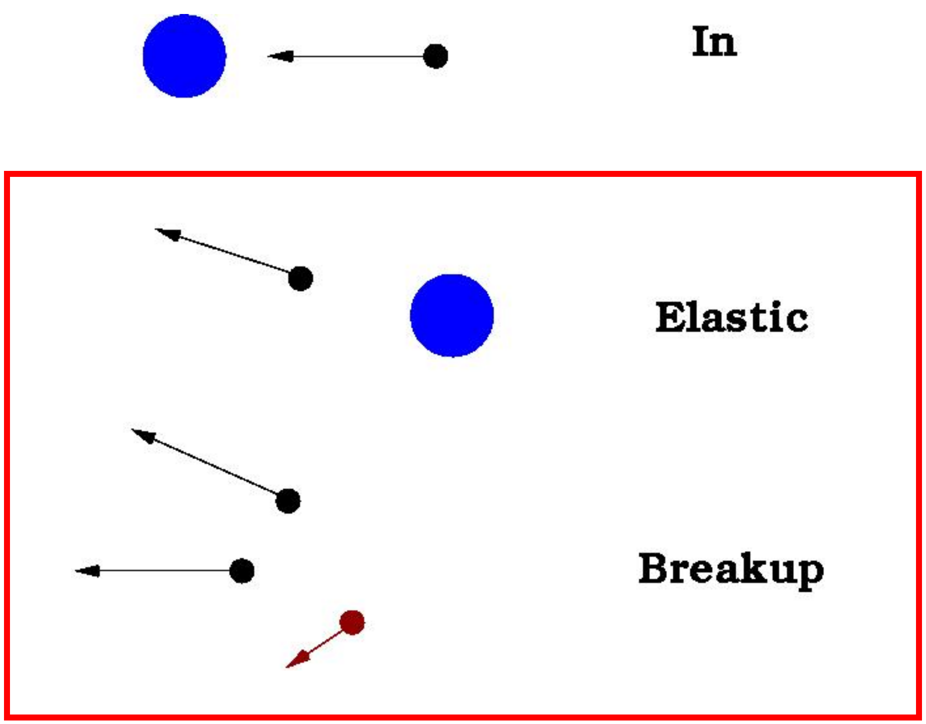
Different consideration:
Folding the ground state wave function
with the nuclear matter g-matrix:

Pioneered by Arellano & Love – cont'd by Karataglidis & Amos

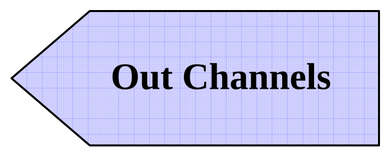
Again Single Scattering: (d,p) Reaction



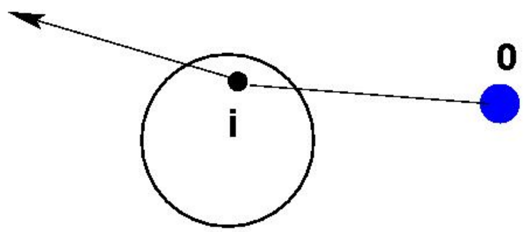
p+d scattering :



Faddeev Formulation of (d,p) Reactions



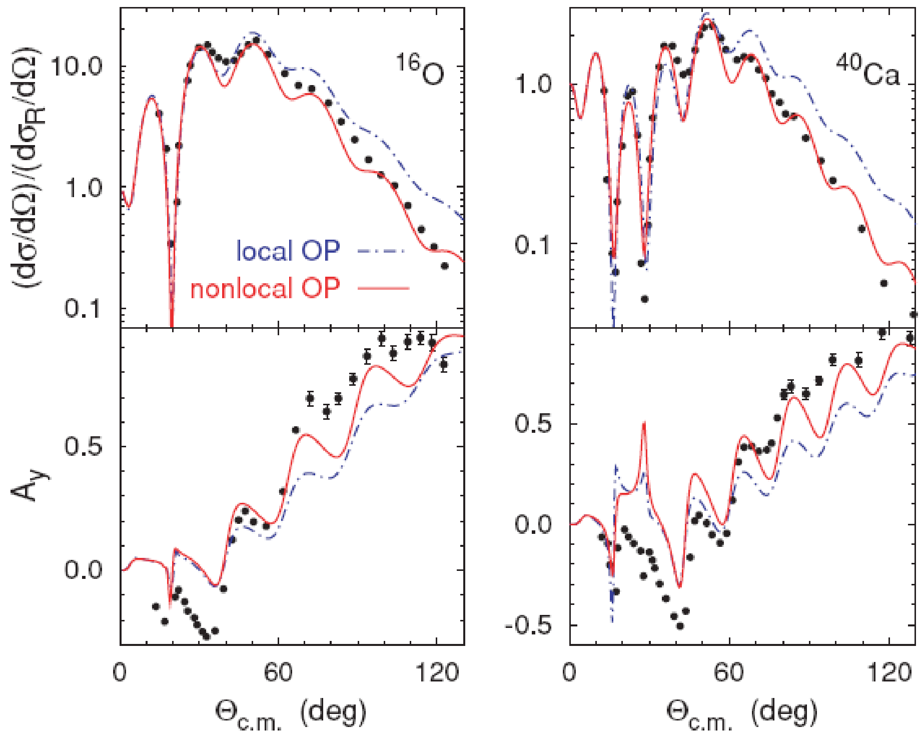
Faddeev Formulation of (d,p) Reactions



Single Scattering

Deuteron: NN interaction
p(n) – nucleon i: optical potential

Elastic deuteron scattering @ 56 MeV



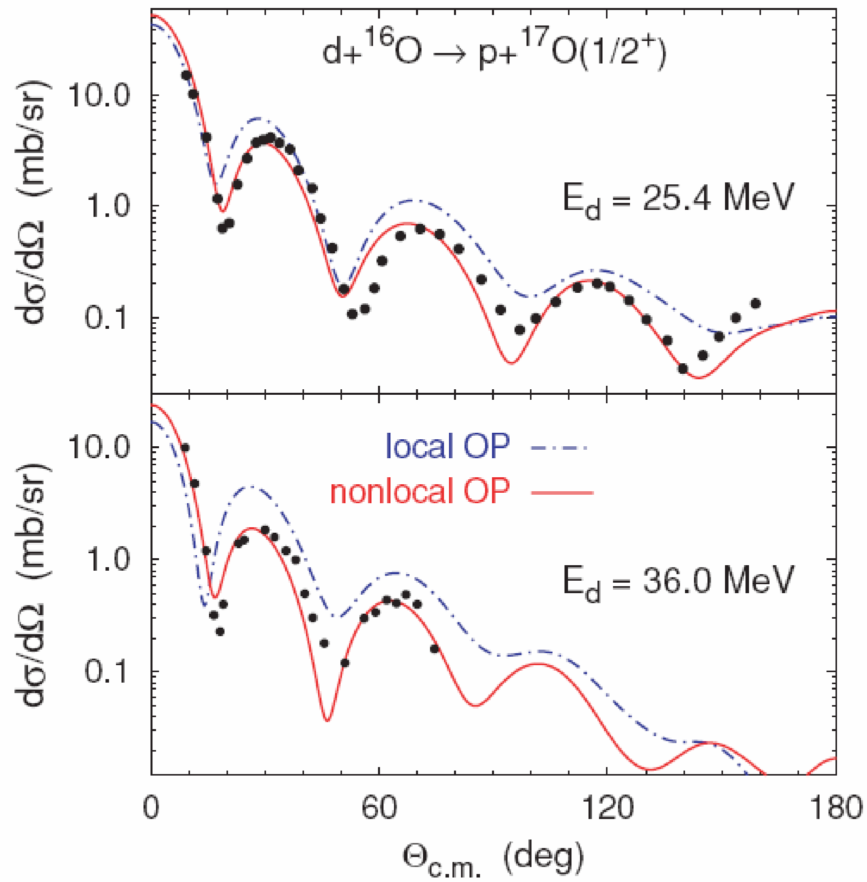
A. Deltuva, PRC 79, 021602(R) (2009)

Interactions:
phenomenological optical potentials

Expected that those capture the important features of a nucleon in the nucleus

Faddeev Formulation of (d,p) Reactions cont'd

A. DELTUVA



Transfer Reaction
(breakup)

Further:

Considerations on optical potential similar to the ones in p+A scattering?

Improvements in treating optical potential in Faddeev calculation?

Talk: A. Fonseca

CDCC: Continuum discretized coupled channel approach

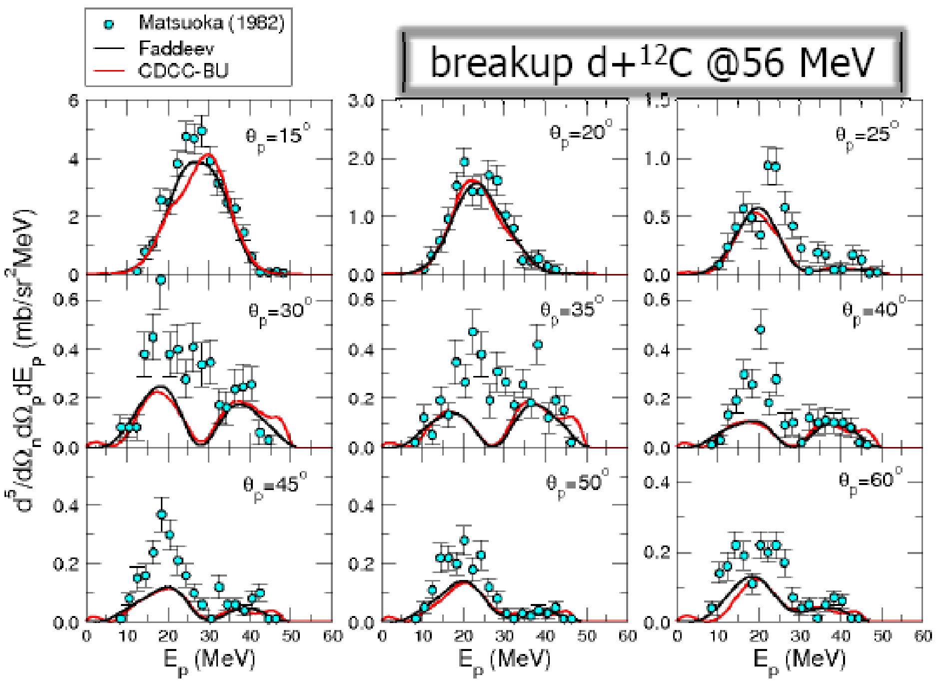
Developed to for calculating deuteron-nucleus reactions (~80s)

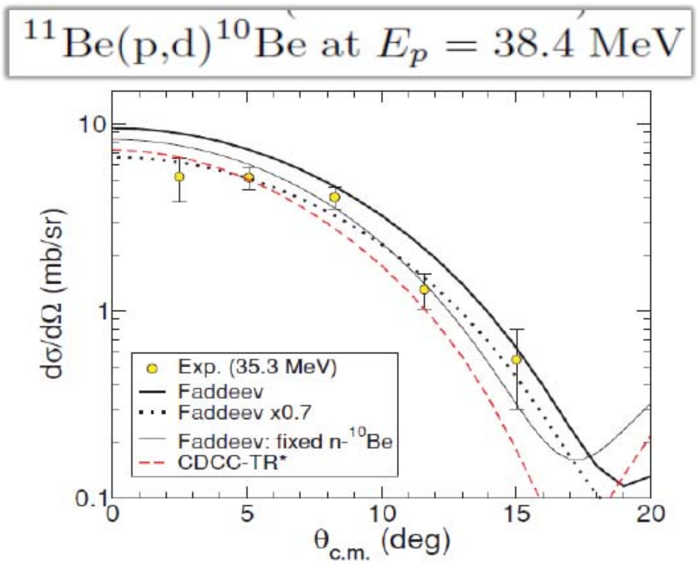
-- Approximate treatment of the 3-body problem including breakup to all orders but -- assuming breakup-transfer couplings are small.

-- Well developed and widely used for d+A

- Expansion in scattering (continuum) states of target and projectile
  - Core excitations can be included naturally
  - Convergence of expansion needs to be established for each reaction
- Difficult to treat breakup and transfer on equal footing
  - Assumptions can and need to be tested today with respect to a Faddeev approach.

Comparing CDCC and Faddeev Calculations





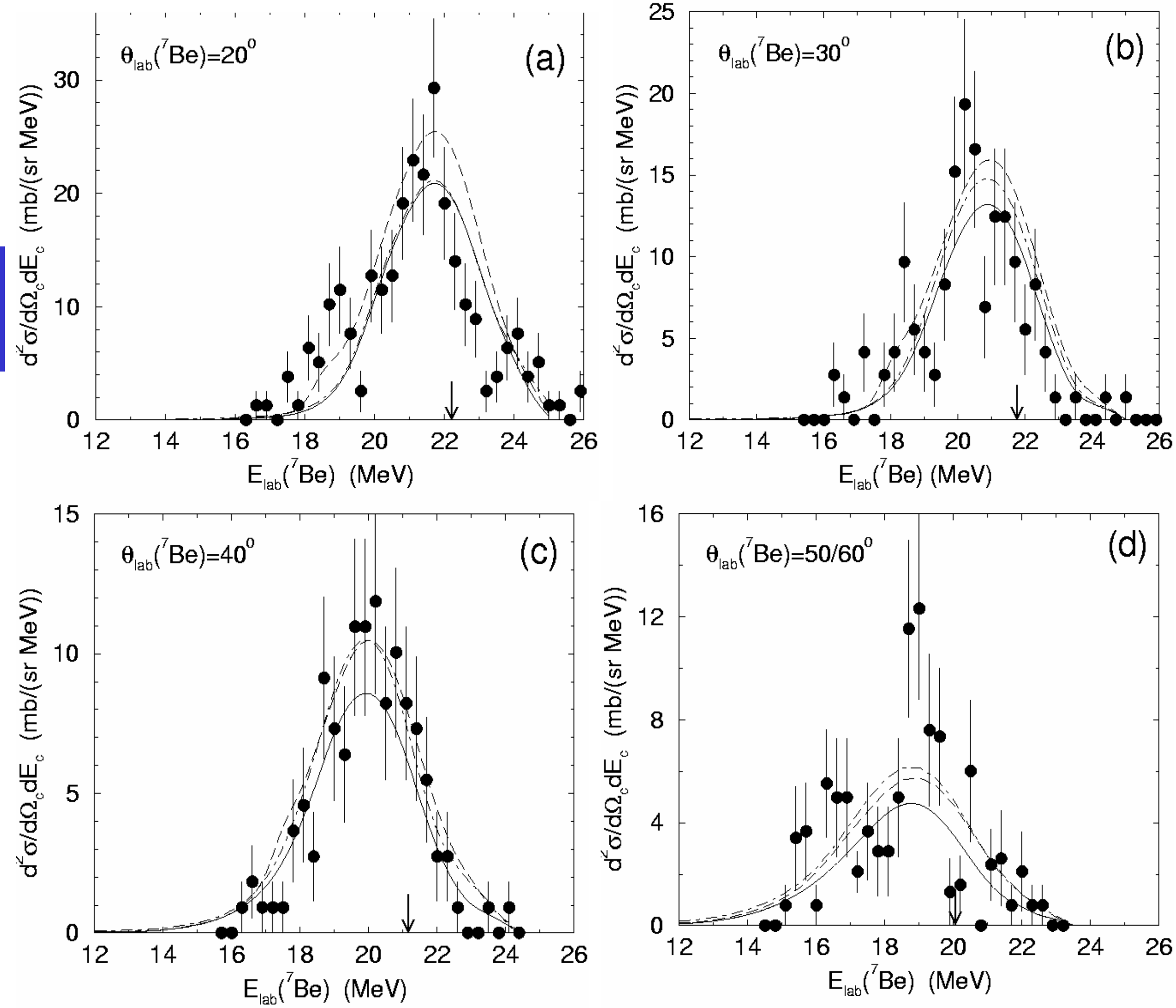
[Deltuva, Moro, Nunes and Fonseca, PRC76, 064602]

Detailed comparisons between CDCC and Faddeev approach needed to improve on short-comings of CDCC

Breakup of ^{8}B

^{8}B breakup on ^{58}Ni (E_{beam}=26 MeV)

Results of CDCC calculations assuming a single particle structure for ^{8}B=^{7}Be+p



[Tostevin, FN, Thompson PRC (2001) 024617]

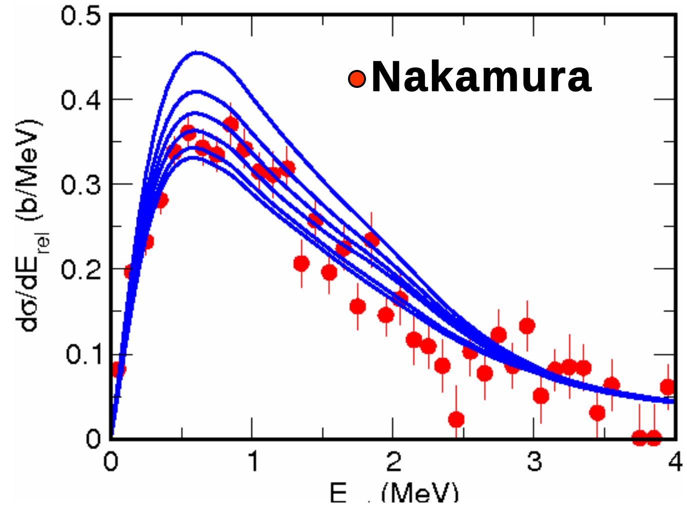
Breakup reactions and (n,γ): methodology

CDCC + set of single particle parameters

- extract ANC from χ^2 minimum
- error from $\varepsilon=\chi_{min}{}^2+1$

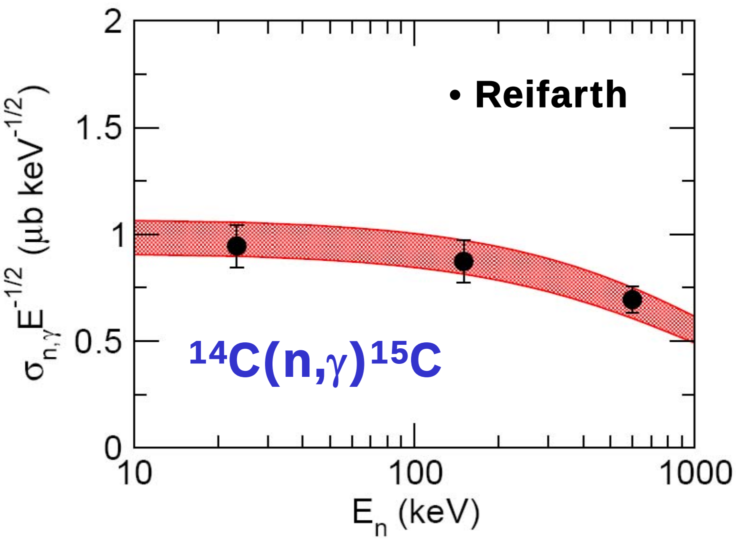
Yao, JPG33 (2006) 1

^{208}Pb(^{15}C,^{14}C+n)^{208}Pb@68 MeV/u



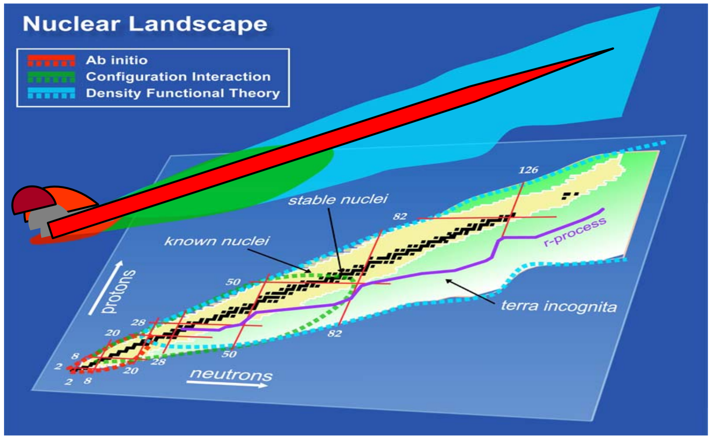
$$ANC = 1.32 \pm 0.07 \ \mathbf{fm^{-1/2}}$$

Summers and Nunes, PRC78(2009)069908



Nakamura et al, NPA722(2003)301c

Reifarth et al, PRC77,015804 (2008)



Goal for Reaction Theory:

Determine the topography of the nuclear landscape according to reactions described in definite schemes

At present `traditional' few-body methods are being successfully applied to a subset of nuclear reactions.

Establish overlaps, where different approaches can be firmly tested.

This `cross fertilization' of two different fields carries a lot promise for developing the theoretical tools necessary for FRIB physics.

It is an exciting time to participate in this endeavor.