INPP @OHIO UNIVERSITY INSTITUTE OF NUCLEAR & PARTICLE PHYSICS

Nuclear Reactions: A Challenge for Few- and Many-Body Theory

Ch. Elster

TORUS collaboration

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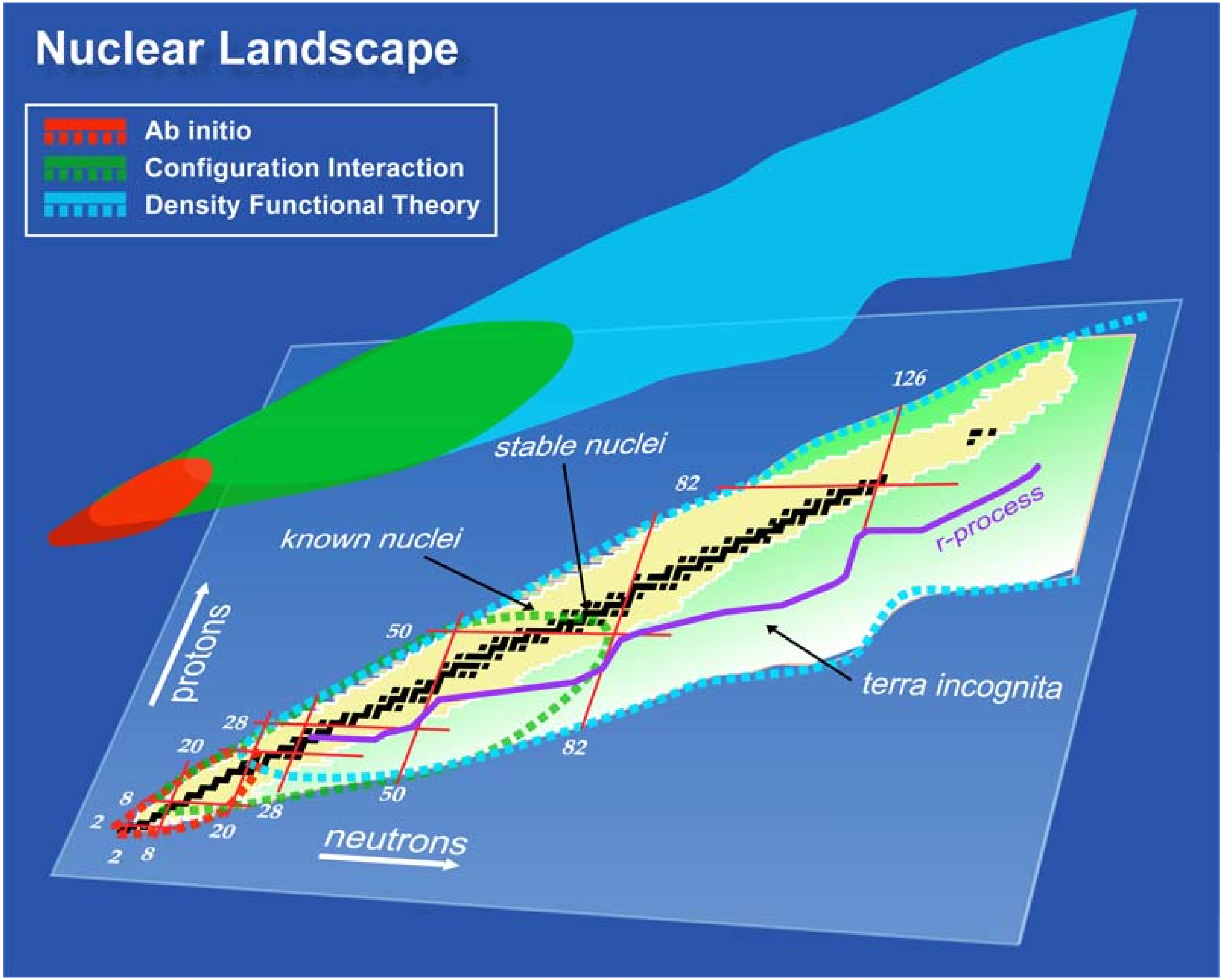
Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

6/4/2012



Witold Nazarewicz

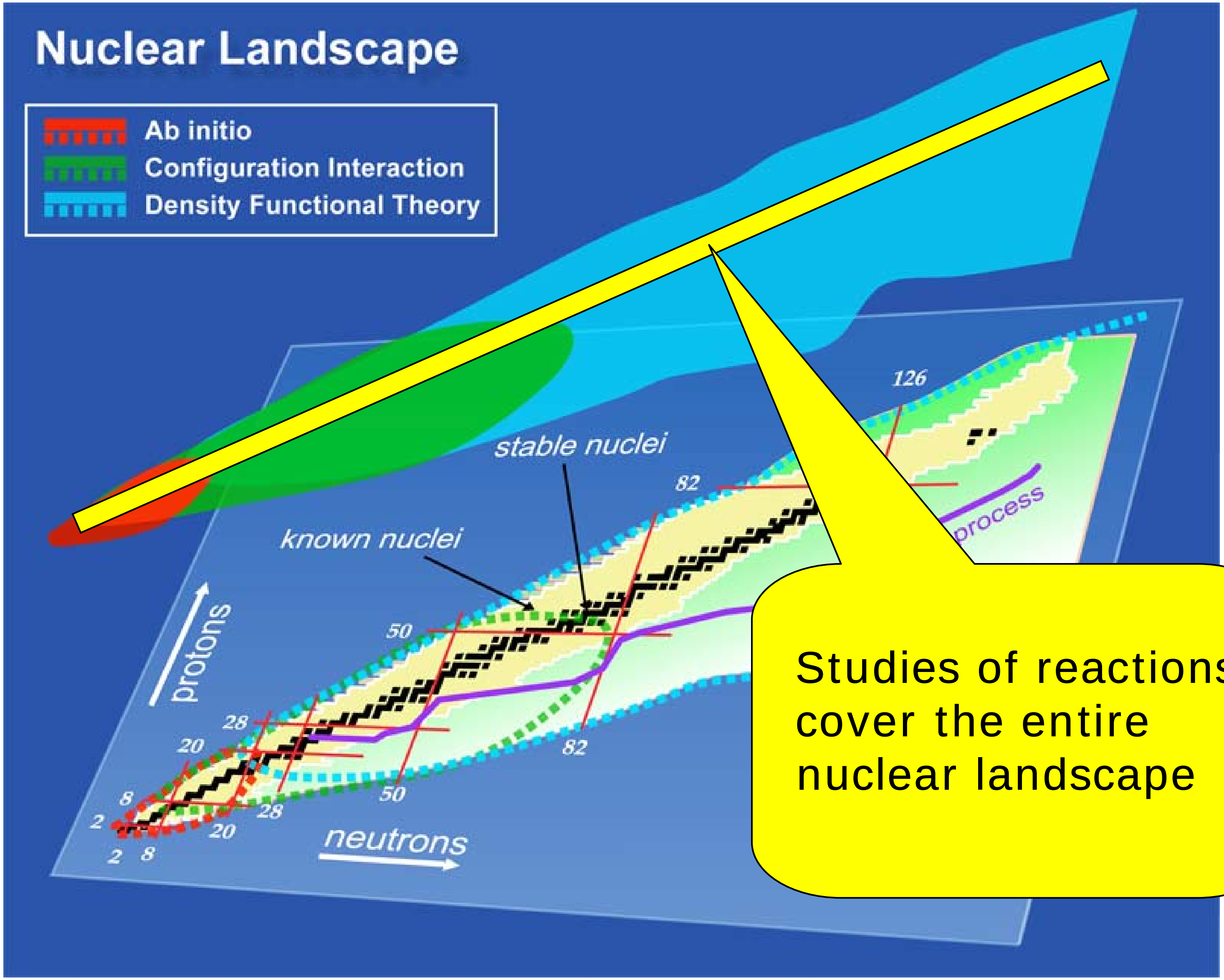
Reactions with Rare Isotopes

- 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

Traditional Few Body Reactions:

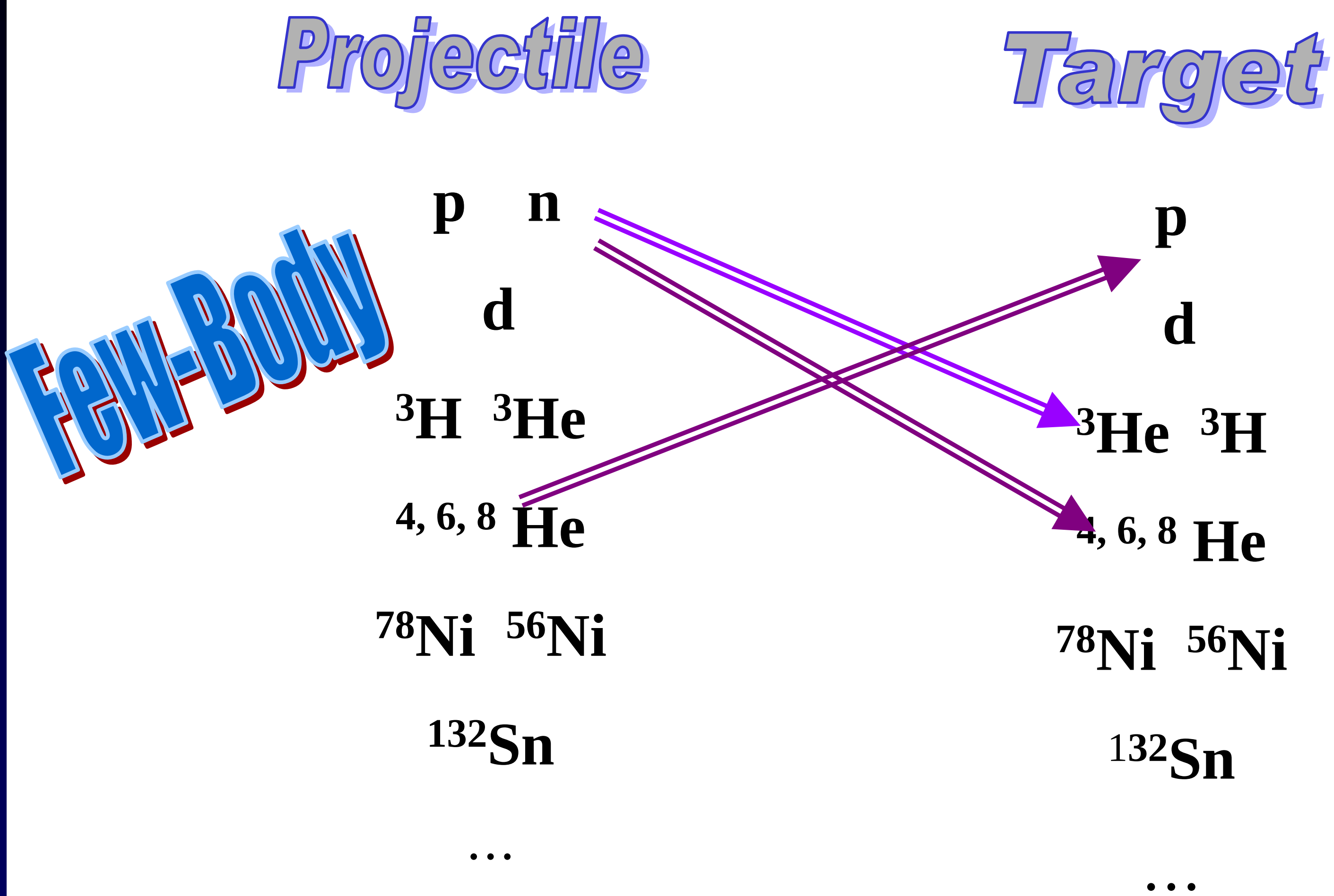
Projectile	Target
p n	p
d	d
^{3}H ^{3}He	^{3}He ^{3}H
$^{4, 6, 8}He$	$^{4, 6, 8}He$
^{56}Ni ^{78}Ni	^{56}Ni ^{78}Ni
^{132}Sn	^{132}Sn
…	…

Long Tradition

Determination of NN forces

Three Nucleon Physics – Reactions: low energy to GeV regime

Development of Faddeev Formulations & Calculations, 3NF's

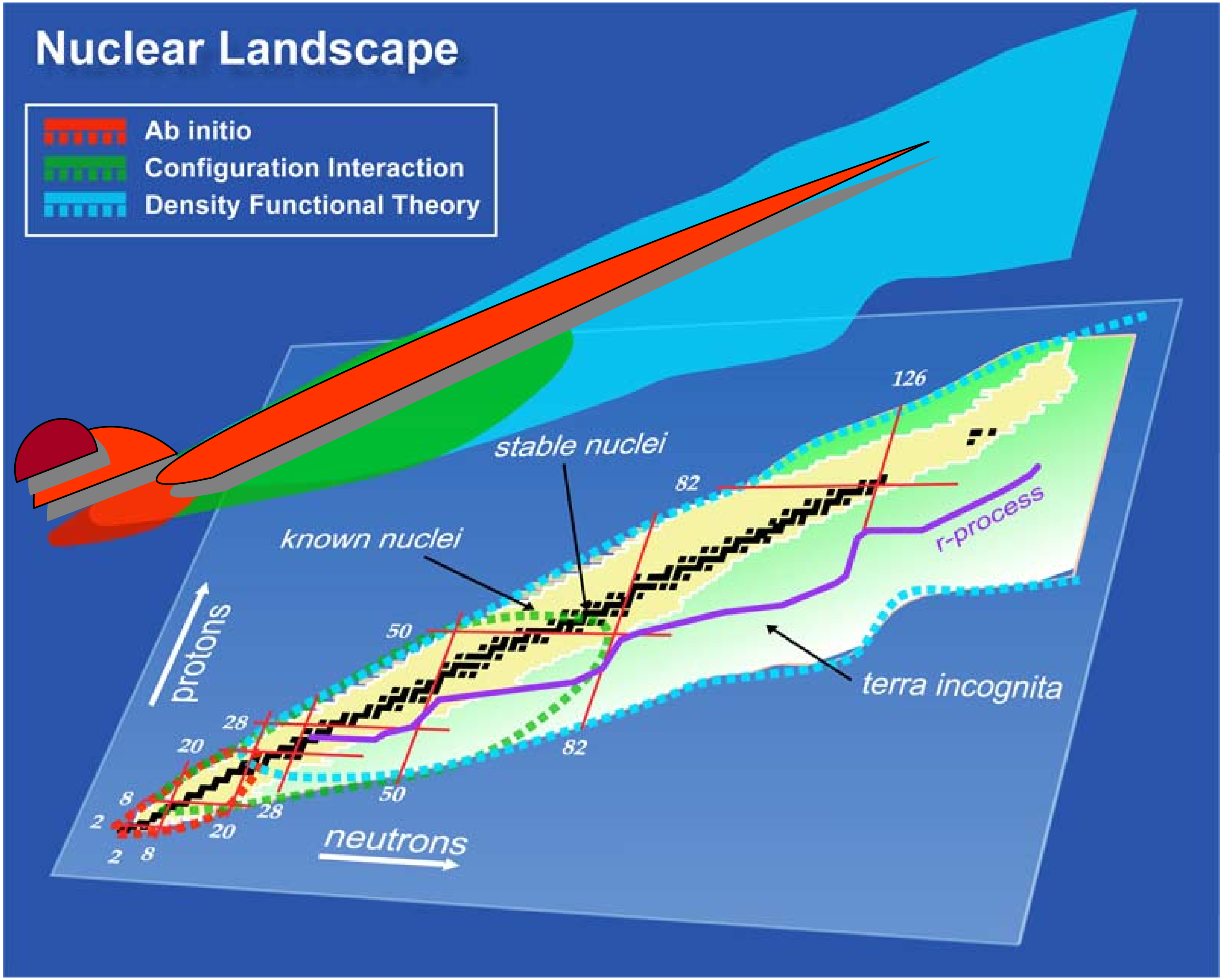


Exact Few-Body Methods:

Faddeev-Yakubovski /

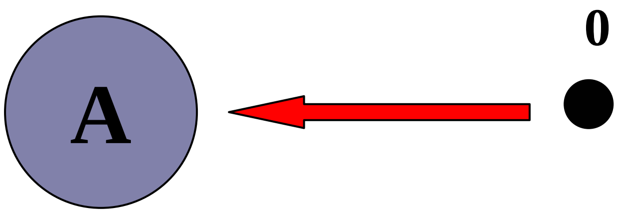
GFMC / Resonating Group / Hyperspherical Harmonics

Reactions

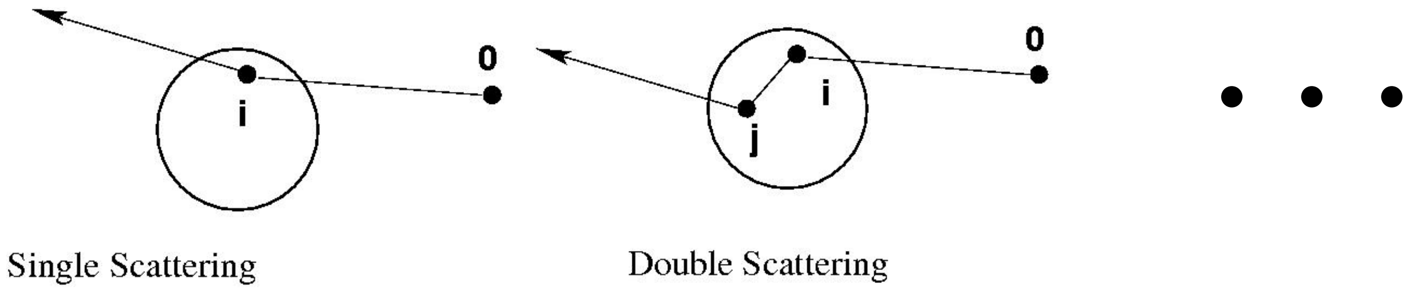


Nuclear Landscape
Ab initio
Configuration Interaction
Density Functional Theory
stable nuclei
known nuclei
terra incognita
r-process
protons
neutrons
2
8
20
28
50
82
126

Nuclear Reactions:
Simplest: p → A



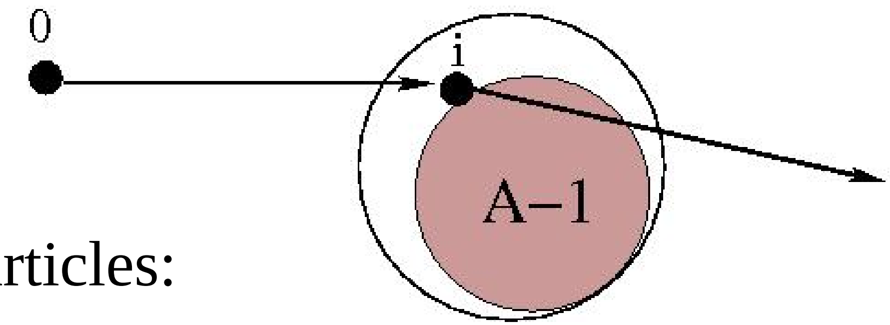
- Hamiltonian: $H = H_0 + V$
- Free Hamiltonian: $H_0 = h_0 + H_A$
- Assume: two-body interactions dominant
  - V: interactions between projectile ‘0’ and target nucleons ‘i’ $V = \sum^{A}_{i=0} v_{0i}$
- Transition Amplitude: $\mathbf{T = V + V\,G_0\,T}$
- **Multiple Scattering Expansion**



Single Scattering picture:

Nucleus

Projectile



Three-body problem with particles:

o – i – (A-1)-core

o – i : NN interaction

i – (A-1) core : e.g. mean field force

Phenomenological Optical Potentials parameterize single scattering term

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
  - $T = U + U\ G_0(E)\ P\ T$
  - $U = V + V\ G_0(E)\ Q\ U$ ⇐ optical potential

Low Energies:

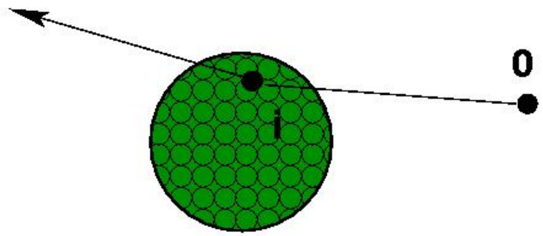
Q-space contains e.g. coupling to resonances

⇒ Take nuclear structure information explicitly into account

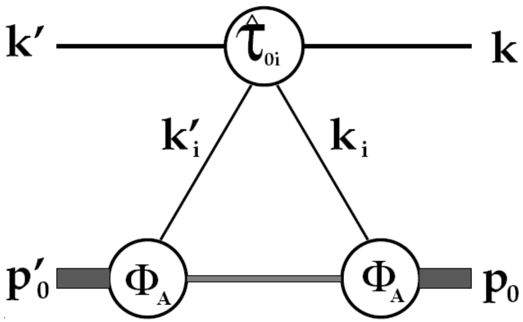
Microscopic :

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

- Single Scattering Optical Potential --- Full Folding



Single Scattering



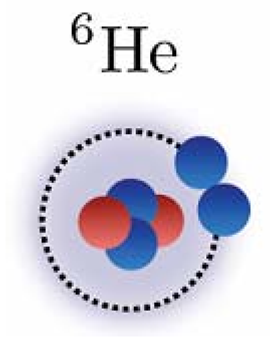
$$\langle \mathbf{k}'|\langle\phi_A|PUP|\phi_A\rangle\mathbf{k}\rangle \equiv U_{el}(\mathbf{k}',\mathbf{k}) = \sum_{i=n,p} \langle \mathbf{k}'|\langle\phi_A|\hat{\tau}_{0i}(\mathcal{E})|\phi_A\rangle\mathbf{k}\rangle$$

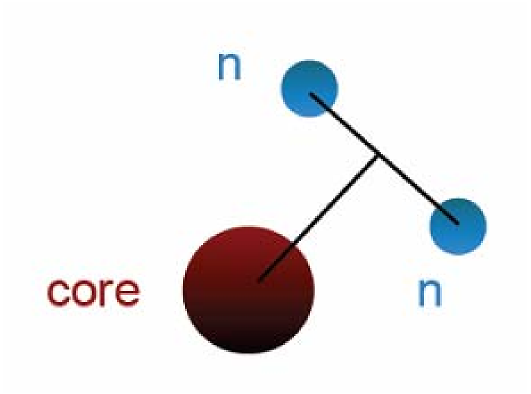
Proton scattering: $U_{el}(\mathbf{k}',\mathbf{k}) = Z\langle\hat{\tau}_{01}^{pp}\rangle + N\langle\hat{\tau}_{01}^{np}\rangle$

Optical Potential is non-local and depends on energy

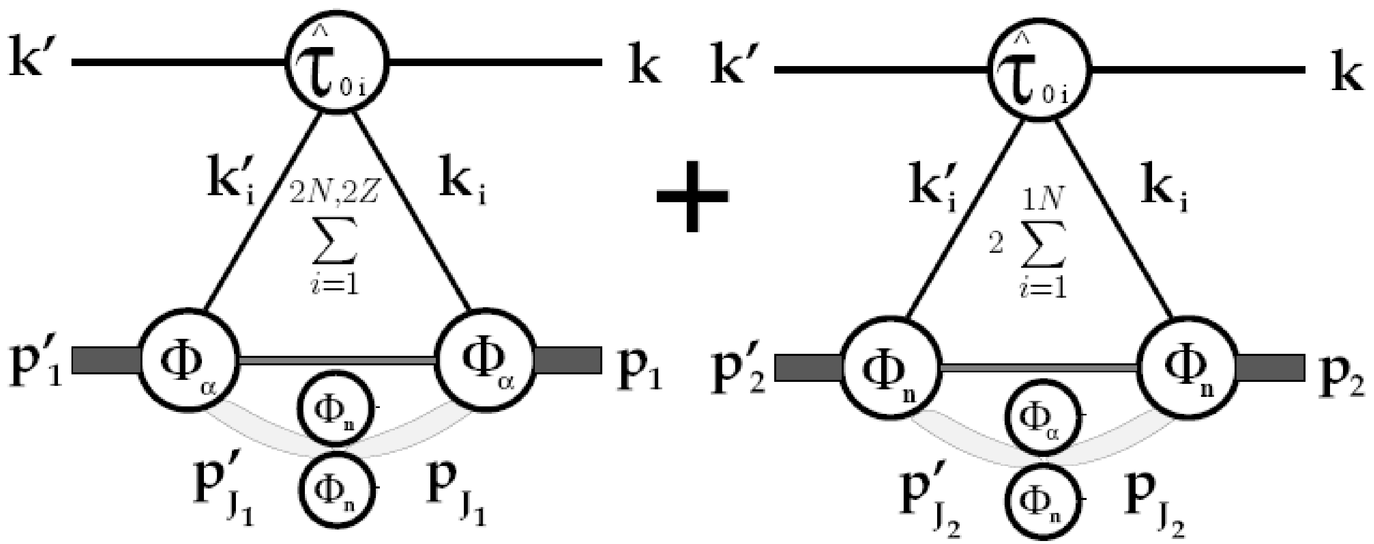
Off-shell NN t-matrix and nuclear density matrix

Halo Nuclei



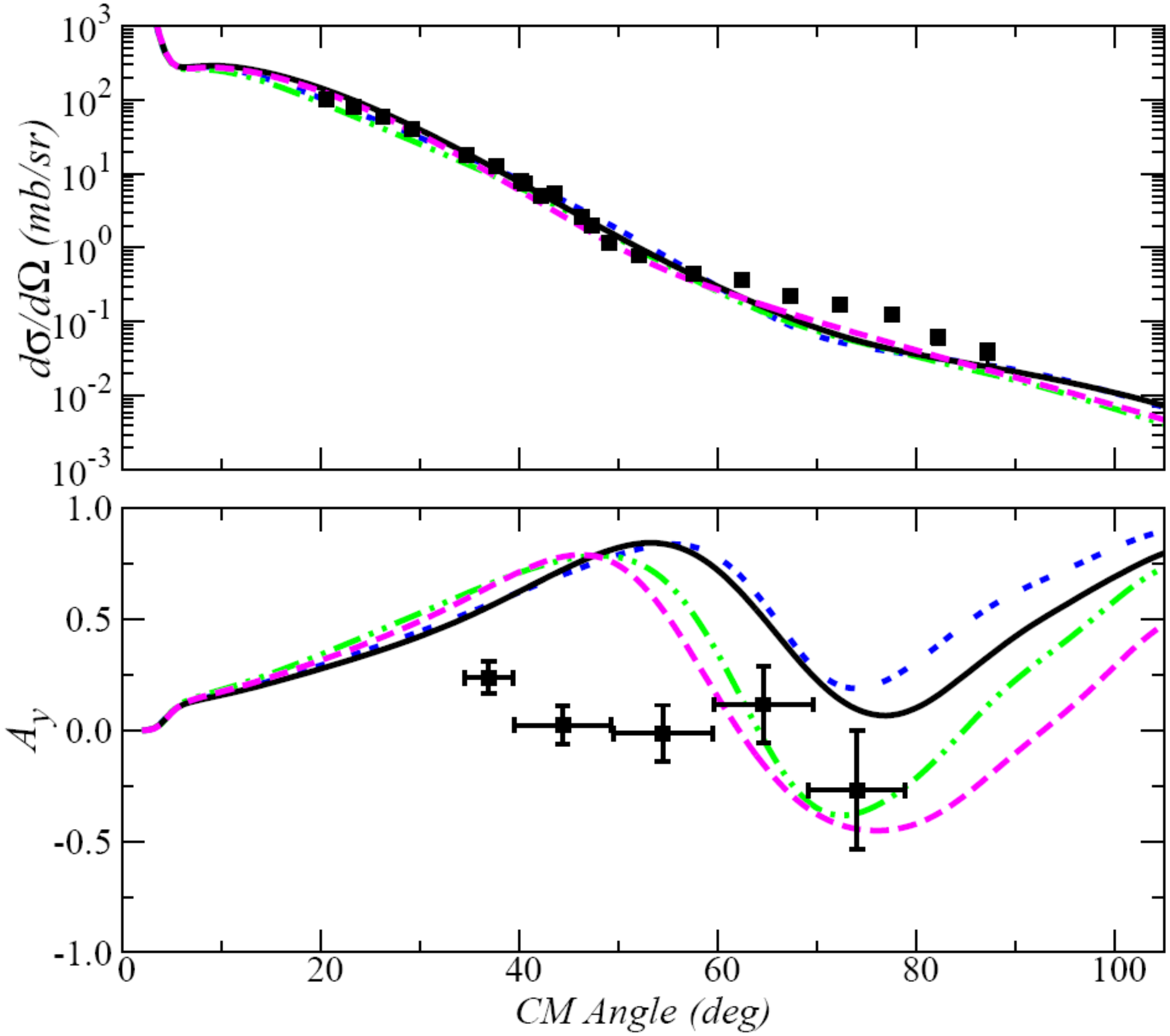


Optical Potential for ^{6}He as cluster α+n+n



^{6}He (p,p) ^{6}He @ 71 MeV

NN: Nijmegen II



COSMA single particle OP

COSMA cluster OP

α- HFB
n - COSMA

α - HFB
n – COSMA
no correlations

S.P. Weppner, Ch. Elster: Phys.Rev. C85 (2012) 044617

RIKEN: $^{6}He(p,p)^{6}He$

S. Sakaguchi et al.

arXiv: 1106.3903

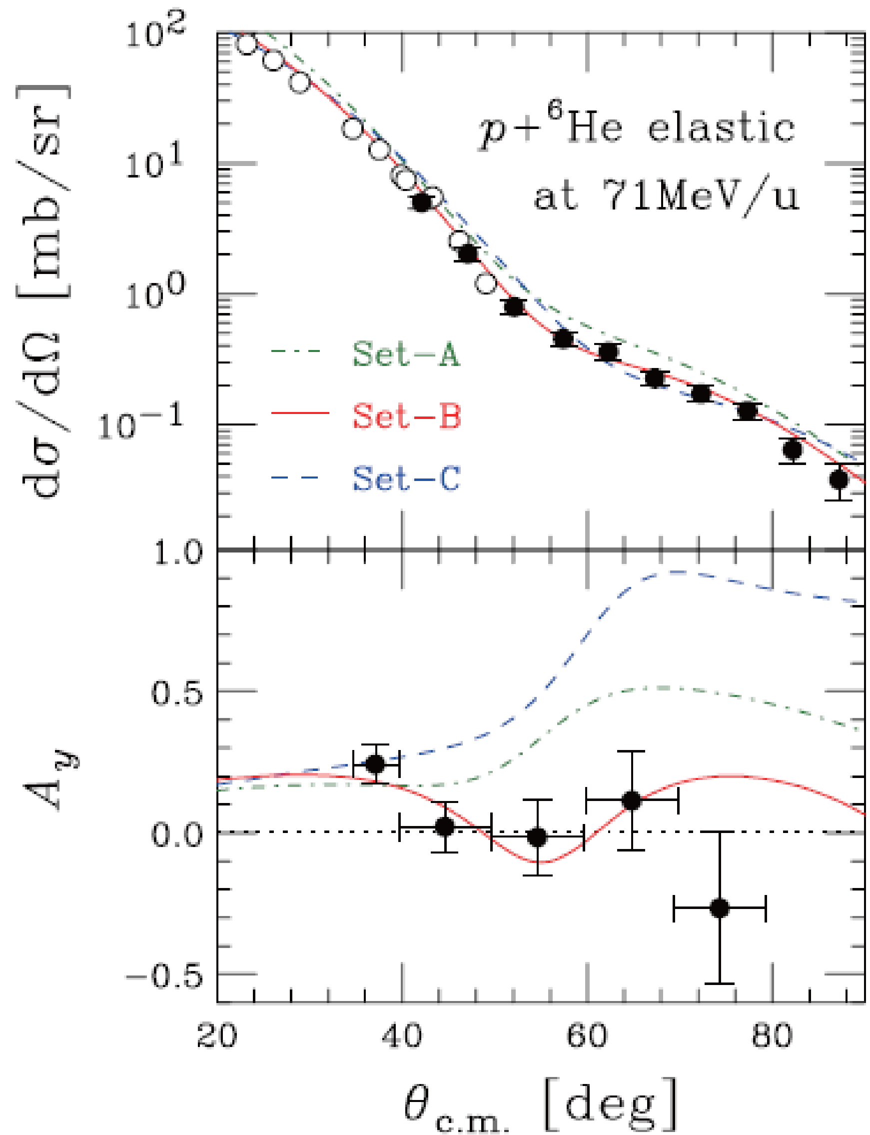
We adopted a standard Woods-Saxon optical potential with a spin-orbit term of the Thomas form:

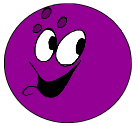
$$U_{\rm OM}(R) = -\ V_0\, f_r(R) - i\, W_0\, f_i(R) + 4i\, a_{id}\, W_d \frac{d}{dR} f_{id}(R) + V_s \frac{2}{R}\frac{d}{dR} f_s(R)\, \boldsymbol{L}\cdot\boldsymbol{\sigma}_p + V_{\rm C}(R) \quad (1)$$

with

$$f_x(R) = \left[1+\exp\left(\frac{R - r_{0x}A^{1/3}}{a_x}\right)\right]^{-1} \quad (2)$$

$$(x = r, i, id, \text{ or } s).$$





- 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)

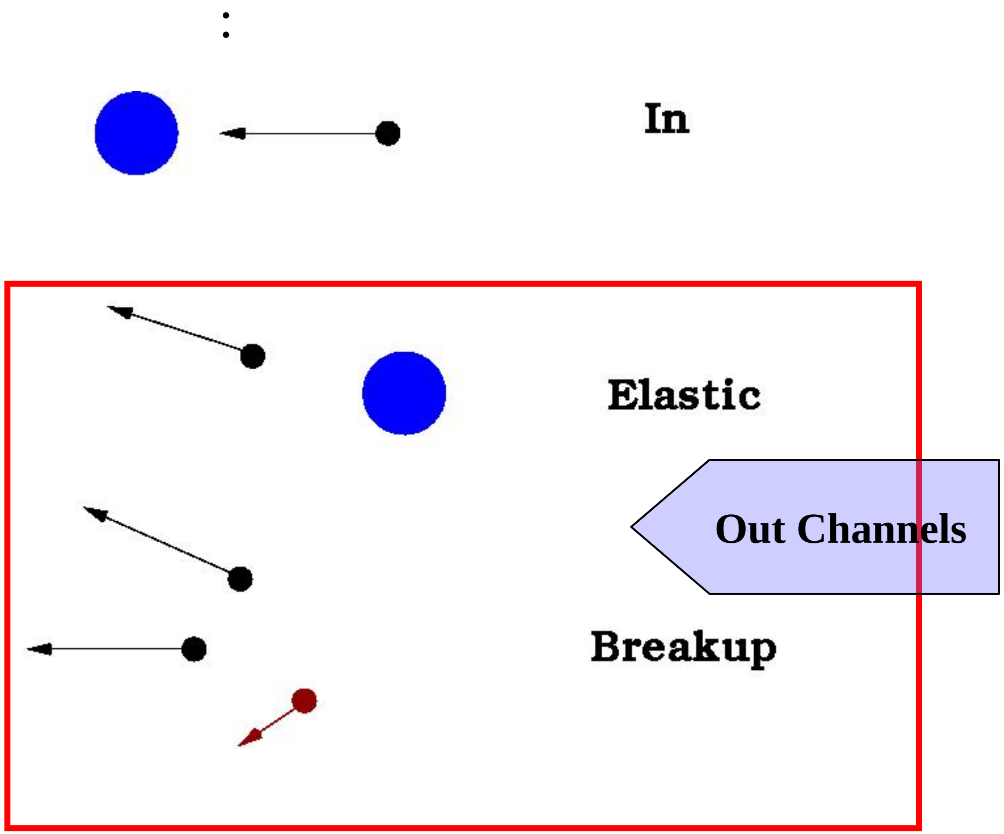
- Today one can start to explore **importance of open-shells in light exotic nuclei** (full complexity of the NN interactions enters) -- ongoing work

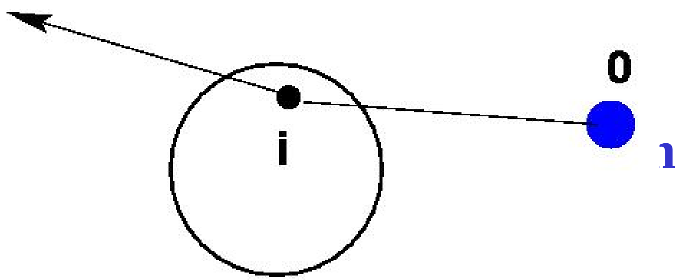
  Experimental relevance:

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

Again Single Scattering: (d,p) Reaction

p+d scattering



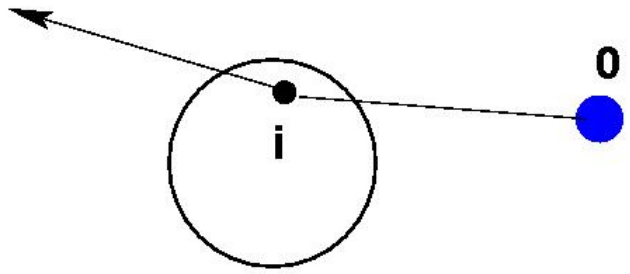


Single Scattering

Faddeev Formulation of (d,p) Reactions

Included in the goals of the TORUS collaboration

Faddeev Formulation of (d,p) Reactions



Single Scattering

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

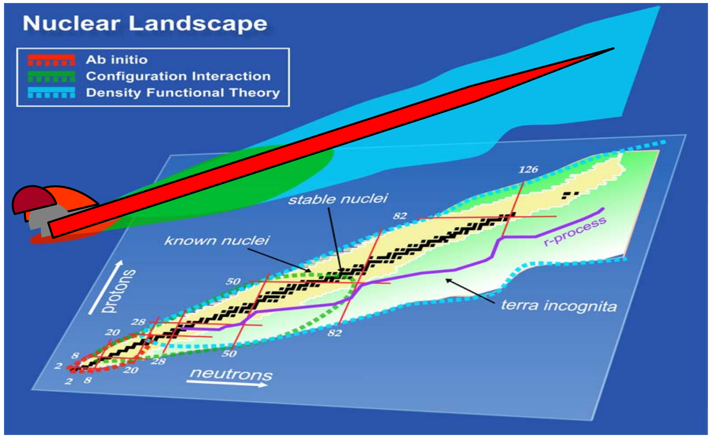
Necessary Extensions:

- Exitations of the nucleus must be allowed
- Careful treatment of the Coulomb force

Optical Potentials:

- **Phenomenological**
- **Capturing essential features, e.g. bound states, resonances**

Work in progress . . .



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.