INPP INSTITUTE OF NUCLEAR & PARTICLE PHYSICS @OHIO UNIVERSITY

Direct Reactions on Nuclei

Ch. Elster

PhD Thesis of L. Hlophe

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Supported by: U.S. Department of Energy

Department of physics + astronomy

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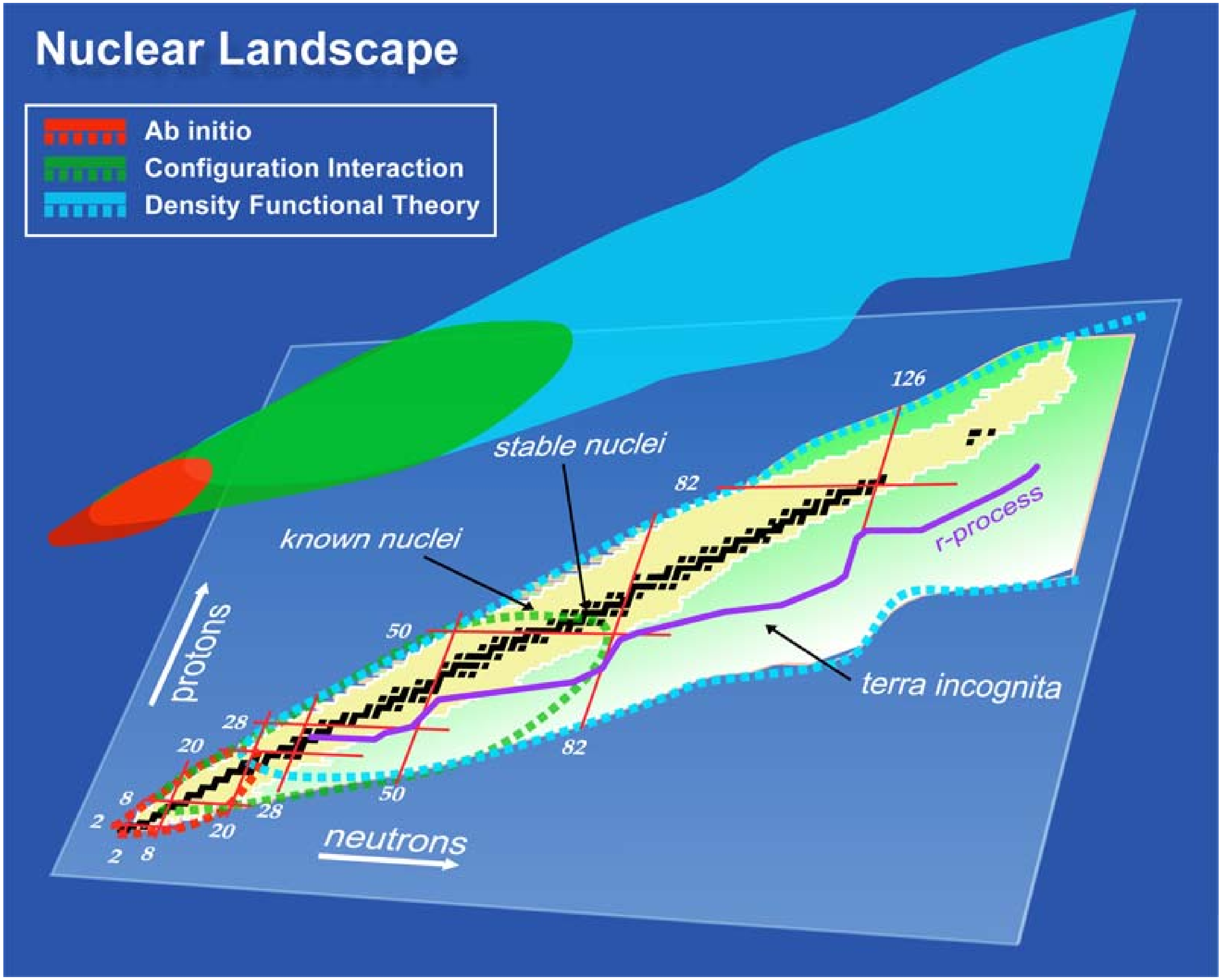
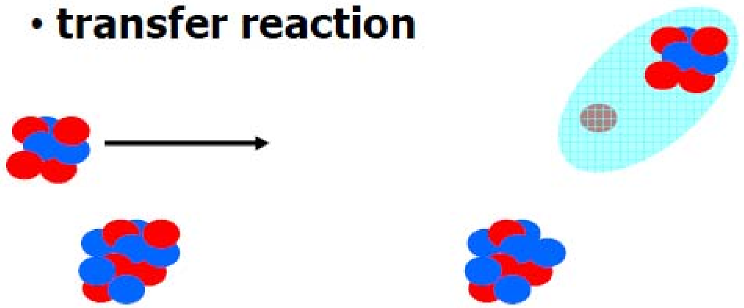


Nuclear Landscape
Ab initio
Configuration Interaction
Density Functional Theory
stable nuclei
known nuclei
r-process
terra incognita
protons
neutrons
126
82
50
28
20
8
2
82
50
28
20
8
2

Indirect Methods: Nuclear Reactions

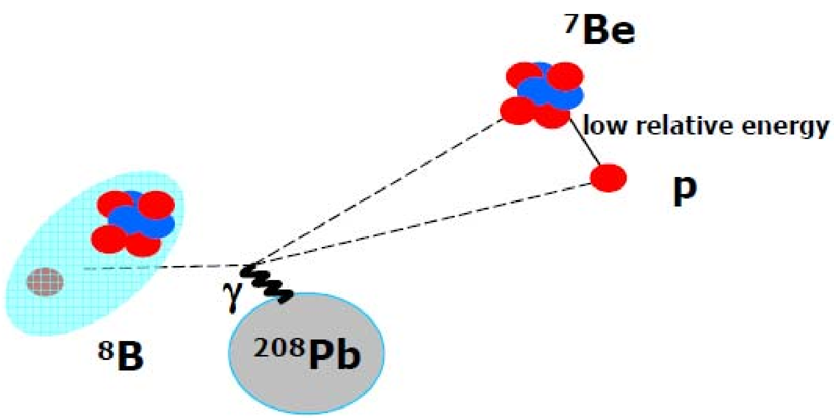
- direct measurement $^{7}Be(p,\gamma)^{8}B$

- transfer reaction



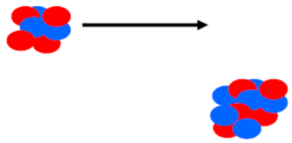
$^{14}N(^{7}Be,\ ^{8}B)^{13}C$

- Coulomb dissociation



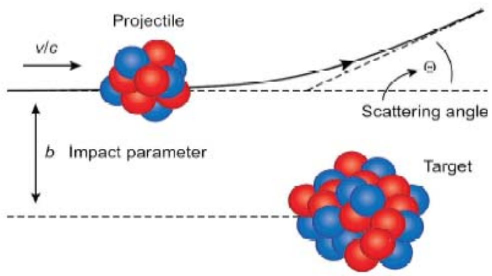
Why Reactions?

Elastic:



Traditionally used to extract optical potentials, rms radii, density distributions

Inlastic:



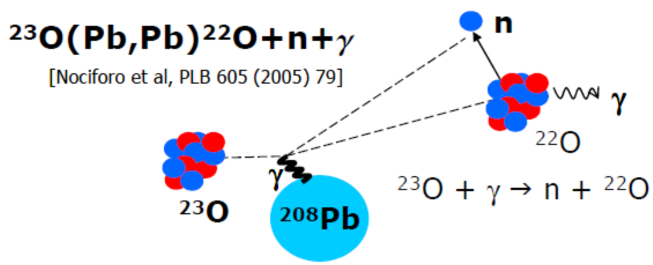
Traditionally used to extract electromagnetic transitions or nuclear deformations.

Transfer:

Traditionally used to extract spin, parity, spectroscopic factors
example: ^{132}Sn(d,p)^{133}Sn

Traditionally used to study two-nucleon correlations and pairing
example: ^{11}Li(p,t)^{9}Li

Breakup:



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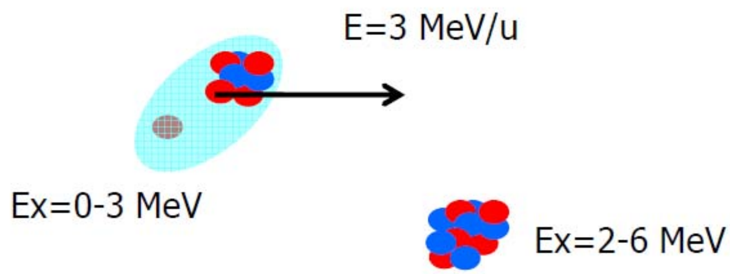
Theory Challenge:

In the continuum theory can solve the few-body problem exactly.

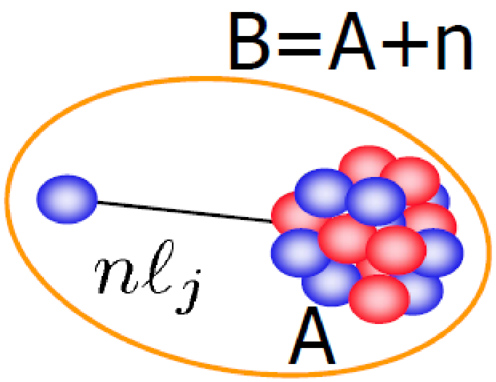
Reaction theories need to map onto the many-body problem!

It is not easy to develop effective field theories for reactions:



There is not always a clear separation of scales.

Often attempted meeting point between Structure and Reactions:



<u>overlap function</u>

$$I_{I_A:I_B}(\mathbf{r}) = \langle \Phi^A_{I_A}(\xi_A) | \Phi^B_{I_B}(\xi_A, \mathbf{r}) \rangle$$

spectroscopic factor (S_{nlj}):
norm of overlap function

Extracting spectroscopic factors can provide some handle on structure theory.

However: spectroscopic factors are not observables

Instead: asymptotic normalization coefficients

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Direct Reactions with Nuclei:

Dominated by few degrees of freedom

- Elastic & inelastic scattering
- Few-particle transfer (stripping, pick-up)
- Charge exchange
- Knockout

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

Many Body Problem ?

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

?

Task:

- **Isolate important degrees of freedom in a reaction**
- **Keep track of important channels**
- **Connect back to the many-body problem**

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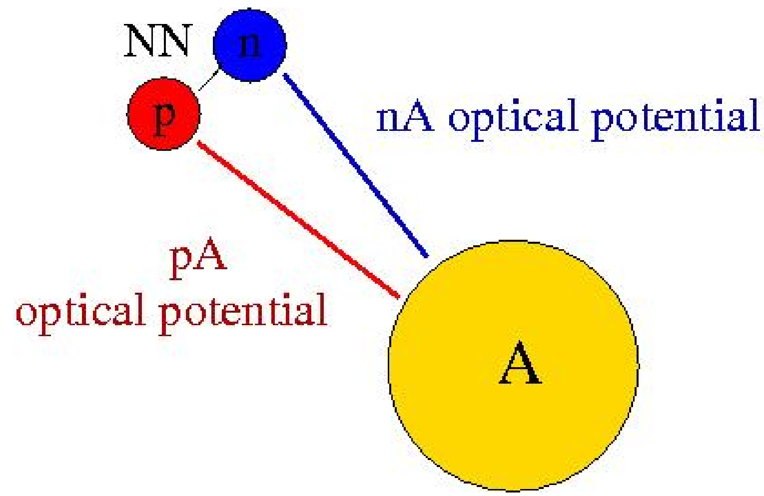
(d,p) Reactions: Effective Three-Body Problem

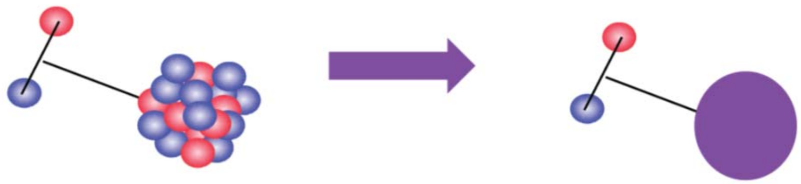
Hamiltonian for the effective few-body poblem:

$$H = H_0 + V_{np} + V_{nA} + V_{pA}$$



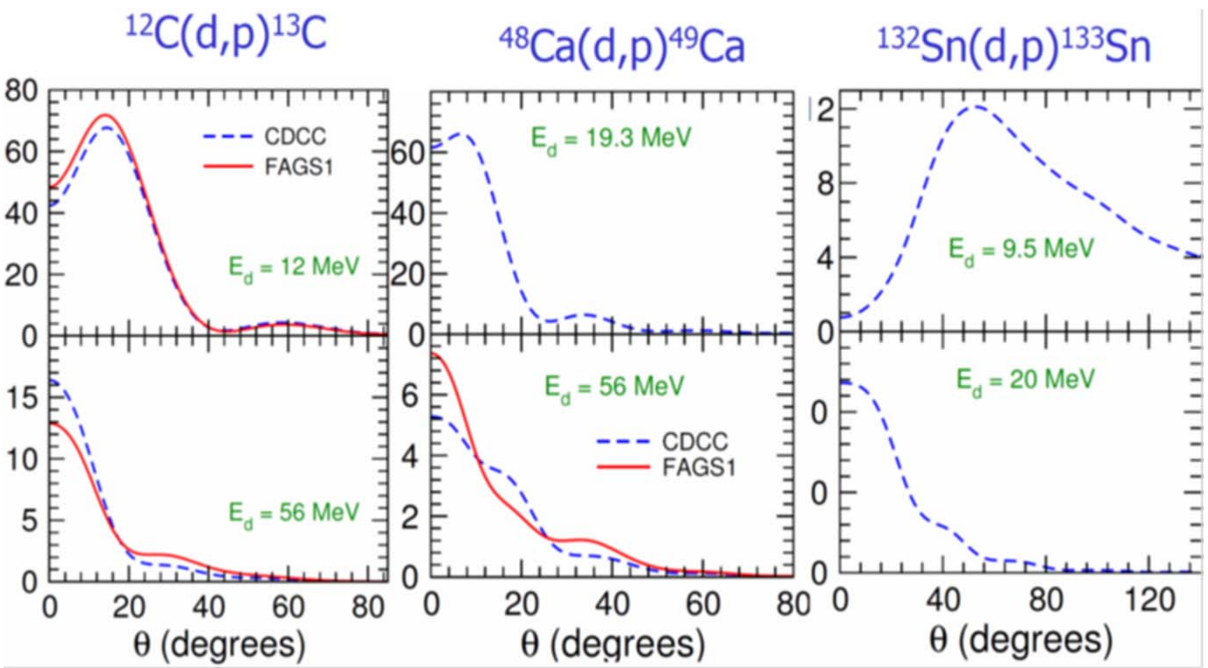
Many-body problem?

(d,p) Reactions as three-body problem



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

Elastic, breakup, rearrangement channels are included and fully coupled (compared to e.g. CDCC calculations)



Courtesy: F.M. Nunes

Issues:

- **current momentum space implementation of Coulomb interaction (shielding) does not converge for $Z \geq 20$**
- **CDCC and FAGS do not agree in breakup up**

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Generalization of Faddeev-AGS approach needed :

Theory: **A.M. Mukhamedzhanov, V.Eremenko and A.I. Sattarov**,
Phys.Rev. C86 (2012) 034001

Generalized Faddeev formulation of (d,p) reactions with:

(a) explicit inclusion of the Coulomb interaction (no screening)

(b) explicit inclusion of target excitations

Explicit inclusion of Coulomb interaction:
Formulation of Faddeev equations in Coulomb basis instead of plane waves
Needs: Formulation with separable interactions to avoid pinch singularities

Target excitations:
Including specific excited states
→ Formulation with separable interactions also useful.

Faddeev Equations in Coulomb Basis :

Three-body scattering state:

$$|\Psi\rangle = |\phi\rangle + \sum_{a=1}^{3} g_0^C(E) V_a^S |\Psi\rangle$$

$$g_0^C(E) = \left(E - H_0 - V_{pA}^C + i0\right)^{-1}$$

Faddeev components ψ_a

$$|\Psi\rangle \equiv \sum_a |\psi_a\rangle = \sum_a \underbrace{\delta_{a,1}|\phi_1\rangle + g_0^C(E) V_a^S |\Psi\rangle}_{|\psi_a\rangle}$$

e.g. $|\phi_1\rangle$ is initial state $A + (pn)$

Faddeev-type equations

$$\begin{cases} |\psi_1\rangle = |\phi_1\rangle + g_0^C(E) V_1^S \sum_a |\psi_a\rangle \\ |\psi_2\rangle = \qquad\qquad g_0^C(E) V_2^S \sum_a |\psi_a\rangle \\ |\psi_3\rangle = \qquad\qquad g_0^C(E) V_3^S \sum_a |\psi_a\rangle \end{cases} \Rightarrow \begin{cases} |\psi_1\rangle = |\phi_1\rangle + g_0^C(E) t_1 \sum_{a\neq 1} |\psi_a\rangle \\ |\psi_2\rangle = \qquad\qquad g_0^C(E) t_2 \sum_{a\neq 2} |\psi_a\rangle \\ |\psi_3\rangle = \qquad\qquad g_0^C(E) t_3 \sum_{a\neq 3} |\psi_a\rangle \end{cases}$$

proof of principle work is here

A(d,p)B Reaction using Coulomb Green's functions

Coulomb-modified Green's function

$$V^C = \frac{Z_1 Z_2 \alpha^2}{r} \qquad g_0^C \equiv [E - H_0 + i0 - V_{pA}^C]^{-1}$$

$$g_0^C = \frac{|\psi_{\mathbf{k},\eta}^C\rangle\langle\psi_{\mathbf{k},\eta}^C|}{E - \overline{H}_0 + i0}$$

* É.I.Dolinskiĭ and A.M.Mukhamedzhanov. Sov. J. of Nucl. Phys. **3** (1966), 180.
* C.R.Chinn *et al.* Phys. Rev. C **44** (1991), 1569.

All matrix elements must be calculated in the Coulomb basis

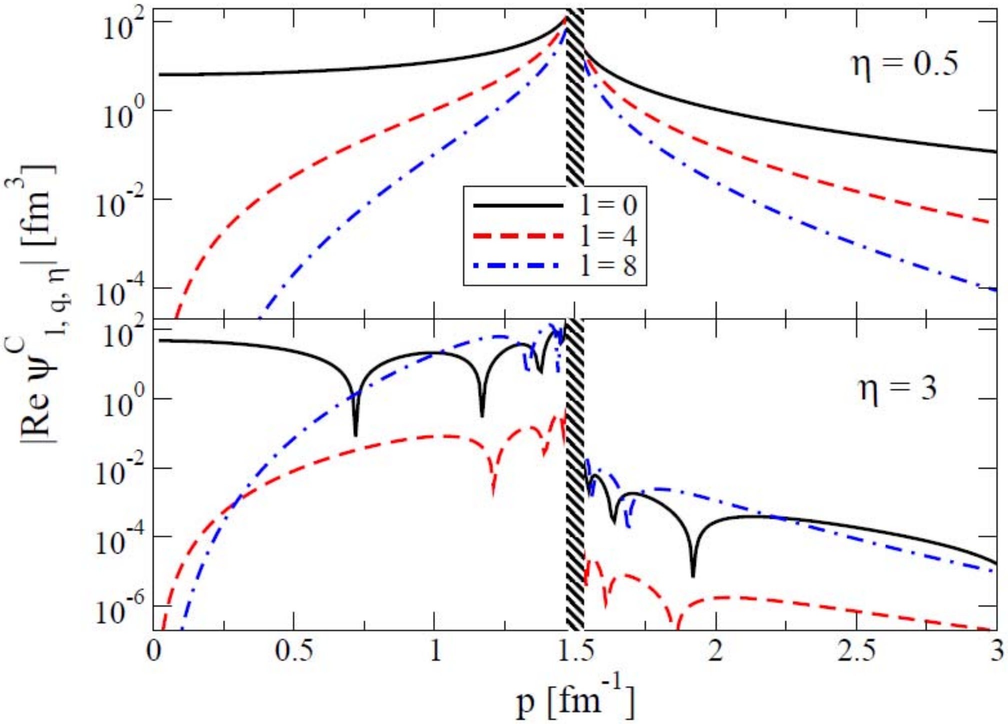
Not trivial !

Challenge: momentum space Coulomb functions

- 'Regular' representation for $p \neq k$.
- 'Pole-proximity' representation for $p \approx k$:

$$\psi^{C}_{l,k,\eta}(p) \sim \frac{1}{(p-k+i0)^{1+i\eta}}.$$

q = 1.5 fm^{-1}



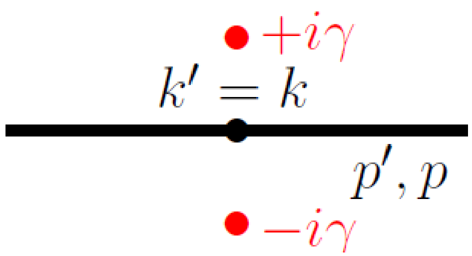
Eremenko *et al.* Comp. Phys. Comm. **187**, 195 (2015)

Challenge: Matrix elements in the Coulomb basis

$$t^C_{a,l}(k',k,E) = \int dp'\, dp\, \psi^C_{l,k',\eta'}(p')^\dagger\, t_{a,l}(p',p,E)\, \psi^C_{l,k,\eta}(p)$$

Pinch singularity in the elastic channel:

- $E = 2\mu k^2 = 2\mu k'^2$
- Since $\gamma \to +0$, singularities of $\psi^{C\dagger}_{l,k',\eta'}$ and $\psi^C_{l,k,\eta}$ are pinching the integration contour



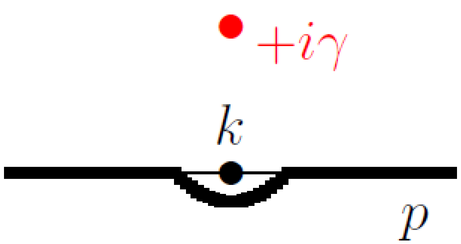
If t-matrix separable

$$t^C_l(k,k',E) = \sum_{zy} u^C_{l,z}(k)\, \lambda_{l,zy}(E)\, u^C_{l,y}(k')^\dagger$$

$$u^C_{l,z}(k) = \int \frac{dp\, p^2}{2\pi^2} u_{l,z}(p)\psi^C_{l,k,\eta}(p)^*$$

No pinch singularity!

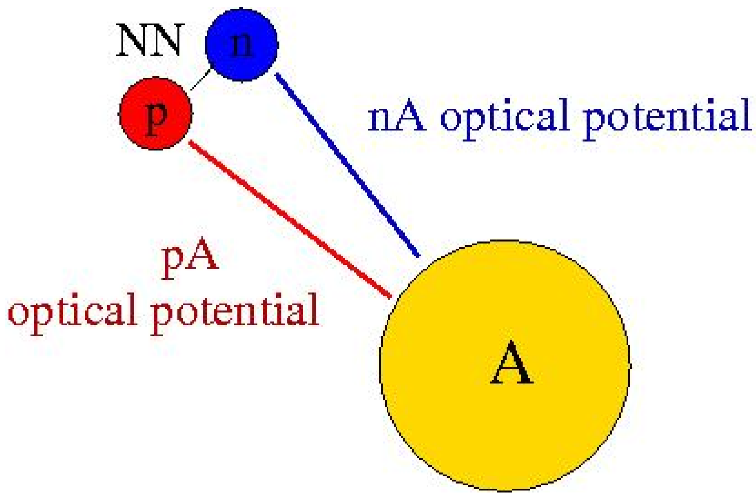
- Two independent integrals over p and p'
- Cauchy's theorem
- Numerical calculations use Gel'fand-Shilov regularization



Effective Three-Body Problem

Hamiltonian for effective three-body poblem:

$$H = H_0 + V_{np} + V_{nA} + V_{pA}$$



Needed:

Separable two-body transition matrices in all channels (NN, nA, pA)

Challenge:

pA and nA effective interactions

- are **complex** and **energy dependent**
- Vary considerably over mass regions of the nuclear chart
- Many nuclei are deformed, i.e. additional degrees of freedom (rotational,vibrational)

Starting point: Ernst-Shakin-Thaler (EST) representation

D. J. Ernst, C. M. Shakin, and R. M. Thaler, Phys.Rev. C9, 1780 (1974)

Separable expansion of Hermitian operator, V, in basis $\{|\psi_i\rangle\}$:

Projection operator: $P = \sum_i |\psi_i\rangle\langle\psi_i|$

Projecting V onto P-subspace yields $v = VP(PVP)^{-1}PV$

In the limit $P \longrightarrow 1$ we obtain $v = V$

EST scheme: choose basis vectors to be $|\psi_i^{(+)}\rangle$, the outgoing solutions of

$(H_0 + V)|\psi_i^{(+)}\rangle = E_i|\psi_i^{(+)}\rangle$, so that $v = \sum_{ij} V|\psi_i^{(+)}\rangle\lambda_{ij}\langle\psi_j^{(+)}|V$

$$\text{Constraints} \Rightarrow \delta_{kj} = \sum_i \langle\psi_k^{(+)}|V|\psi_i^{(+)}\rangle\lambda_{ij}$$

$$\delta_{ik} = \sum_j \lambda_{ij}\langle\psi_j^{(+)}|V|\psi_k^{(+)}\rangle$$

Constraints ensure that at EST support points, E_i, wavefunctions corresponding to v and V are identical

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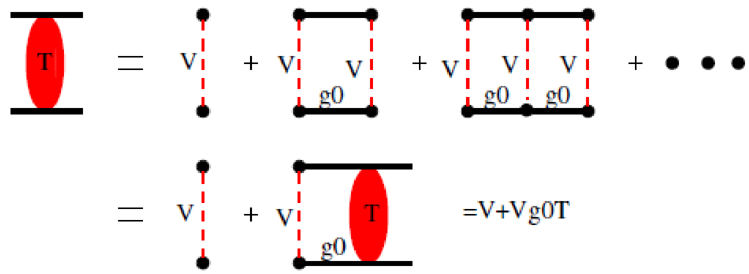
Explicit Construction in Momentum Space:

1. Form factor (half-shell t-matrix): $T(E)|k_i\rangle \equiv V|\psi^{(+)}\rangle$ given by LS equation



2. Separable t-matrix elements are given by

$$\langle k'|t(E)|k\rangle = \sum_{ij} \langle k'|V|\psi_i^{(+)}\rangle \tau_{ij}(E) \langle \psi_j^{(-)}|V(E_j)|k\rangle$$

$$\tau_{ij}^{-1}(E) = \langle \psi_i^{(-)}|V(E_i)|\psi_j^{(+)}\rangle - \langle \psi_i^{(-)}|V(E_i) g_0(E) V(E_j)|\psi_j^{(+)}\rangle$$

Choosing scattering wave functions as basis is easy in momentum space

Evaluating $\tau_{ij}^{-1}(E)$ involves only integrals over half-shell t-matrices, numerically straightfoward

Quite different from the original EST work in coordinate space!

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Complex potentials

(L. Hlophe, *et al.* Phys. Rev. C88, 064608 (2013))

Given a time-reversal operator, $\mathcal{K}$, reciprocity is fulfilled if

$$\mathcal{K} v \mathcal{K}^\dagger = v^\dagger$$

Separable potential v does not satisfy this relation for complex potentials

Remedy: use 'in' states $|\psi_i^{(-)}\rangle$, eigenstates of $H' = H_0 + V^*$

For non-Hermitian potential V: $v = \sum_{ij} V|\psi_i^{(+)}\rangle \lambda_{ij} \langle \psi_j^{(-)}|V$

Constraints $\Rightarrow$ $\delta_{kj} = \sum_i \langle \psi_k^{(-)}|V|\psi_i^{(+)}\rangle \lambda_{ij}$

$$\delta_{ik} = \sum_j \lambda_{ij} \langle \psi_j^{(-)}|V|\psi_k^{(+)}\rangle$$

v fulfills reciprocity since λ is symmetric, i.e. $\lambda_{ij} = \lambda_{ji}$

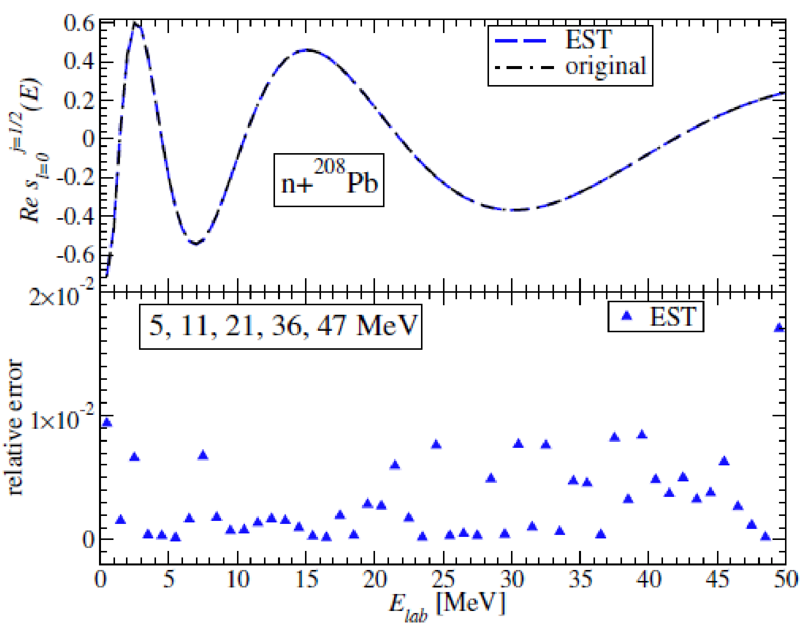
t-matrix: $t(E) = \sum_{ij} V|\psi_i^{(+)}\rangle \tau_{ij}(E) \langle \psi_j^{(-)}|V$

Highlights for n-A potential: general set of EST support points

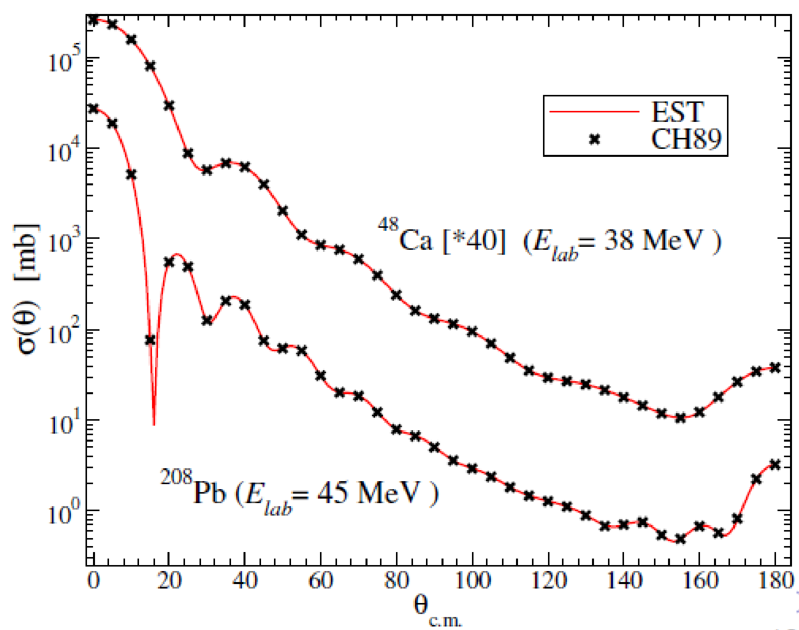
system	partial wave(s)	rank	EST support point(s) [MeV]
n+^{48}Ca	$l \geq 10$	1	40
	$l \geq 8$	2	29, 47
	$l \geq 6$	3	16, 36, 47
	$l \geq 0$	4	6, 15, 36, 47
n+^{132}Sn and n+^{208}Pb	$l \geq 16$	1	40
	$l \geq 13$	2	35, 48
	$l \geq 11$	3	24, 39, 48
	$l \geq 6$	4	11, 21, 36, 45
	$l \geq 0$	5	5, 11, 21, 36, 47 ⟵ Universal set

These EST support points provide good description of the s-matrices and cross sections from 0 to 50 MeV

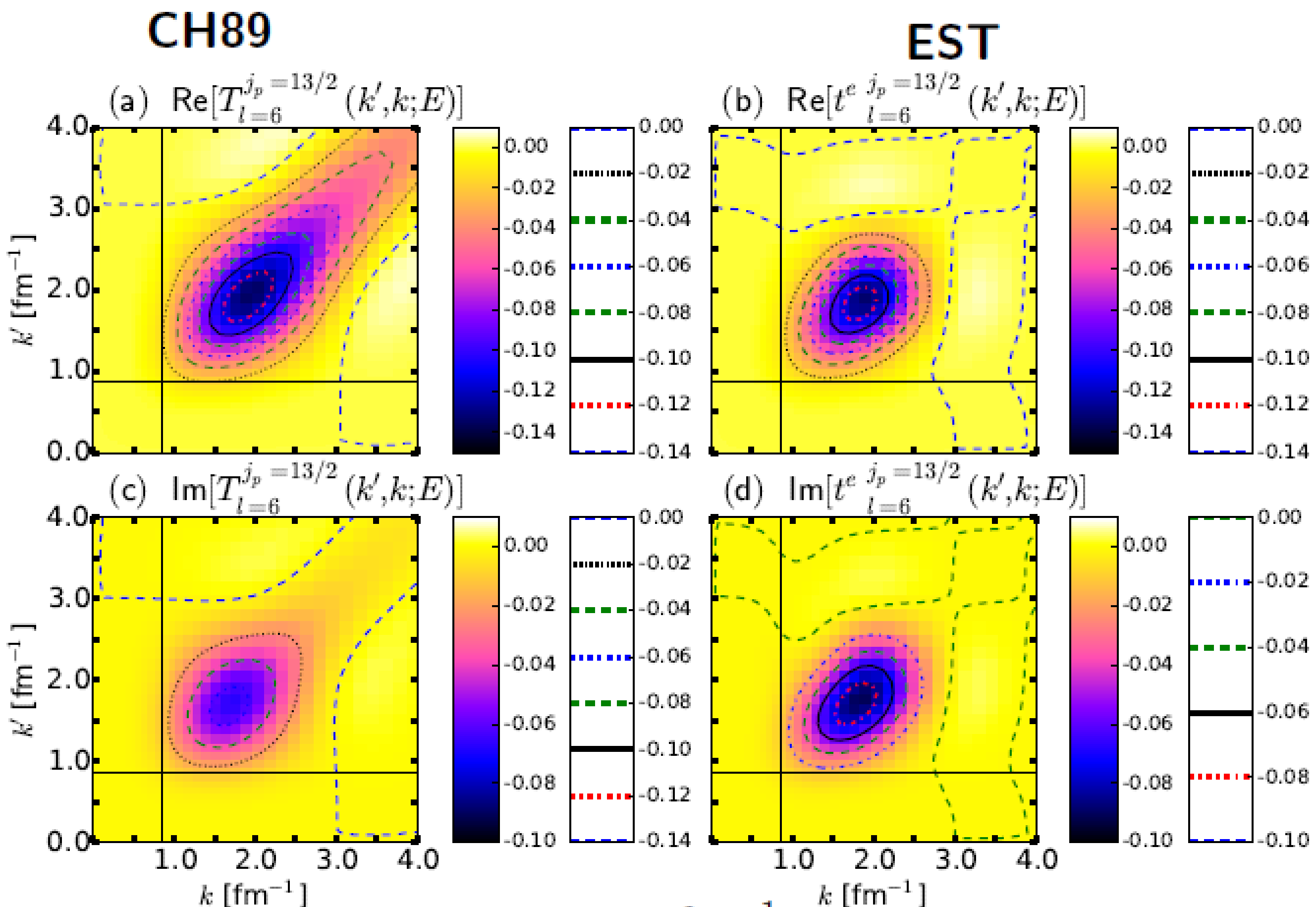
Elastic scattering s-matrix



Differential cross section



Off shell t-matrix: n+^{48}Ca, $l = 6$, $E_{lab} = 16$ MeV



$k_0 = 0.86\ \text{fm}^{-1}$

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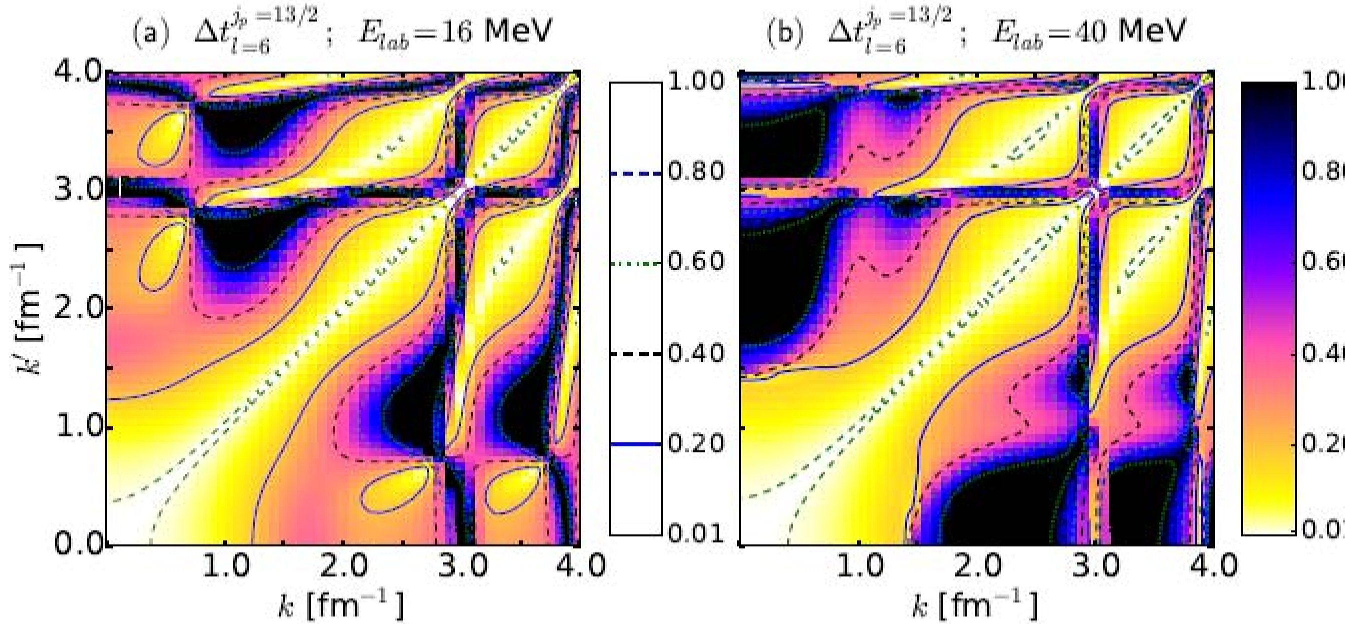
Off-shell t-matrix

Asymmetry: $\Delta t_l^{j_p}(k', k; E) = \left| \frac{t_l^{j_p}(k',k;E) - t_l^{j_p}(k,k';E)}{[t_l^{j_p}(k',k;E) + t_l^{j_p}(k,k';E)]/2} \right|$



Not completely symmetric!

Complex, energy dependent potentials

L. Hlophe et al. PRC 93, 034601 (2016)

Revisit: EST Constraints $\Rightarrow \delta_{kj} = \sum_i \langle \psi_k^{(-)} | V(E_i) | \psi_i^{(+)} \rangle \lambda_{ij}$

$$\delta_{ik} = \sum_j \lambda_{ij} \langle \psi_j^{(-)} | V(E_k) | \psi_k^{(+)} \rangle$$

Energy dependence of V breaks symmetry: $\lambda_{ij} \neq \lambda_{ji} \Rightarrow$ violation of reciprocity

New: Energy dependent EST (eEST)

Define $v(E) = \sum_{ij} V(E_i) | \psi_i^+ \rangle \lambda_{ij}(E) \langle \psi_j^- | V(E_j)$

Constraint $\Rightarrow \langle \psi_m^- | V(E) | \psi_n^+ \rangle = \langle \psi_m^- | v(E) | \psi_n^+ \rangle$

$$\Downarrow$$

Matrix elements of $v(E)$ and $V(E)$ are identical at all energies

Both EST constraints are satisfied and $\lambda_{ij} = \lambda_{ji}$

EST vs eEST separable representation

- EST and eEST schemes have same form factors
- Evaluation of $\tau_{ij}(E)$ is different

  EST:

  $$R(E) \cdot \tau(E) \equiv \mathbf{1}$$

  $$R_{ij}(E) = \langle \psi_i^- | V(E_i) | \psi_j^+ \rangle - \langle \psi_i^- | V(E_i) g_0(E) V(E_j) | \psi_j^+ \rangle$$

  eEST:

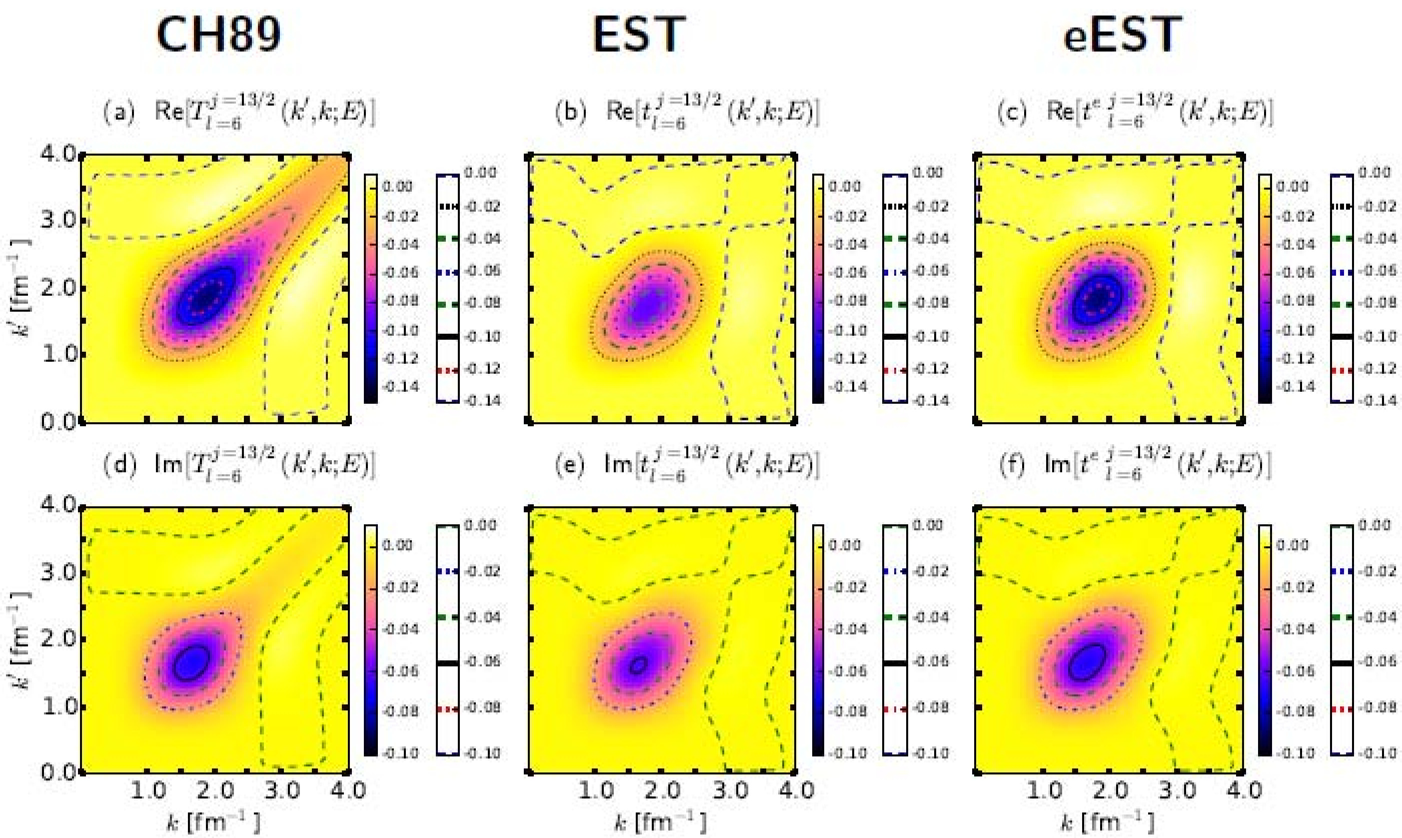
  $$R(E) \cdot \tau(E) \equiv \mathcal{M}(E)$$

  $$R_{ij}(E) = \langle \psi_i^- | V(E_i) | \psi_j^+ \rangle - \sum_n \mathcal{M}_{in}(E) \langle \psi_n^- | V(E_n) g_0(E) V(E_j) | \psi_j^+ \rangle$$

- For energy independent potentials $\mathcal{M}_{in}(E) = \delta_{in}$ then EST and eEST schemes are identical

On-shell: no visible difference

Off shell t-matrix: $n+^{48}$Ca, $l=6$, $E_{lab}=16$ MeV

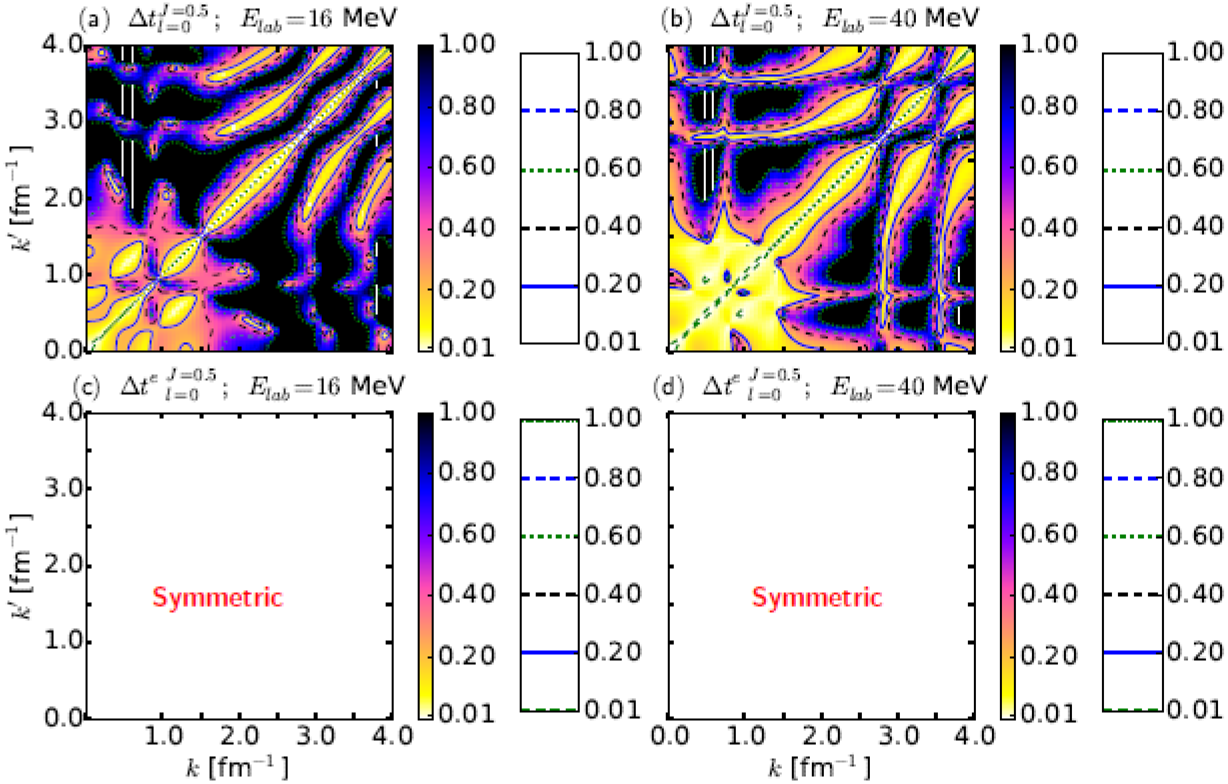


- t-matrix in [fm^2], on shell momentum at $k_0 = 0.86$ fm^{-1}

$$\text{Asymmetry: } \Delta t_l^{jp}(k',k;E) = \left| \frac{t_l^{jp}(k',k;E) - t_l^{jp}(k,k';E)}{[t_l^{jp}(k',k;E) + t_l^{jp}(k,k';E)]/2} \right|$$

EST

eEST



- On shell momentum: $k_0 = 0.86$ fm^{-1} at 16 MeV,
  $k_0 = 1.36$ fm^{-1} at 40 MeV

EST and eEST schemes for proton-nucleus scattering

(L. Hlophe, *et al.*, Phys. Rev. **C90**, 061602 (2014))

(1) Coulomb-distorted nuclear scattering states, $|\psi_i^{sc(+)}\rangle$ are used in the separable expansion

(2) Free propagator $g_0(E) = (E - H_0 + i\varepsilon)^{-1}$ replaced by Coulomb Green's function $g_c(E) = (E - H_0 - V^c + i\varepsilon)^{-1}$

♦ Separable t-matrix becomes

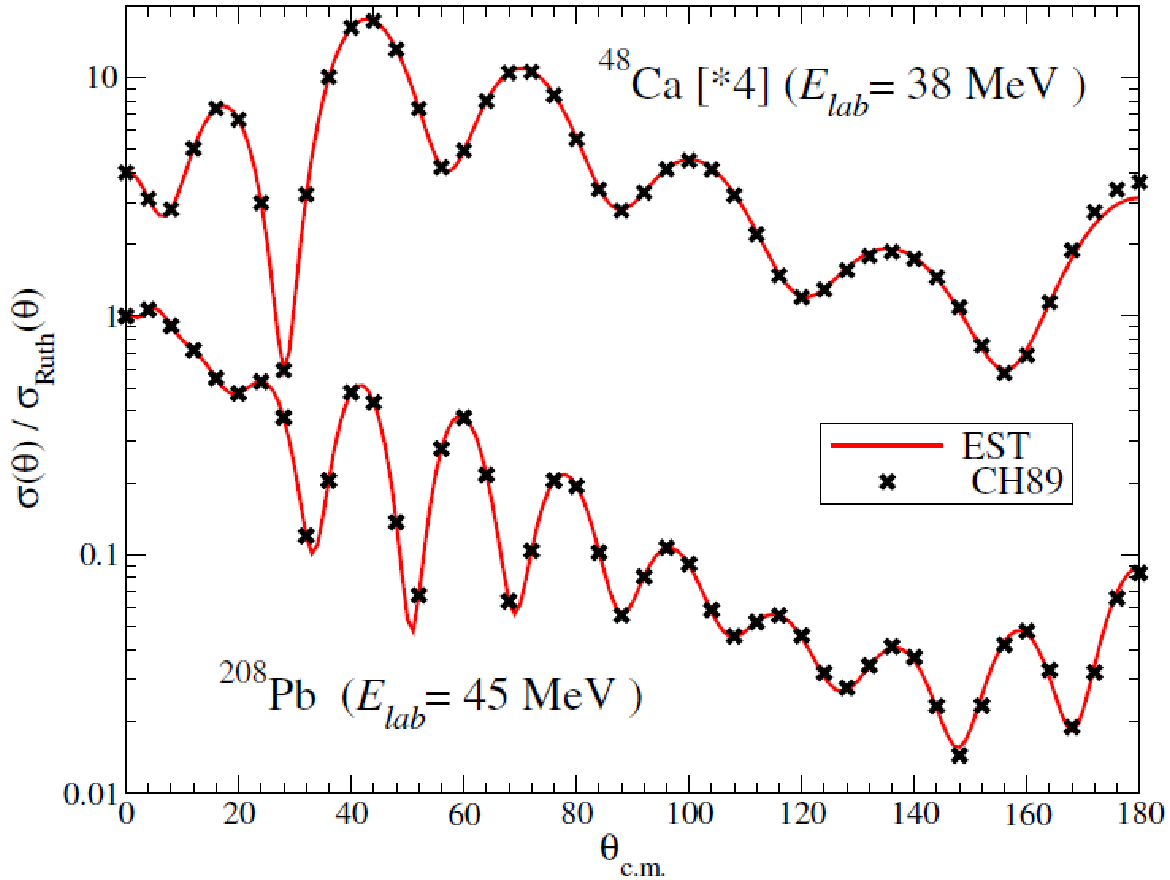
$$t^{sc}(E) = \sum_{ij} V^s(E_i)|\psi_i^{sc(+)}\rangle \tau_{ij}^c(E) \langle \psi_j^{sc(-)}|V^s(E_j)$$

■ Form factor $V^s(E_i)|\psi_i^{sc(+)}\rangle \equiv T_l^{sc}(E)|\phi_{lk_0}^c\rangle$ evaluated from

$$\begin{aligned}\langle \phi_{lk}^c|T_l^{sc}(E)|\phi_{lk_0}^c\rangle &= \langle \phi_{lk}^c|U_l^{sc}|\phi_{lk_0}^c\rangle + \int dpp^2\ \langle \phi_{lk}^c|U_l^{sc}|\phi_{lp}^c\rangle \\ &\times\ \langle \phi_{lp}^c|g_c(E)|\phi_{lp}^c\rangle\ \langle \phi_{lp}^c|T_l^{sc}(E)|\phi_{lk_0}^c\rangle\end{aligned}$$

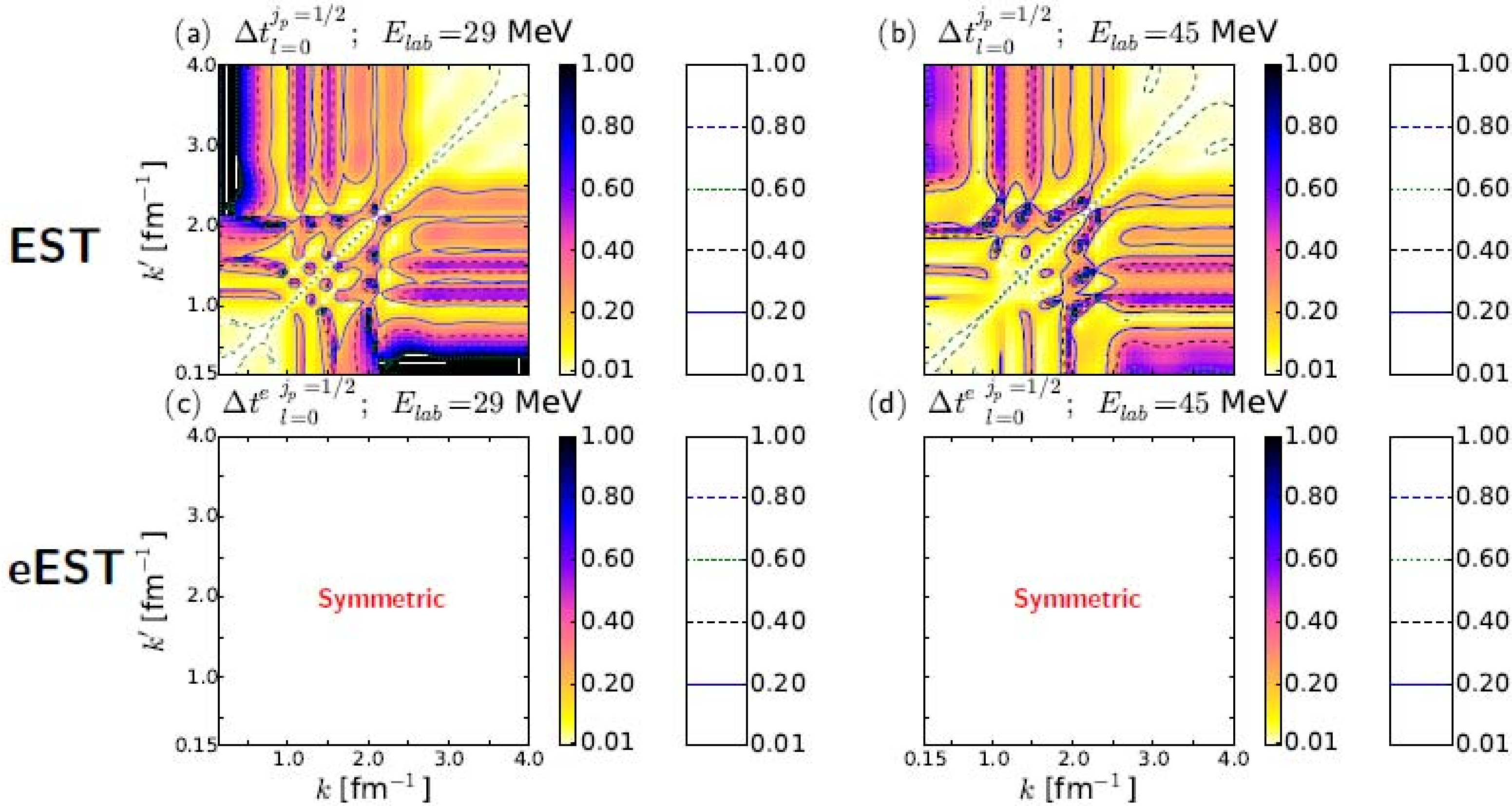
[Ch. Elster *et al.*, J.Phys. **G19**, 2123 (1993)]

Proton-nucleus differential cross section



General set of EST support points also valid for $p+$A optical potentials

Off shell t-matrix: $p+^{208}$Pb208, $l = 0$



- On shell momentum: $k_0 = 0.96$ fm^{-1} at 16 MeV,
  $k_0 = 1.36$ fm^{-1} at 40 MeV

Excitations of Nucleus: Multichannel Separable Potentials

- EST form factors become the multichannel half-shell t-matrices $T^J_{\alpha_0\rho}(E_i)\left|\phi_{l_\rho k_i^\rho}\right\rangle$
- Requires solutions of the multichannel t-matrix LS equation
- Multichannel separable t-matrix

$$t^J_{\alpha_0\alpha}(E) = \sum_{\rho\sigma}\sum_{ij} T^J_{\alpha_0\rho}(E_i)\left|\phi_{l_\rho k_i^\rho}\right\rangle \tau^{\rho\sigma}_{ij}(E)\left\langle\phi_{l_\sigma k_j^\sigma}\right| T^J_{\sigma\alpha}(E_j)$$

where $\tau^{\rho\sigma}_{ij}(E)$ is defined by

$$R(E)\cdot\tau(E) = \mathcal{M}(E),$$

$$\begin{aligned} R^{\rho\sigma}_{ij}(E) \;=\; & \left\langle\phi_{l_\rho k_i^\rho}\right| T^J_{\rho\sigma}(E_i) + \sum_{\beta} T^J_{\rho\beta}(E_i) G_\beta(E_j) T^J_{\beta\sigma}(E_j)\left|\phi_{l_\sigma k_j^\sigma}\right\rangle \\ & - \sum_{\beta\beta'}\sum_{n} \mathcal{M}^{\rho\beta}_{in}(E)\langle\phi_{l_\beta k_n^\beta}\left| T^J_{\beta\beta'}(E_n) G_{\beta'}(E) T^J_{\beta'\sigma}(E_j)\right|\phi_{l_\sigma k_j^\sigma}\rangle \end{aligned}$$

Neutron Scattering from a deformed nucleus

- Deformed nuclei possess rotational excitation levels
- During a scattering process the low-lying rotational levels couple strongly to the ground state
- Employ a deformed optical model potential (DOMP)

$$R(\theta) = R_0\left(1 + \sum_{\lambda\neq 0} \delta_\lambda Y_\lambda^0(\theta, 0)\right)$$

- DOMP is expanded in multipoles

$$\hat{U}(r,\theta) = \sum_\lambda \sqrt{4\pi} U_\lambda(r) Y_\lambda^0(\theta, 0)$$

$$U_\lambda(r) = \sqrt{\pi} \int_{-1}^{1} d\cos\theta \, \hat{U}(\tilde{r}) Y_\lambda^0(\theta, 0)$$

Olsson 89 DOMP: n+^{12}C scattering

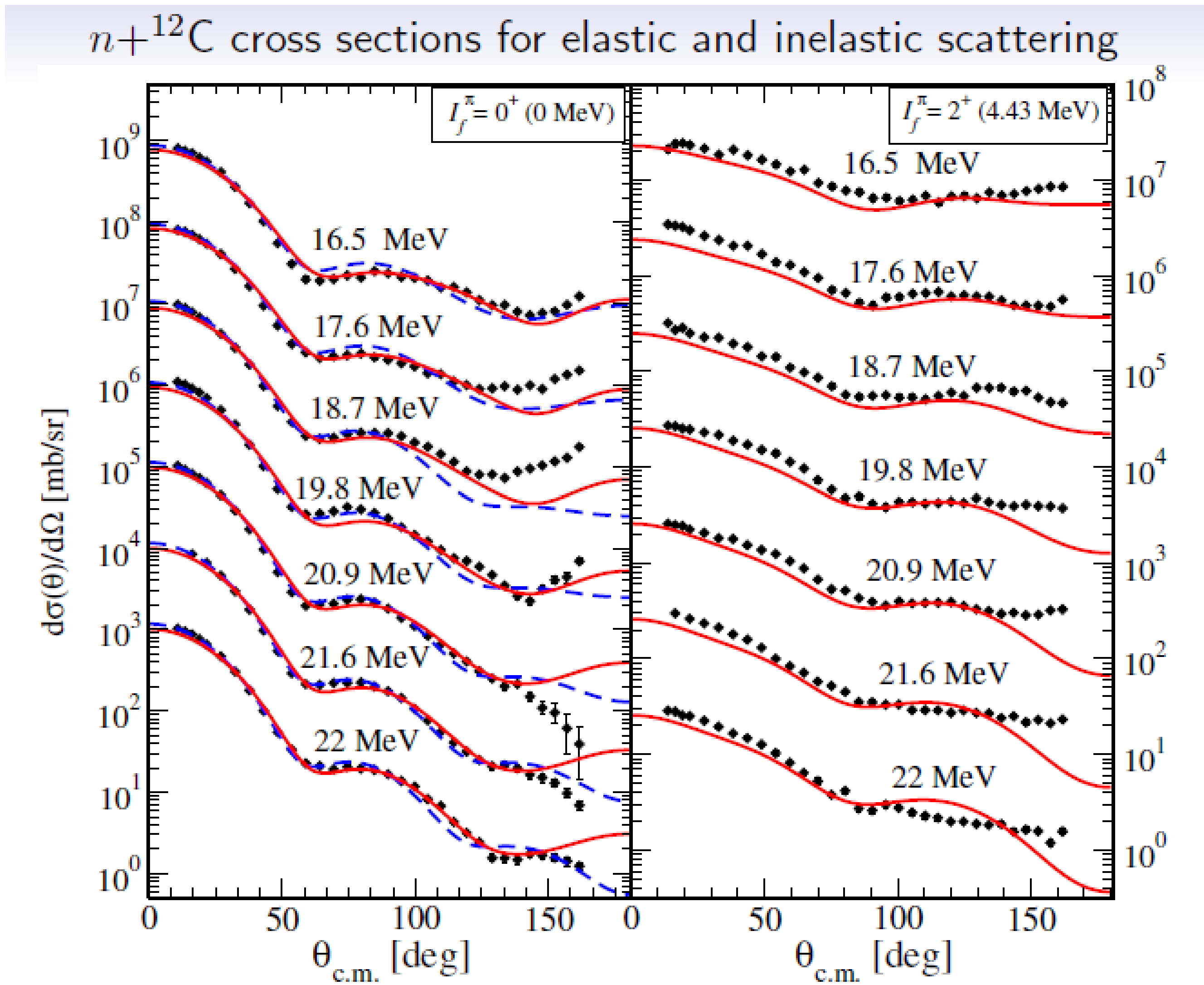
- ^{12}C rotational band: $I^\pi = 0^+,\ 2^+,\ 4^+,\ \ldots$
- Scattering processes: elastic $0^+ \longrightarrow 0^+$ and inelastic scattering $0^+ \longrightarrow 2^+$
- Olsson 89 DOMP n+^{12}C fitted to elastic and inelastic scattering data

  [B. Olsson,*et al.*, Nucl. Phys. **A469**, 505, (1989).]

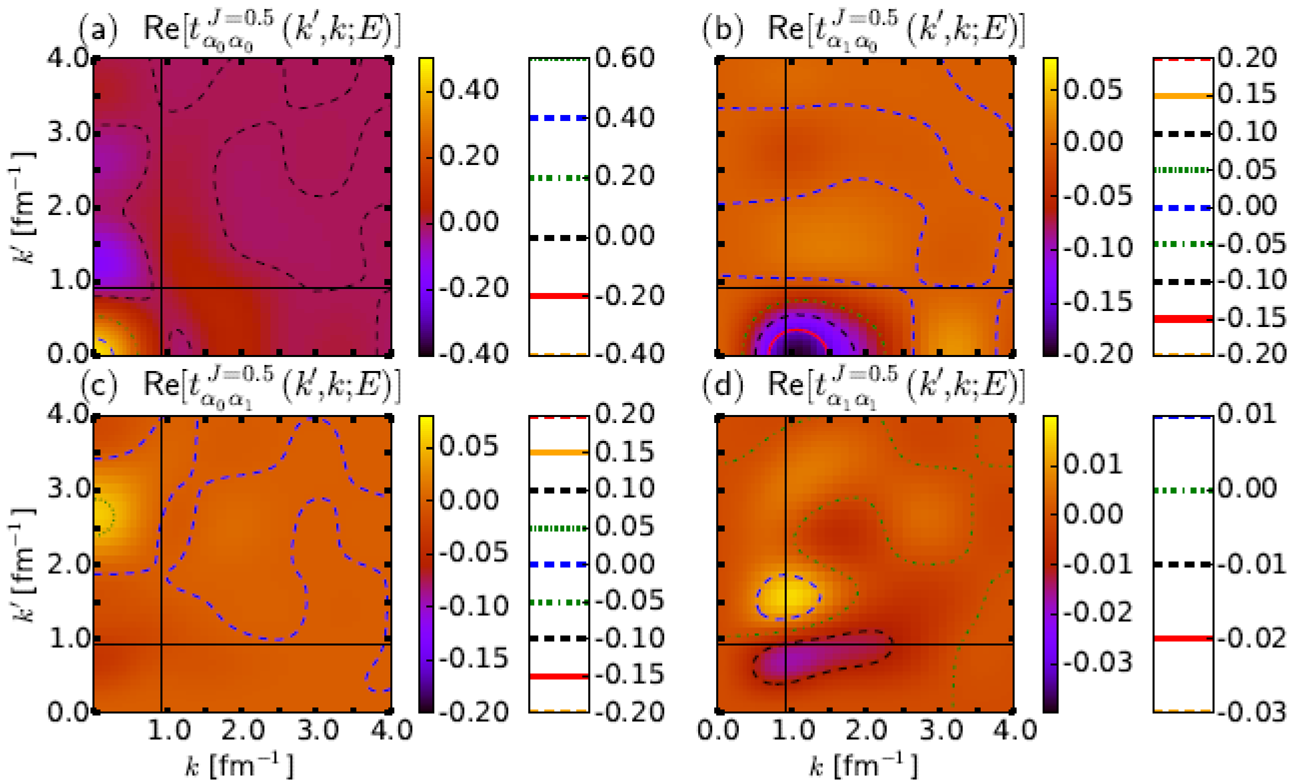
- Parameters:

Strength [MeV]	Radius [fm]	Diffusiveness [fm]
$V_r = 64.02 - 0.674E_n$	$R_r = 1.093A^{1/3}$	$a_r = 0.619$
$W_s = 1.16 + 0.251E_n$	$R_r = 1.319A^{1/3}$	$a_s = 0.327$
$V_{so} = 6.2$	$R_r = 1.050A^{1/3}$	$a_{so} = 0.550$

Reproduced the Olsson calculations with an eEST separable representation:

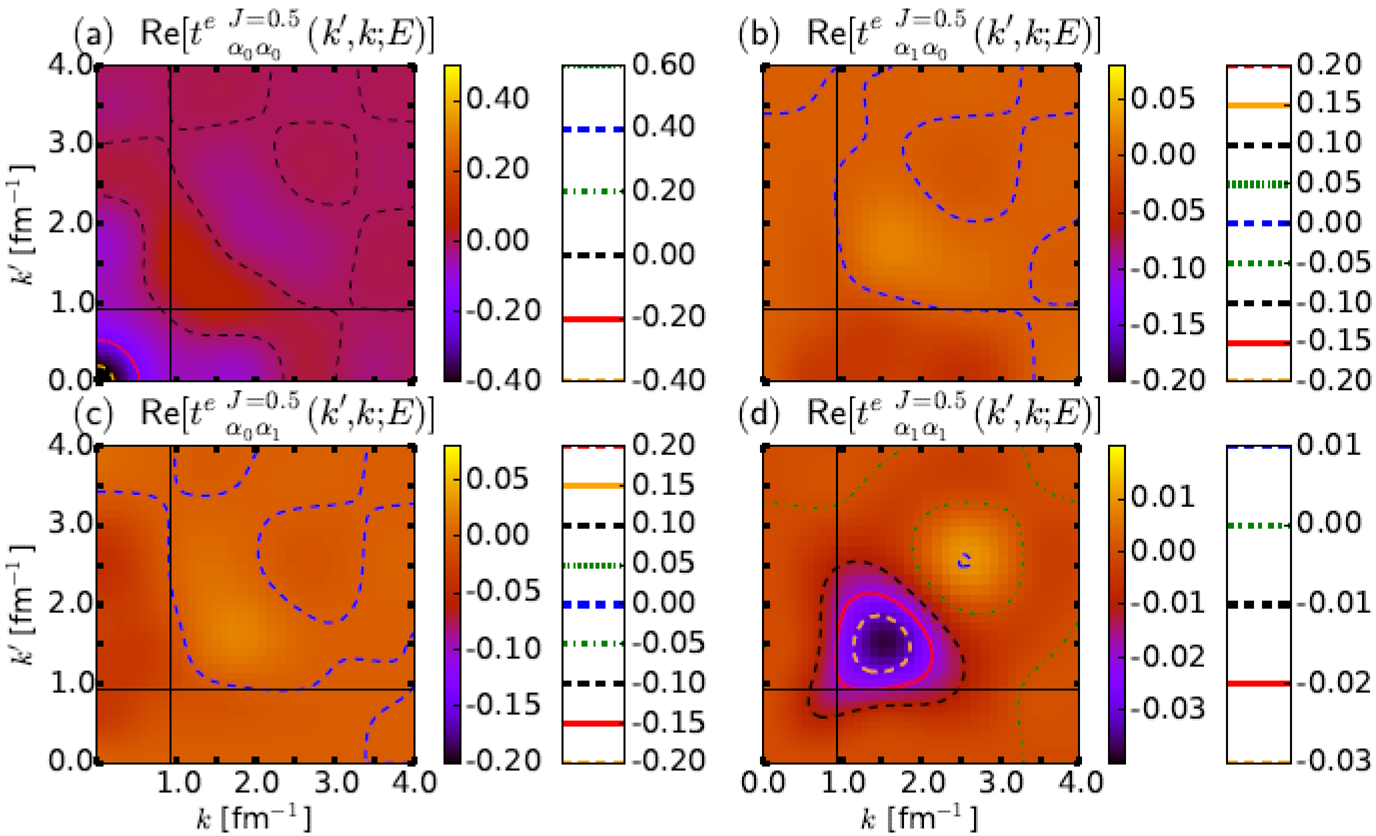


Off-shell EST separable t-matrix $n+^{12}$C, $E_{lab} =$ 20.9



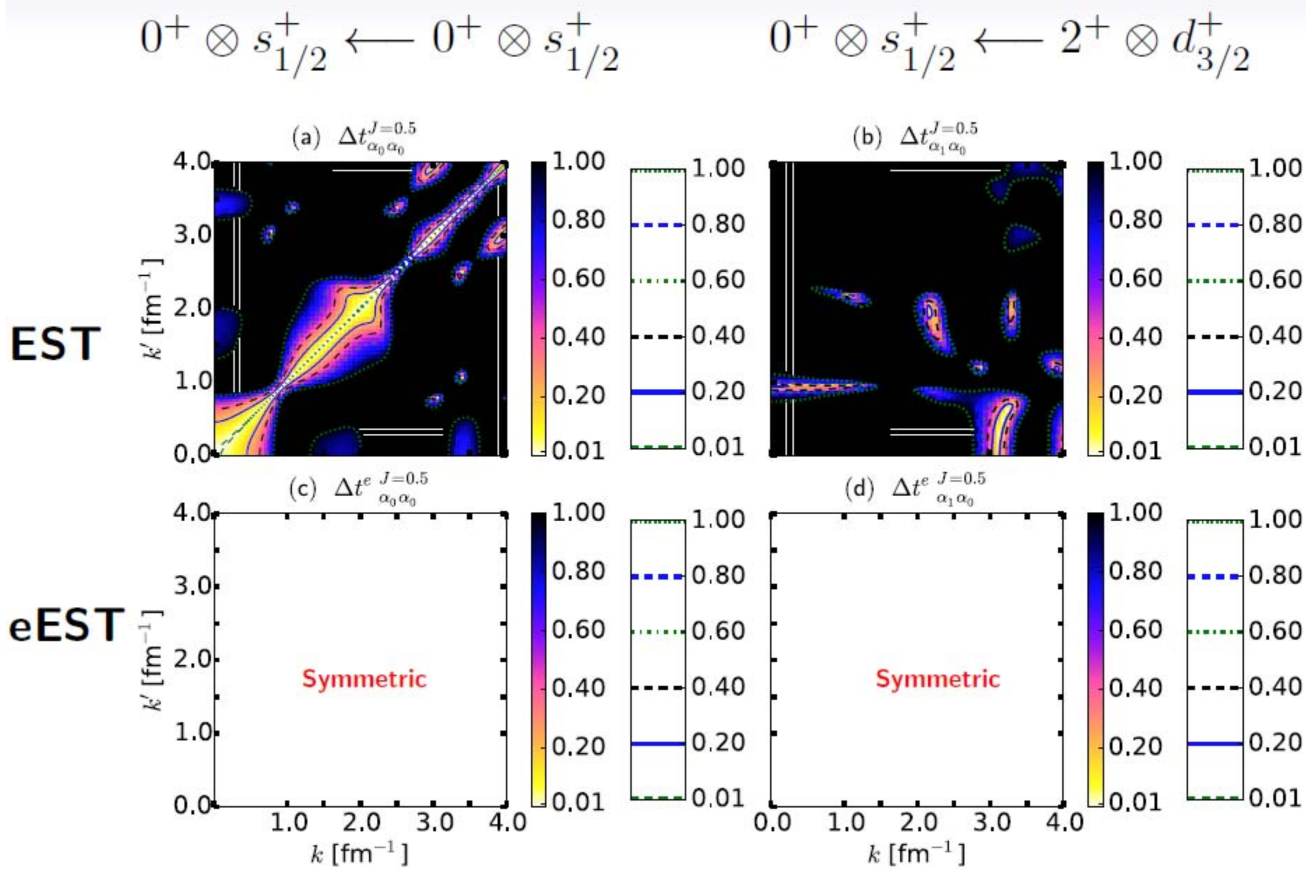
- EST support points: 6, 20, 40 MeV
- Asymmetry much more pronounced, off-diagonal on-shell t-matrix is not symmetric

Off-shell eEST separable t-matrix $n+^{12}$C, $E_{lab} = 20.9$



- eEST scheme leads to symmetric off-shell t-matrix

Asymmetry, $n+^{12}$C, $E_{lab} =$ 20.9 MeV



Asymmetry for EST more pronounced in multichannel scattering

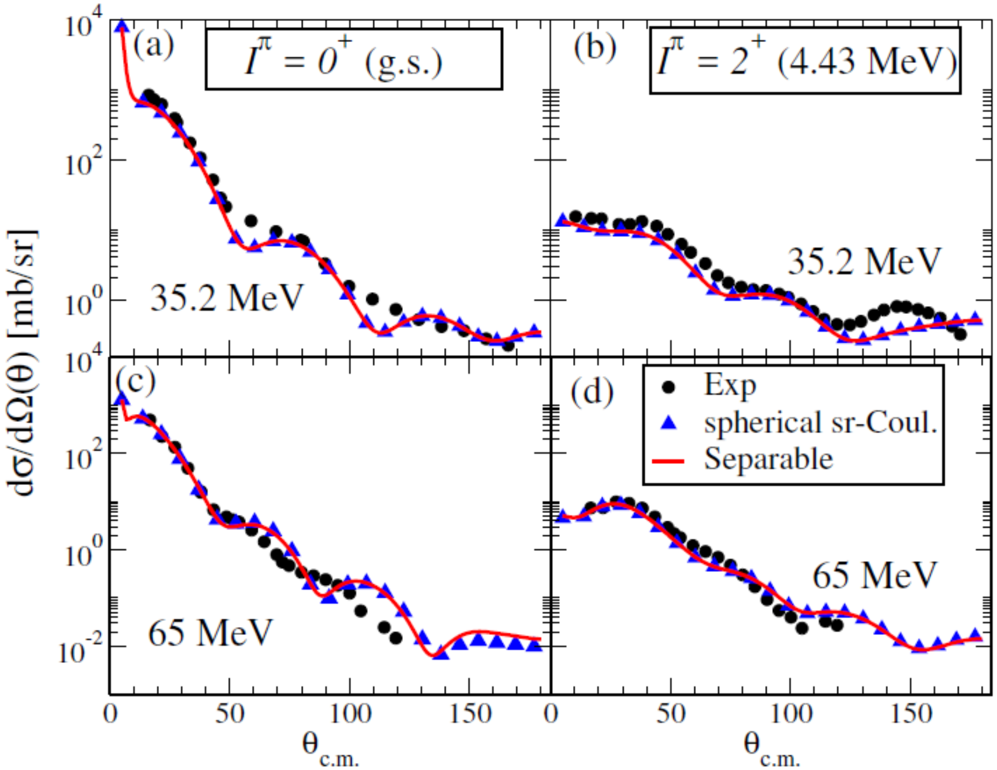
eEST important when taking into account excitations

Straightforward extension to p+^{12}C scattering

Similar to single-channel case:

(1) Coulomb-distorted nuclear scattering states, $|\psi_i^{sc(+)}\rangle$ are used in the separable expansion

(2) Free propagator $g_0(E) = (E - H_0 + i\varepsilon)^{-1}$ replaced by Coulomb Green's function $g_c(E) = (E - H_0 - V^c + i\varepsilon)^{-1}$

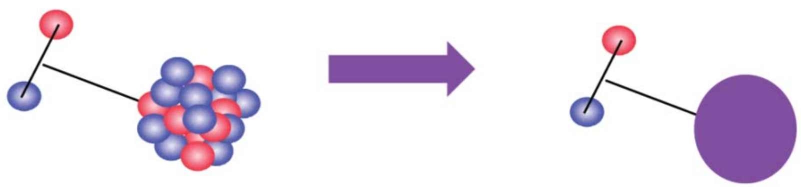


Potential and data from:

A. S. Meigooni, R. W. Finlay, J. S. Petler, and J. P. Delaroche, *Nucl. Phys.*, vol. A445, pp. 304–332, 1985.

Future: Numerical implementation of Faddeev-AGS equations

With this we can solve the effective three-body problem for (d,p) reactions for nuclei across the nuclear chart



Can we test this picture?

Scattering **d+^{4}He** can be calculated as many body problem by NCSM+RGM

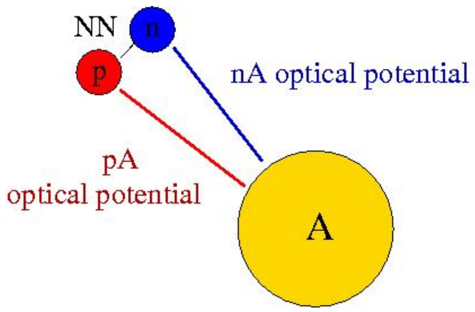
Benchmark elastic and breakup scattering for d+^{4}He

Only reactions with light nuclei will allow benchmarks

(i.e. with calculations by A. Deltuva)

Further Challenge:
Determine effective interactions V_{eff}

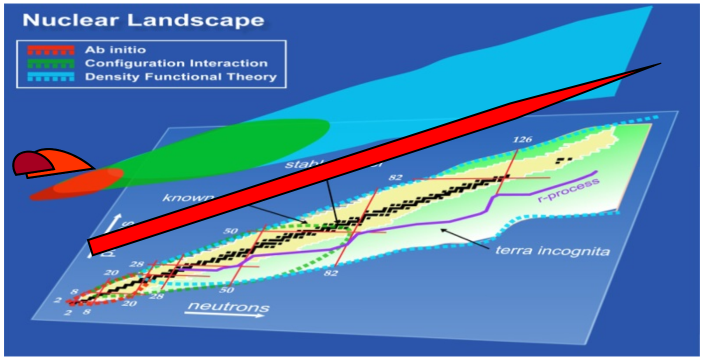
- V_{eff} is effective interaction between N+A and should describe elastic scattering



Hamiltonian for effective few-body poblem:

$$\mathbf{H = H_0 + V_{np} + V_{nA} + V_{pA}}$$

- V_{np} is well understood
- V_{nA} and V_{pA} are effective interactions
- Most used: phenomenological approaches
    - Global optical potential fits to elastic scattering data
    - Most data available for stable nuclei
    - Extrapolation to exotic nuclei questionable
- Microscopic approaches need to be developed or existing ones refined and adapted for exotic nuclei
    - Microscopic approaches were developed for A being a closed shell nucleus.



Goal for Reaction Theory:

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

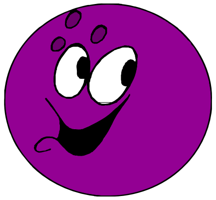
- At present `traditional' few-body methods are being successfully applied to a subset of nuclear reactions (with light nuclei)
  - Challenge: reactions with heavier nuclei

- Establish overlaps and benchmarks, where different approaches can be firmly tested.

- `cross fertilization' of different fields (structure and reactions) carries a lot of promise for developing the theoretical tools necessary for R physics.

Department of physics + astronomy

p+A and n+A effective interactions (optical potentials)



- Renewed urgency in reaction theory community for microscopic input to e.g. (d,p) reaction models .
- Most likely complementary approaches needed for different energy regimes

- **In the multiple scattering approach not even the first order term is fully explored: all work concentrates on closed-shell nuclei**

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 nuclei** full complexity of the NN interactions enters

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