Optical potentials: From stable to exotic nuclei

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CNA

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Feshbach formalism: Beauty and The beast

$$
\begin{aligned}
U &= {\color{blue}PVP} + {\color{red}PVQG(E+i\epsilon)QVP} \\
&\simeq V(E,r) + iW(E,r)
\end{aligned}
$$

- P is the projector on the g.s. of projectile and target, or alternatively, on a set of low lying states of projectile and target.
- The optical potential U is a complicated operator which is approximated by $V(E,r) + iW(E,r)$, a local, L-independent potential obtained by fitting the elastic differential cross section.
- The hope is that the elastic wave functions, solutions of U, will be similar to those obtained form the solutions of $V(E,r) + iW(E,r)$, which only contain information on the asymptotic part of the elastic wavefunction.

Microscopic Optical model paradigm. 1979-

- Microscopic calculations using the M3Y effective nucleon-nucleon interaction [a]. **Real potential as a folding potential.**

$$V(E,r) = \int d^3\vec{r}_p d^3\vec{r}_t \rho_p(r_p)\rho_t(r_t) u(|\vec{r}-\vec{r}_p+\vec{r}_t|)$$

$$u(s) = \text{OPEP} + v_2 \frac{e^{-a_2 s}}{a_2 s} - v_3 \frac{e^{-a_3 s}}{a_3 s} - u_{ex}(E)\delta^3(\vec{s})$$

- **Imaginary potential as a phenomenologic Woods-Saxon** fitted to elastic differential cross sections. $r_W \simeq 1.2 - 1.3$ fm. $a_W \simeq 0.5 - 0.6$ fm. $W(R_s)/V(R_s) \simeq 0.6$.
- Successes: Good results, in general, for nucleus-nucleus and nucleon-nucleus elastic scattering with renormalization $N_r \simeq 1.1 \pm 0.1$. Sound basis for DWBA calculations of inelastic and transfer.
- Limitations: ^{6}Li, ^{7}Li and ^{9}Be weakly bound stable nuclei require renormalization $N_r \simeq 0.6$. Extrapolation to exotic nuclei unreliable.

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[a] G. R. Satchler and W. G. Love, Phys. Reports 55 (1979) 183

Microscopic Coupled Channels paradigm. 1983-

- **Extend Beauty** P: projector on low-lying states. Coupling potentials calculated by double folding with transition densities.

$$\rho_{if}(\vec{r}) = \langle \Phi_i | \sum_{j=1}^{A} \delta^3(\vec{r}_j - \vec{r}) | \Phi_f \rangle$$

- Successes: ^{6}Li, ^{7}Li differential cross sections with $N_r \simeq 1$ [a]. Fusion enhancement through the barrier. Spin polarization observables. Neutron transfer effects beyond DWBA. [b]
- Limitation: **Nuclear coupling potentials are found to be complex.** A general microscopic theory of the nucleus-nucleus imaginary potential is missing. We cannot estimate the value of the imaginary potentials for unknown exotic nuclei.

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[a] JGC, M Lozano, M.A.Nagarajan Phys Lett B161 (1985)39-42. Nuclear Physics A440 (1985) 543-556. H.Nishioka, R.C. Johnson (Cluster Folding). M. Kamimura et al (CDCC calculations)

[b] Fusion enhancement, Dasso et al, scattering of polarized ^{6,7}Li, ^{23}Na, JGC and Johnson, ^{16}O+^{208}Pb scattering, Thompson and Nagarajan

Imaginary potentials: What do we know about the beast?

- $PVQG(E+i\epsilon)QVP$: Separate contributions as Q projects compound nucleus or direct channels. $W(E,r) = W_{CN}(E,r) + W_D(E,r)$.

$$\sigma_R(E) = \frac{2}{\hbar v}\int d^3\vec{r}|\Psi(\vec{r})|^2 W(E,r) = \sigma_{CN}(E) + \sigma_D(E).$$

- **Beast W_{CN}:** Volume type. Radial dependence ((r_W, a_W)) is not very critical. The depth of W_{CN} can be obtained from $\sigma_{CN}(E)$. Statistical models applicable, extrapolable to exotic nuclei.
- **Beast W_D:** Surface type. Strongly dependent on reaction mechanism. Radial dependence is critical. Sharp energy dependence, as thresholds are crossed.
- Dispersion relations [1] :

$$\Delta V(E,r) = \frac{\mathcal{P}}{\pi}\int dE' \frac{W(E',r')}{E'-E}$$

[1] Mahaux, Ngo, Satchler Nucl.Phys.A 449 (1986) 354-394

Microscopic determination of the dynamic polarization potential

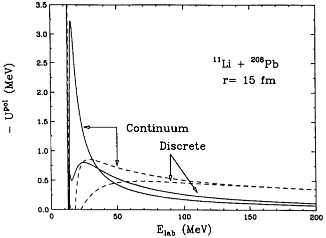
- Electric quadrupole excitation to rotational states:[2] A long range absorption $W(r,E) \simeq \frac{8\pi Z_t^2 e^2}{75\hbar v} \frac{B(E2, 0^+ \to 2^+)}{r^5}$
- Electric dipole excitation to break-up states [3]. **Beauty hidden in the beast !**

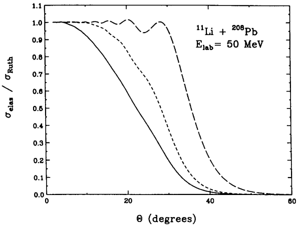
$$U(r,\xi) = -\frac{4\pi Z_t e^2}{9\hbar v} \frac{B(E1, gs \to d)}{r(r-a_0)^2} \left(i f(r,\xi) + g(r,\xi) \right)$$

- $f(r,\xi), g(r,\xi)$ are analytic Bessel-type functions, linked by dispersion relations. For large r, $f(r,\xi) \sim \exp\left(-\frac{2(e_d - e_g)r}{\hbar v}\right)$.
- Halo nuclei have low energy dipole states, generating long-range imaginary potentials ($a_i \simeq 2 - 4 fm$) producing the phenomenon of **long-range absorption**.

[2] Love Teresawa and Satchler, Phys Rev Lett 39 (1977) 6.
[3] Andres, JGC, Nagarajan, Nucl.Phys. A579 (1994) 273

Coulomb dipole polarization potential:



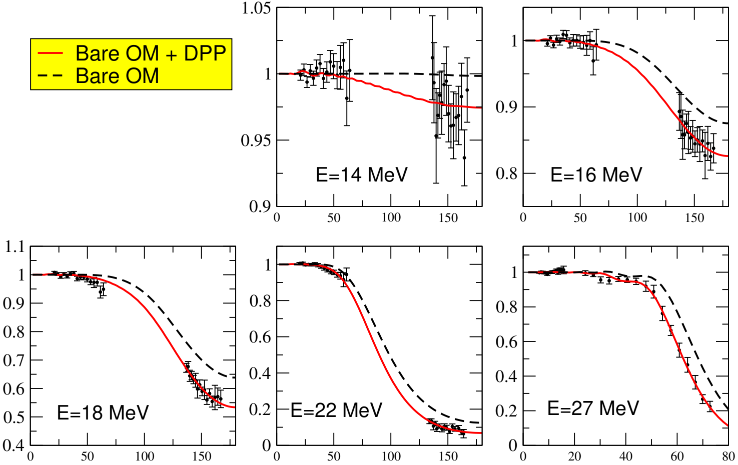


- **Dipole Polarizability** Halo nuclei have very important contributions of the coulomb dipole polarization potential, that alter strongly the elastic cross sections, even below the barrier.
- The elastic cross sections of halo nuclei on heavy targets are strongly affected by **long range absorption** due to **dipole polarizability**[4], so they give information about the B(E1) distribution: **Case for Experimental Proposals**.

[4] Andres, JGC, PRL82 (1999) 1387

^{6}He scattering experiments: Louvain la Neuve, 2006-2008

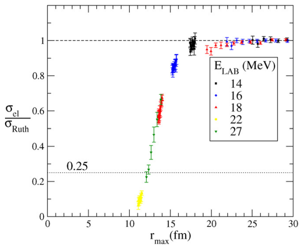
- ^{6}He is a 2n Halo nucleus, $B_{2n} = 0.973$ MeV. $\tau = 807$ ms.
- Long range absorption effects are seen in ^{6}He scattering on ^{208}Pb [5], partly due to Coulomb dipole polarizability.

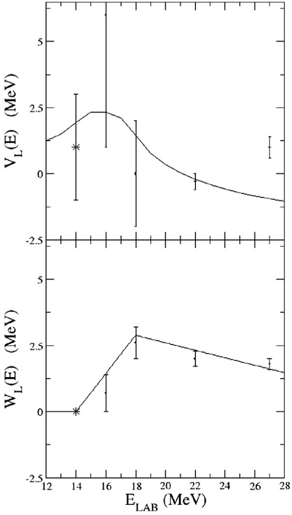


[5] Sanchez et al, Nuclear Physics A803 (2008), 30-45

Optical Model Approach

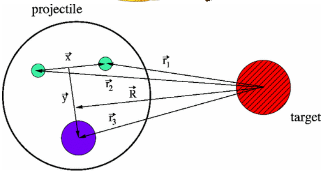
- Parameter free, analytic Coulomb polarization potential can be used with a standard short-range nuclear potential.
- Long-range complex nuclear potentials, consistent with dispersion relations, can be extracted from the data, but uncertainties are large.
- Long range absorption kill the rainbow and make cross sections rather insensitive to optical potentials.

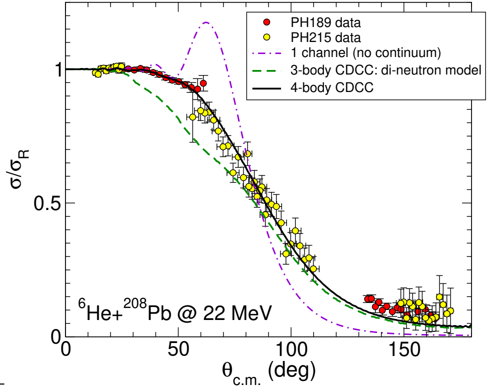




Coupled Channels approach:

- ^{6}**He can be described microscopically** with a bound gs and the 3-body continuum.
- Parameter free phenomenological interactions of ^{4}He and n with the target.
- **4 body CDCC calculations**[6] including dipole excitation, reproduce elastic cross sections fairly well.

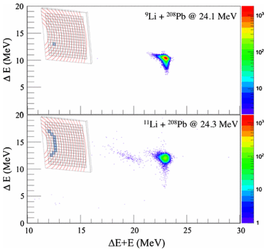


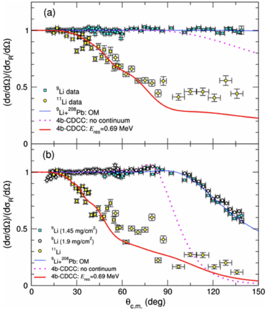


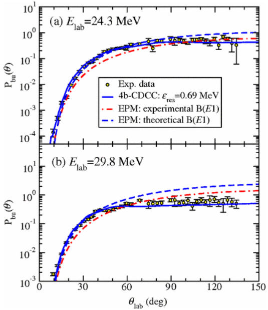
[6] Acosta et al PRC84 (2011) 044604

11Li scattering experiments. TRIUMF 2011-2013

- ^{11}Li is a 2n Halo nucleus, $B_{2n} = 0.295$ MeV. $\tau = 8$ ms. [7]
- Elastic scattering and break-up of ^{11}Li on ^{208}Pb below and just above the Coulomb barrier.
- 4B-CDCC calculations using ^{9}Li+ ^{208}Pb and n + ^{208}Pb optical potentials.



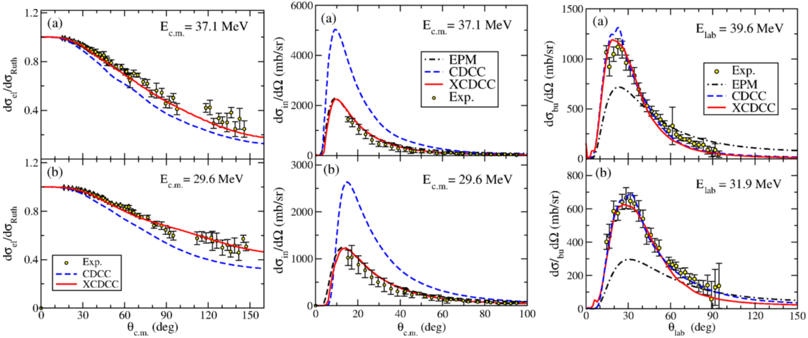




[7] Cubero et al, PRL109 (2012), 262701; Fernandez-Garcia PRL110 (2013 142701

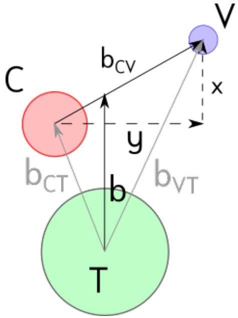
11Be scattering experiments: TRIUMF 2017

- ^{11}Be is a 1n Halo nucleus, $B_n = 0.503$ MeV. $\tau = 13,8$ s. [8]
- Elastic scattering, inelastic scattering and break-up of ^{11}Be on ^{197}Au below and just above the Coulomb barrier.
- X-CDCC calculations including core excitation using ^{10}Be+ ^{197}Au and n + ^{197}Au optical potentials.



[8] Pesudo et al, PRL118 (2017) 152502

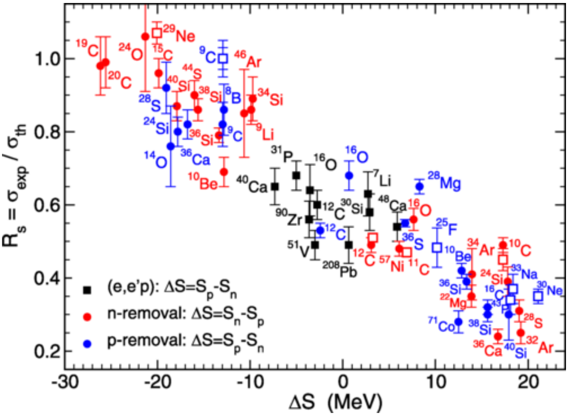
Eikonal theory



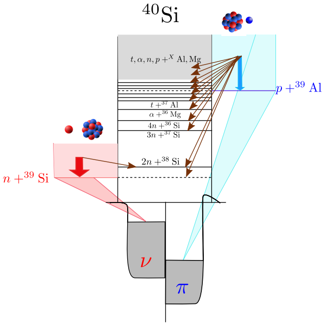
- Closure property of core-valence states at all energies (valid for real core-valence) interaction with no bound states)
  $\langle \vec{r}_2 | \rho_f | \vec{r}_1 \rangle =$
  $\int d^3\vec{k} \, \left(\psi^{(-)}(\vec{k}, \vec{r}_2) \right)^* \psi^{(-)}(\vec{k}, \vec{r}_1) =$
  $\delta^3(\vec{r}_2 - \vec{r}_1)$.
- Stripping probability:
  $P^{\rm Ei}_{\rm str}(\vec{b}) =$
  $\int d^3\vec{r} \, |\phi_g(\vec{r})|^2 |S^0_{CT}(b_{CT})|^2 \left(1 - |S^0_{VT}(b_{VT})|^2\right)$.

Tostevin-Gade Plot:

J. A. Tostevin and A. Gade Phys.Rev.C10 (2021) 054610



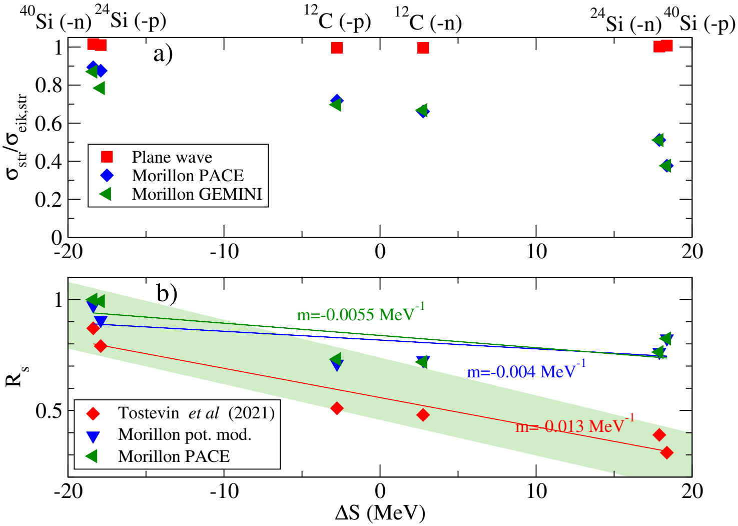
Core removal by interaction with the valence:



- The valence particle can interact, and eventually break. the core, through an optical potential [a]
- The explicit evaluation of $\langle \vec{r}_2 | \rho_f | \vec{r}_1 \rangle$ is done, leading to the breaking of closure, and a reduction of the stripping probabilities for some nuclei.
- The global dispersive nucleon-nucleus potential[b] is used, corrected to discount compound elastic scattering.
- The global nucleon-nucleus potential, fitted to stable nuclei (n + ^{39}K), is assumed to be valid for exotic nuclei (n+ ^{39}Si, p + ^{39}Al).

[a] Gomez-Ramos, JGC, Moro, PLB847 (2023) 138284

[b] Morillon, Romain PRC76 (2007) 044601.



ΔS dependence of stripping cross sections is explained, to a large extent

Take home messages

- Complex optical potentials are a key ingredient to extract structure information from measured cross sections.
- The imaginary part of the optical potentials must, still, be obtained phenomenologically from elastic and reaction cross section data.
- Scattering of halo nuclei require CDCC calculations, using fragment-target optical potentials. **No safe Coulomb for halo nuclei!**
- The interpretation of nucleon removal experiments require nucleon-core optical potentials. **The "removed´´ nucleon still interacts!**
- It is very important to complete data of elastic and reaction cross sections of nucleons with exotic nuclei. **Are global potentials (i.e. Morillon) extrapolable for exotic nuclei?**

Acknowledgements

M.A.Nagarajan, M.Lozano, R.C.Johnson, G. Tungate, I. Martel, M.V. Andres, A.M. Moro, M.J.G. Borge, O. Tengblad, A. Sánchez-Benitez, O. Kakuee, D. Escrig, M. Rodriguez-Gallardo, L. Acosta, M.Cubero, J.P. Fernandez, M.A.G. Álvarez, A. di Pietro, V. Pesudo, J.A. Lay, M. Gómez-Ramos.

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Financiado por la Unión Europea
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