Selective sensitivity of proton scattering to densities on the nuclear surface

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EURISOL Topical Meeting: Valencia, Feb 21-23, 2011

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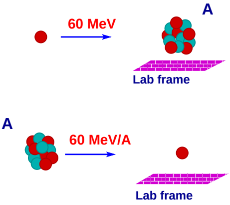
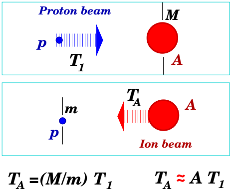
Route

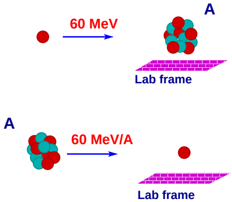
The problem

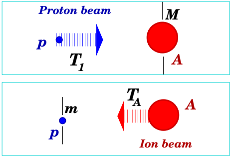




- EURISOL: With a simple change of reference frame we are faced with fascinating short-lived, exotic nuclear structures.
- From an experimental point this little change leads to enormous technological and experimental challenges; theoretically, we have to revisit many of our simplifying assumtions.
- New landscape involving exotic structures: shapes, veils, halos, surface, etc.
- Can microscopic g-folding optical model potential help us to understand the transit of the projectile through exotic nuclei? Can we identify energies/probes to selectively study particular mechanisms?

The problem





$T_A = (M/m)\, T_1$ $\quad T_A \approx A\, T_1$

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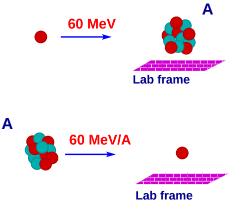

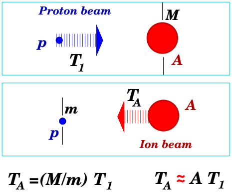

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The $NN \rightarrow N + A$ connection

Microscopic connection

$$\underbrace{\mathbf{NN} \rightarrow \left\{ \begin{array}{c} \left(\frac{d\sigma}{d\Omega}\right)_{NN} \\ \downarrow\uparrow \\ \delta_L(E) \end{array} \right\}}_{\text{2-Body}} \rightleftharpoons \underbrace{V_{NN} \begin{array}{c} \nearrow \\ \searrow \end{array} \left. \begin{array}{c} \mathscr{G}_{NN} \\ \\ t_{NN} \end{array} \right\}}_{\text{Effective Interaction} \rightarrow T} \rightarrow \underbrace{\underbrace{U_{opt}(\mathbf{k}', \mathbf{k}; E)}_{\uparrow\, |\Psi_{g.s.}\rangle} \rightarrow \left\{ \begin{array}{c} |\psi\rangle \\ \left(\frac{d\sigma}{d\Omega}\right)_{NA} \\ \sigma(E) \end{array} \right.}_{\text{N+A}}$$

Realistic V_{NN} $(E_{Lab} < 350 MeV)$:

Paris, Argonne v_{18}, Nijmegen I-II, Bonn A, Bonn B, CD Bonn, etc.

NA Scattering:

$$[\hat{K} + \hat{U}(E)]|\psi\rangle = E|\psi\rangle$$

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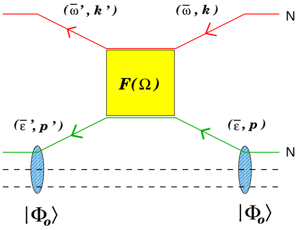
Different energies pose different challenges:

- Low E (below 30 MeV): Sensitivity to shell structure.
- Low-intermediate and intermediate energies: Medium effects ...+ relativity
- High-intermediate: Relativistic effects + meson production (inelasticities).

Unabridged *NA* optical potential

[Arellano-Bauge, PRC 76, 014613 (2007)]

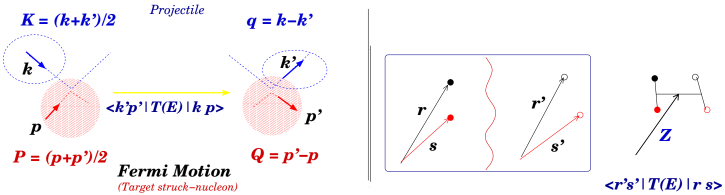


$$U(\mathbf{k}',\mathbf{k};E) = \int d\mathbf{p}\, d\mathbf{p}' \underbrace{\rho(\mathbf{p}',\mathbf{p})}_{HFB} \underbrace{\langle \mathbf{k}'\,\mathbf{p}' \,|T(E)|\, \mathbf{k}\,\mathbf{p} \rangle_{\mathscr{A}}}_{NN}$$

Alternatively,

$$U(\mathbf{r}',\mathbf{r};E) = \sum_{\alpha\le F} \int d\mathbf{s}\, d\mathbf{s}'\, \phi_\alpha(\mathbf{s}') \,\langle \mathbf{r}'\,\mathbf{s}' \,|T(E)|\, \mathbf{r}\,\mathbf{s} \rangle_{\mathscr{A}}\, \phi^\dagger_\alpha(\mathbf{s})$$

Simplified picture



$Z \longrightarrow$ Mean Coordinate

General property:

$$\langle \mathbf{k}'\,\mathbf{p}' \mid T \mid \mathbf{k}\,\mathbf{p}\rangle = \frac{1}{(2\pi)^3}\int d\mathbf{Z}\; e^{i\mathbf{Z}\cdot(\mathbf{W}'-\mathbf{W})}\, g_{\mathbf{Z}}[\tfrac{1}{2}(\mathbf{W}'+\mathbf{W});\mathbf{b}'\,\mathbf{b}]$$

Short-hand...

$$\tilde{T} = \frac{1}{(2\pi)^3}\int d\mathbf{Z}\; e^{i\mathbf{Z}\cdot\mathbf{W}_\perp}\, g_Z$$

g_Z: reduced NN (effective) int.

OBS: Z-independence $\Rightarrow \langle \mathbf{k}'\,\mathbf{p}' \mid T \mid \mathbf{k}\,\mathbf{p}\rangle = \delta(\mathbf{k}'+\mathbf{p}'-\mathbf{k}-\mathbf{p})\, t(\mathbf{k}+\mathbf{p};\mathbf{b}'\,\mathbf{b})$

Asymptotic separation for $\langle \mathbf{k}' \, \mathbf{p}' \mid T \mid \mathbf{k} \, \mathbf{p} \rangle$

- Consider $g_{\mathbf{Z}}$ depends only on the magnitude $|\mathbf{Z}| = Z$;
- g_Z depends on the Local Density at Z;
- g_ρ corresponds to the g matrix (Brueckner-Bethe-Goldstone) for infinite nuclear matter; • identify $g_\infty \equiv t$ (zero-density limit), then

$$\tilde{T} = \delta(W_\perp)\, t - \frac{1}{2\pi^2} \int_0^\infty Z^3 \, dZ \, \frac{j_1(Z\, W_\perp)}{Z\, W_\perp} \underbrace{\times \frac{\partial g_Z}{\partial Z}}_{\text{Surface peacked!}}$$

- Medium-free (t matrix) and intrinsic medium effects (Pauli - Mean Fields) become disentangled.
- Since $\frac{\partial g_Z}{\partial Z} = \left(\frac{\partial g}{\partial \rho}\right)\left(\frac{\partial \rho(z)}{\partial Z}\right)$ $\rightarrow$ peaks on the surface!
- Separation of T yields separation for the optical potential:

$$\boxed{U = U_0[t] + U_1[\delta g]}$$

The $U = U_0 + U_1$ decomposition

U_0: Free t-matrix full-folding (KMT):

$$U_0(\vec{k}',\vec{k}) = \int d\mathbf{P}\,\rho(\mathbf{P}-\frac{\mathbf{q}}{2},\mathbf{P}+\frac{\mathbf{q}}{2})\; t[(\mathbf{K}+\mathbf{P}+\mathbf{q})/2,(\mathbf{K}+\mathbf{P}-\mathbf{q})/2,\mathbf{K}+\mathbf{N}]$$

U_1 (intrinsic medium effects) given by 7D integrals: $d\vec{Q}d\vec{Q}dZ$

$$\begin{aligned} U_1(\vec{k}',\vec{k}) &= -\frac{1}{2\pi^2}\int d\mathbf{p}\,d\mathbf{p}'\,\rho(\mathbf{p}',\mathbf{p})\int_0^\infty Z^3 dZ\,\frac{j_1(Z|\mathbf{Q}-\mathbf{q}|)}{Z|\mathbf{Q}-\mathbf{q}|}\,\frac{\partial g_Z}{\partial Z} \\ &= \int_0^\infty dZ \underbrace{\left[\frac{Z^3}{2\pi^2}\int d\mathbf{p}\,d\mathbf{p}'\,\rho(\mathbf{p}',\mathbf{p})\frac{j_1(Z|\mathbf{Q}-\mathbf{q}|)}{Z|\mathbf{Q}-\mathbf{q}|}\left(\frac{-\partial g_Z}{\partial Z}\right)\right]}_{u(Z)} \end{aligned}$$

$\boxed{U_1 = \int_0^\infty u(Z)\,dZ}$ $u(Z) \sim$ energy density...

Observations and questions

- Theory allows separation of intrinsic medium effects from those stemming from the free interaction.
- Is there any systematics exhibited by proton scattering from proton-rich nuclei?

Reminder & terminology:

- If U was local then

$$U(\vec{k}',\vec{k}) = \int d\vec{r} e^{i(\vec{k}'-\vec{k})\cdot\vec{r}} V_{Loc}(\vec{r}) = \tilde{V}(\vec{q})$$

- On shell: $|\vec{k}'| = |\vec{k}| = \sqrt{2mE}$
- If U local, on-shell forward limit: $U(\vec{k},\vec{k}) = \int d\vec{r} V_{Loc}(\vec{r})$; $\boxed{ImU \sim \sigma}$.
- Pauli, Fermi motion, antisymmetrization, mean fields blur the above picture.

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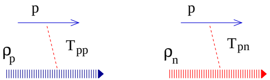
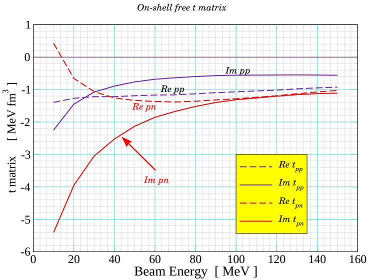
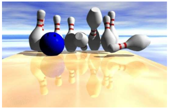
$U = U_0[t] + U_1[\partial_Z \rho]$ PRC 78, 014608 (2008)

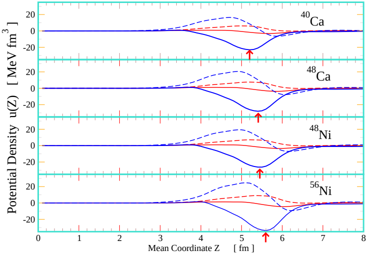
Actual calcs. vs estimates (proton scattering): Z protons and N neutrons:
Coupling to PROTON distributions: $\sim Z t_{pp} + \delta g_{pp}$
Coupling to NEUTRON distributions: $\sim N t_{pn} + \delta g_{pn}$



◀◀ Free space

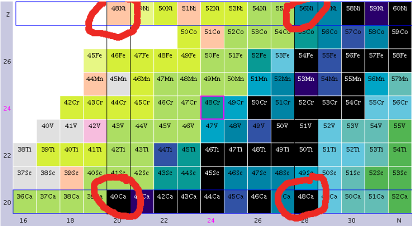


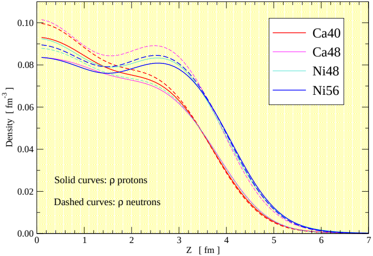




Medium (surface) ▶▶

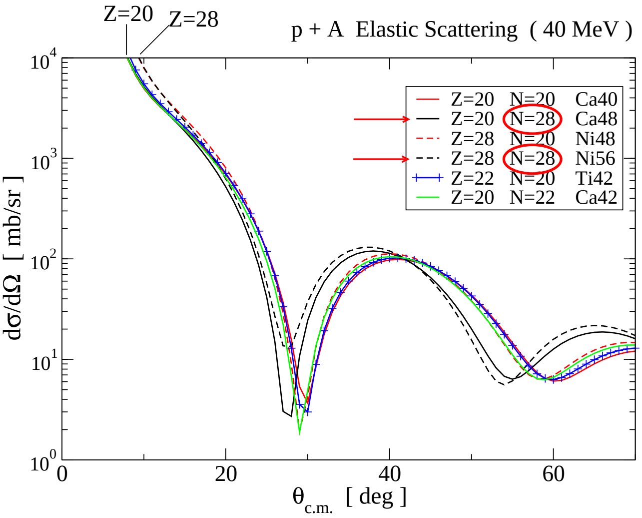
Case ^{40}Ca - ^{48}Ca - ^{48}Ni - ^{56}Ni



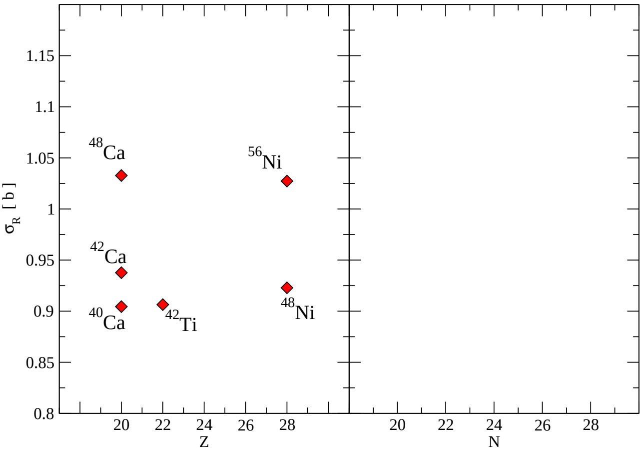


Nucleus	rms (prot) [fm]	rms (neut) [fm]
^{40}Ca	3.408	3.365
^{48}Ca	3.432	3.573
^{48}Ni	3.664	3.417
^{56}Ni	3.614	3.640

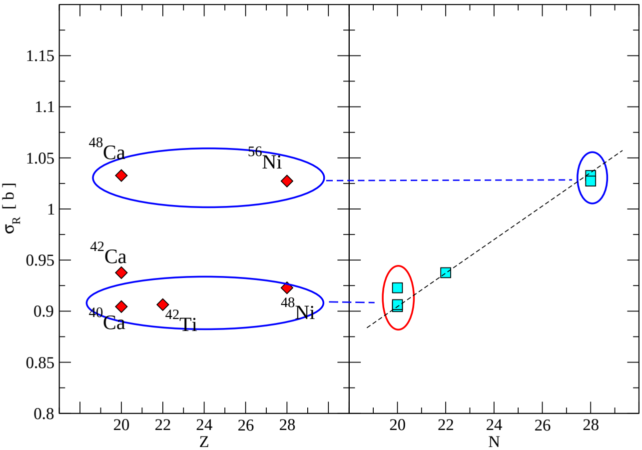
- Hartree-Fock ground state densities (D1S Gogni interaction).
- $p + A$ elastic scattering (40 MeV).
- Argone v_{18} bare NN interaction.
- Brueckner-Bethe-Goldstone g-matrix: off-shell; fully non-local.
- Folding in momentum space $\otimes$ Z integration.
- Non-local optical potentials $\rightarrow$ scattering calculations
- Outcomes: $\underline{d\sigma/d\Omega}$, A_y, $\underline{\sigma_R}$, distorted waves, etc.


Z=20
Z=28
p + A Elastic Scattering (40 MeV)
Z=20 N=20 Ca40
Z=20 N=28 Ca48
Z=28 N=20 Ni48
Z=28 N=28 Ni56
Z=22 N=20 Ti42
Z=20 N=22 Ca42
dσ/dΩ [mb/sr]
θ c.m. [deg]
0
20
40
60

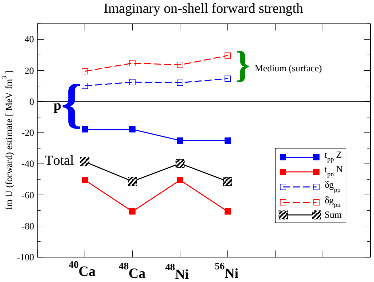
Reaction cross sections as function of Z ...

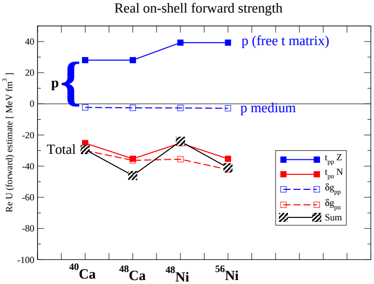


Reaction cross sections as function of Z and N



Forward strength, p-scattering; 40 MeV





Conclusions

- Proton scattering is sensitive to medium effects on the surface.
- Reaction and differential cross sections more sensitive to the neutron number than proton (40 MeV).
- Energy dependence of volume/surface strength allows guidance on ion energies under which a particular reaction information can be extracted.
- These findings are relevant for the study of nuclear reactions involving exotic structures (microscopic understanting).
- 150-MeV case to be included in the Report.

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