Nucleus-nucleus potentials from chiral effective field theory

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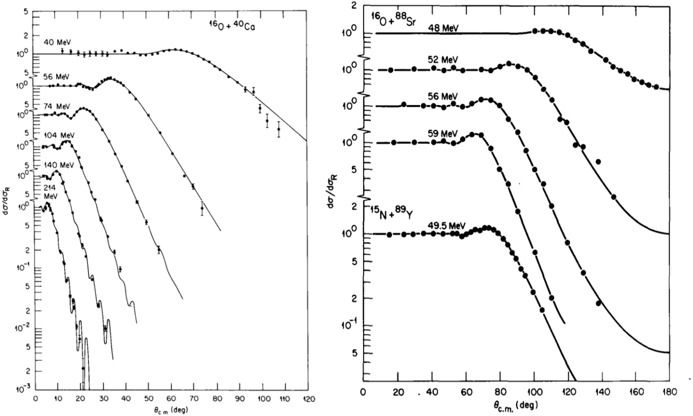
Motivation

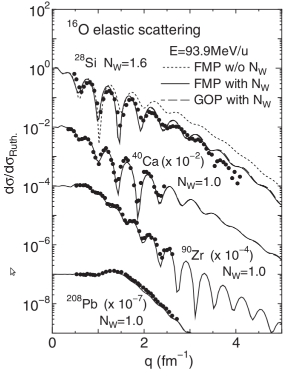
- Double-folding potentials provide potentials for nucleus-nucleus scattering, relevant for structure and astrophysical rections.



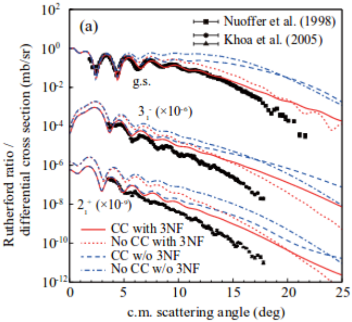
G.R. Satchler and W.G. Love, Phys. Rep. **55**, 183 (1979)

Motivation

- In recent years there has been successful work using microscopic interactions based on G-matrix formalism.



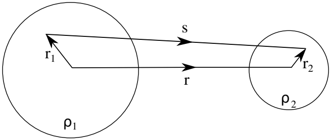
T. Furumoto *et al.* Phys. Rev. C **85**, 044607 (2012)



T. Minomo *et al.*, Phys. Rev. C **93**, 014607 (2016)

Double-folding model

- Double-folding procedure applied to calculate nucleus-nucleus potential using a realistic NN interaction.
- Nucleus-nucleus potential obtained by averaging the interaction over the matter distribution between colliding ions.



$$\mathbf{s} = \mathbf{R} - \mathbf{r}_1 + \mathbf{r}_2$$

- Our work: explore double-folding potentials based on local chiral EFT interactions.

Double-folding model - input

- The nucleus-nucleus potential can be written as:

$$V_F = \sum_{i\in A_1, j\in A_2} \left[\langle ij|v_D|ij\rangle + \langle ij|v_{\mathrm{Ex}}|ji\rangle\right] = V_D + V_{\mathrm{Ex}}\,.$$

- Form of the double-folding potential

$$V_{\mathrm{D}}(\mathbf{r}) = \sum_{i,j=n,p} \int\int \rho_1^i(\mathbf{r}_1)\, v_{\mathrm{D}}^{ij}(\mathbf{s})\, \rho_2^j(\mathbf{r}_2)\, d^3\mathbf{r}_1 d^3\mathbf{r}_2\,,$$

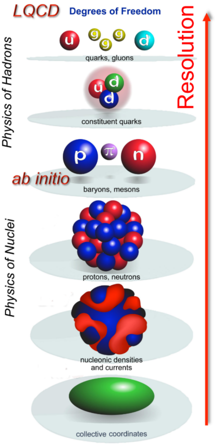
$$V_{\mathrm{Ex}}(\mathbf{r}, E_{\mathrm{cm}}) = \sum_{i,j=n,p} \int\int \rho_1^i(\mathbf{r}_1, \mathbf{r}_1+\mathbf{s})\, v_{\mathrm{Ex}}^{ij}(\mathbf{s}) \rho_2^j(\mathbf{r}_2, \mathbf{r}_2-\mathbf{s}) \exp\left[\frac{i\mathbf{k}(\mathbf{r})\cdot\mathbf{s}}{\mu/m_N}\right]\, d^3\mathbf{r}_1 d^3\mathbf{r}_2\,.$$

- Two-parameter Fermi distribution as input density

L. C. Chamon *et al.*, PRC, **85**, 044607 (2012)

$$\rho_{p,n}(r) = \frac{\rho_0}{1+\exp\left(\frac{r-R_{p,n}}{a_{p,n}}\right)}$$

Chiral EFT

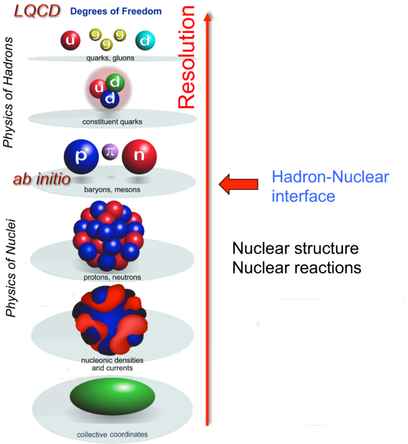


Hadron-Nuclear interface

Nuclear structure
Nuclear reactions

W. Nazarewicz, J. Phys. G **43**, 044002 (2016)

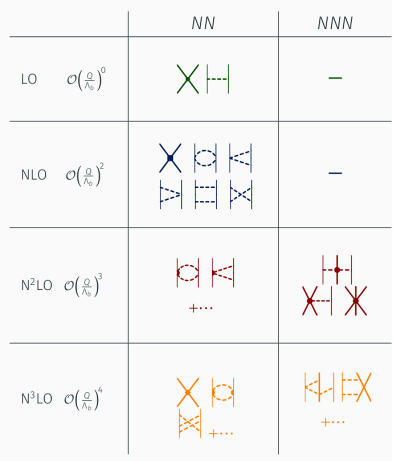
Chiral EFT



W. Nazarewicz, J. Phys. G **43**, 044002 (2016)

- Chiral EFT describes interactions between nucleons based on symmetries of QCD.

Chiral EFT

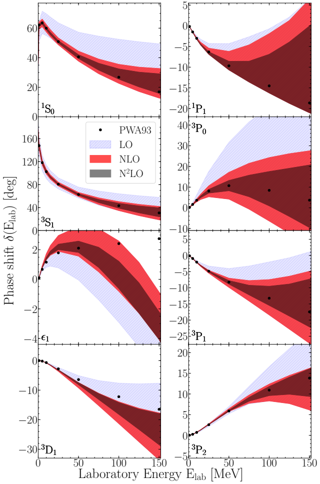


Courtesy of Joel Lynn

- Chiral EFT: expansion in powers of Q/Λ_b. $Q \sim m_\pi \sim 100$ MeV; $\Lambda_b \sim 500$ MeV.
- Long-range physics: given explicitly by pion exchanges.
- Short-range physics: contact interactions with low-energy constants (LECs) fit to πN, NN, 3N... data.
- Many-body forces and currents enter systematically.
- Allows for estimation of uncertainties.

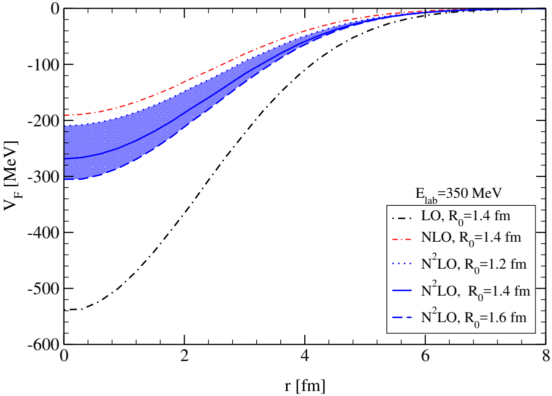
Local form of chiral potentials

- Existing local potentials not suitable for double-folding potential calculations (too high momentum cutoff).
  A. Gezerlis *et al.*, PRL **111**, 032501 (2013)
  A. Gezerlis *et al.*, PRC **90**, 054323 (2014)
  J. Lynn *et al.*, PRL **113**, 192501 (2014)
- Local regulator form: $f_{\text{long}}(r) = 1 - e^{-(r/R_0)^4}$
- Construction of new (softer) local potentials with cutoffs R_0 =1.4 and 1.6 fm.
- Good reproduction of *NN* phase shifts vs. Nijmegen partial-wave analysis.



V. Durant, P. Capel, *et al.*, PLB 782, 668 (2018)

Form of the double-folding potential



V. Durant, P. Capel, *et al.*, PLB 782, 668 (2018)

- Clear systematics in the order-by-order expansion.
- Small sensitivity to the r-space cutoff R_0.

Imaginary part of nucleus-nucleus potentials

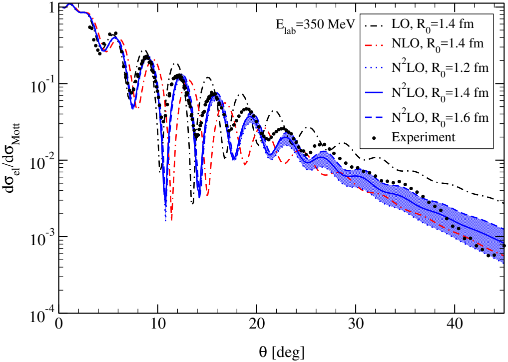
- The resulting double-folding potential, V_F, is purely real.
- To describe elastic scattering
  $\rightarrow$ we need an absorptive imaginary contribution to the potential.
- First approximation: imaginary part proportional to the real double-folding potential motivated by D. Pereira *et al.*, PLB **670**, 330 (2009)

$$U_F(r, E_{\rm cm}) = (1 + iN_W)V_F(r, E_{\rm cm})$$

- Typical choices: $N_W = 0.6 - 0.8$

Elastic scattering cross sections

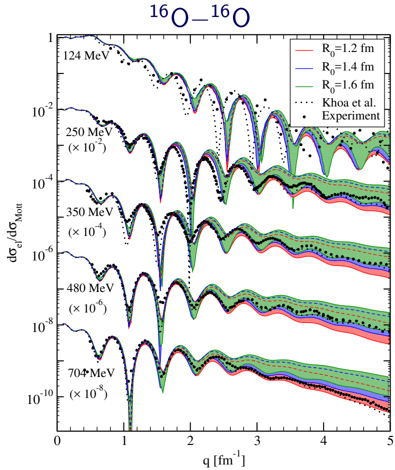
N_W=0.8, ^{16}O−^{16}O



V. Durant, P. Capel, *et al.*., PLB 782, 668 (2018)

- Good agreement with the data without any adjustment.
- Clear systematics in the order-by-order expansion.
- Small sensitivity to the r-space cutoff R_0.

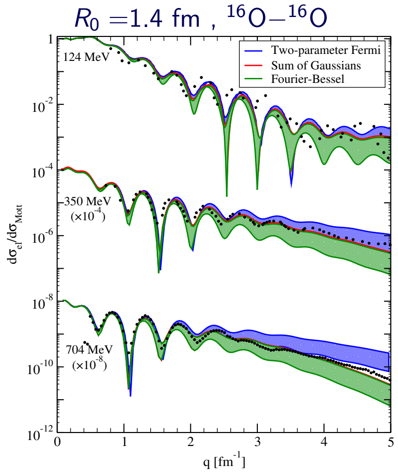
Elastic scattering cross sections



V. Durant, P. Capel, *et al.*, PLB 782, 668 (2018)

- For each R_0, the bands give the $N_W = 0.6 - 0.8$ range.
- Good agreement with experimental data and phenomenological potentials Khoa *et al.*, NPA **672**, 387 (2000)
- Different collision energies using the same input *NN* potential.
- At large momentum transfer: experimental points close to the spread obtained for N_W.

Elastic scattering cross sections



- For each R_0, the bands give the $N_W = 0.6 - 0.8$ range.
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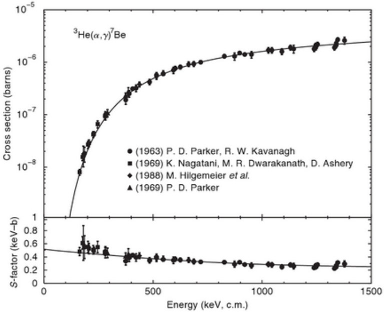
- Different collision energies using the same input *NN* potential.
- At large momentum transfer: experimental points close to the spread obtained for N_W.
- The impact of different density profiles is smaller than the impact of the imaginary part.

Astrophysical S-factor

$$S(E) = Ee^{2\pi\eta}\sigma_{\text{fus}}(E)\ ;\ \eta = \frac{Z_P Z_T e^2}{4\pi\epsilon_0 \hbar v}$$

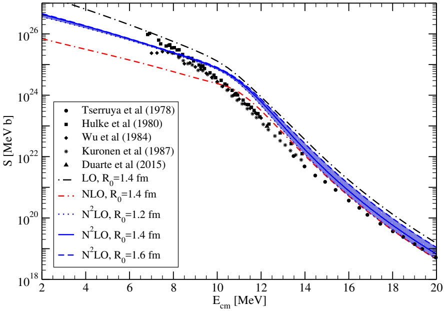
- Oxygen fusion is crucial in medium-mass nuclei burning chains.
- Due to Coulomb repulsion, cross sections drop rapidly when E_{cm} decreases.
- It is useful to define the S-factor, which accounts for the Coulomb repulsion.



Nuclear Reactions for Astrophysics: Principles, Calculations and Applications of Low-Energy Reactions, Ian Thompson and Filomena Nunes

Astrophysical S-factor for $^{16}O+^{16}O$

- At low energy, fusion takes place through quantum tunneling of $V_{\text{eff}}(r, E_{\text{cm}}) = V_F(r, E_{\text{cm}}) + V_{\text{Coul}}(r) + \frac{l(l+1)}{2\mu r^2}$.



V. Durant, P. Capel, *et al.*, PLB 782, 668 (2018)

- $S(E) = Ee^{2\pi\eta}\sigma_{\text{fus}}(E)$.
- Systematics in the order-by-order expansion.
- Small sensitivity to the r-space cutoff R_0.
- Agreement with experiment and systematic order-by-order behavior.

Summary and Outlook

- New soft local chiral interactions to construct double-folding potentials.
- Applications to $^{16}\mathrm{O}-^{16}\mathrm{O}$ elastic scattering in good agreement with experiment without adjustments.
- Important role of the imaginary part for elastic scattering.
- Similar good agreement for $^{16}\mathrm{O}+^{16}\mathrm{O}$ fusion.
- Observables show small sensitivity to the cutoff of the NN interaction.

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Outlook

- Improvement of the description of the imaginary potential.
- Calculation beyond Hartree-Fock level.
- Extension to non closed-shell nuclei.
- Inclusion of $3N$ interactions.

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Thank you for your attention!

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Appendix: phenomenological imaginary potentials