Microscopic potential with Gogny interaction

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P(ND)^2-2, Bruyères-le-Châtel, 14-17 octobre 2014

Phenomenology/Microscopy

- Phenomenological optical potentials

  —

  - Very good in the parametrization range
  - Very useful for applications

  —

  - Lack of predictive power when experiments are missing
  - Local/Non-local potential

- Microscopic approaches

  —

  - Link with NN interaction
  - Predictive power

  —

  - Computer cost
  - Non-local, energy-dependent, complex potential

  —

Microscopic approaches

- Bare NN interaction:
  - Nuclear matter method

    H. F. Arellano et al., PRC 66,024602 (2002).
  - SCRPA

    H. Dussan et al., PRC 84, 044319 (2011).
  - Coupled Cluster

    G. Hagen et al., PRC **86**, *021602(R) (2012).*
  - NCSM

    S. Quaglioni et al., PRL 101, 092501 (2008).

- Effective NN interaction:
  - Nuclear structure method

    N. Vinh Mau, Theory of nuclear structure (IAEA, Vienna 1970) p. 931.

    Y. Xu et al., JPG 41, 015101 (2014).
  - cPVC

    K. Mizuyama et al., PRC 86, 041603 (2012).

NUCLEAR STRUCTURE METHOD

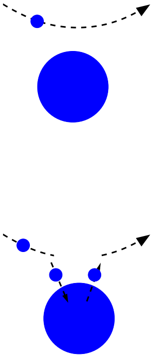
N. Vinh Mau, Theory of nuclear structure (IAEA, Vienna 1970)
N. Vinh Mau, A. Bouyssy. NPA 257 (1976) 189-220
V. Bernard and N.V. Giai, NPA 327, 397 (1979)
F. Osterfeld, et al. PRC 23, 179 (1981)

$$V = V_{HF} + \Delta V_{RPA}$$

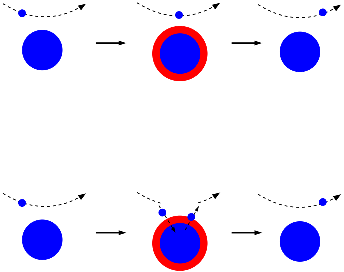
Nuclear structure method

$$V = V_{HF} + \Delta V_{RPA}$$

Elastic scattering off a mean field



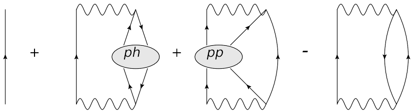
Elastic scattering with excitation of the target



Nuclear structure approach

Optical potential

$$V = V^{HF} + V^{PP} + V^{RPA} - 2V^{(2)}$$



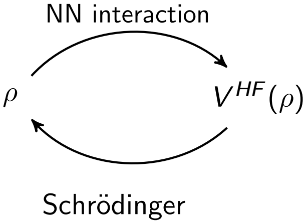
Use of EDF (Gogny interaction)

Particle-particle correlations already contained in Hartree-Fock

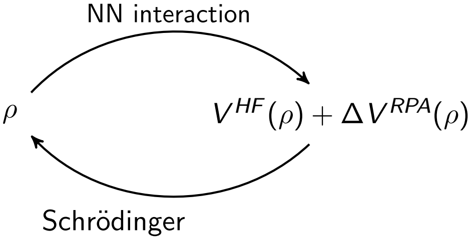
$$\mathrm{Im}\left[V^{PP}\right] \approx \mathrm{Im}\left[V^{(2)}\right]$$

$$V = V^{HF} + \mathrm{Im}\left[V^{(2)}\right] + V^{RPA} - 2V^{(2)}$$

Self-consistency



SCHF



SCRPA

Schrödinger integro-differential equation

- n+A complex, non-local and energy-dependent potential

$$\left[\frac{d^2}{dr^2} + \frac{l(l+1)}{r^2} - k^2\right] f_{jl}(r) + r\int \nu_{jl}(r,r';E) f_{jl}(r') r' dr' = 0$$

$$V(\mathbf{r},\mathbf{r'};E) = \sum_{ljm} \mathcal{Y}_{ljm}(\hat{\mathbf{r}}) \nu_{lj}(r,r';E) \mathcal{Y}^{\dagger}_{ljm}(\hat{\mathbf{r}}')$$

- No localization of the potential
- Solved in a 15 fm box
  - Bound states
    R. H. Hooverman, NPA 189, 155 (1972).
  - Continuum
    J. Raynal, DWBA98, 1998, (NEA 1209/05).

HARTREE-FOCK APPROXIMATION

$$V(\mathbf{r},\mathbf{r'},E) = V_{HF}(\mathbf{r},\mathbf{r'}) + \Delta V_{RPA}(\mathbf{r},\mathbf{r'},E)$$

C. B. Dover and N. V. Giai, NPA 190 (1972) 373
C. B. Dover and N. V. Giai, NPA 177 (1971) 559

HF approximation to the n+A potential

$$V_{HF}(\mathbf{r},\mathbf{r'}) = \int d\mathbf{r}_1 v(\mathbf{r},\mathbf{r}_1)\rho(\mathbf{r}_1)\delta(\mathbf{r}-\mathbf{r'}) - v(\mathbf{r},\mathbf{r'})\rho(\mathbf{r},\mathbf{r'})$$

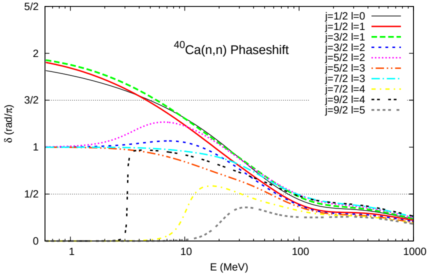
$$\rho(\mathbf{r}) = \sum_i n_i|\phi_i(\mathbf{r})|^2,$$

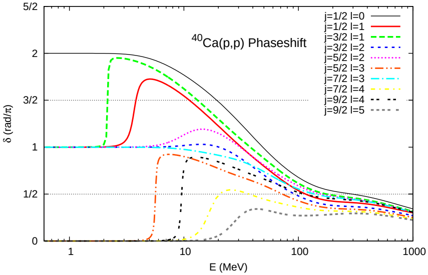
$$\rho(\mathbf{r},\mathbf{r'}) = \sum_i n_i\phi_i^*(\mathbf{r})\phi_i(\mathbf{r'})$$

- v: Gogny force
  Finite range NN interaction → V_{HF} non-local.
- v is real and energy independent
  V_{HF} is real and energy independent.
- HF in coordinate space
  → Good asymptotic behavior of the wave functions
  (not the case with HO basis).
  → Correct treatment of the continuum
  (Distorted Wave ϕ_λ, Resonances).

K. Davies, S. Krieger, and M. Baranger, Nuclear Physics 84, 545 (1966).

HF phase shift n/p+^{40}Ca

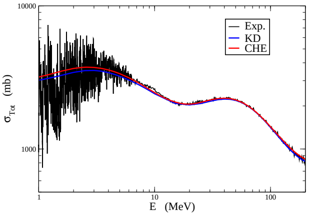


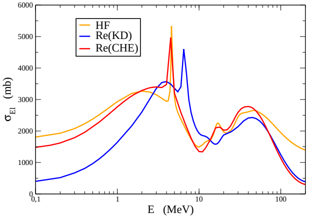


- Resonances when $\delta = n\pi/2$ (n odd).
- Correct DW treatment of the intermediate wave ϕ_λ.
- Impact on ΔV_{RPA}

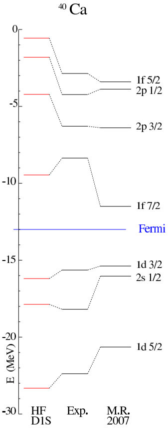
V^{HF} vs. $Re(V_{pheno})$

Total cross section n+^{40}Ca





Bound states HF/D1S Exp. CHE

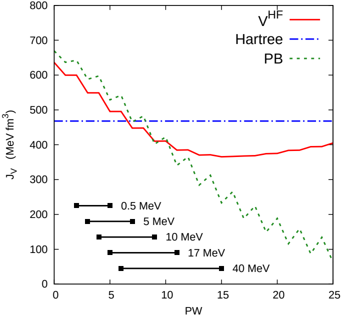


- V^{HF} gives the main contribution to the real part of the potential

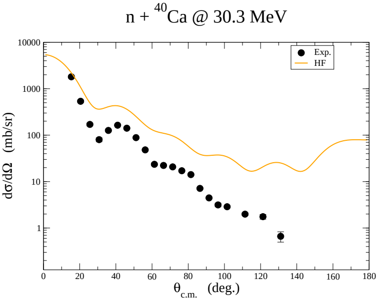
(B. Morillon and P. Romain, Phys. Rev. C 70, 014601 (2004).) → dispersive potential

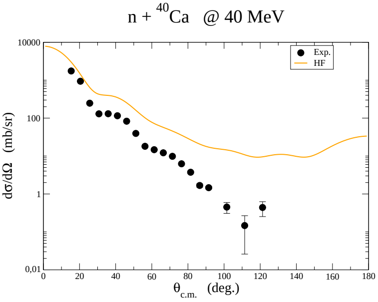
(A. J. Koning and J. P. Delaroche, Nuclear Physics A 713, 231 (2003).)

Hartree-Fock volume integral



Elastic cross section n+^{40}Ca





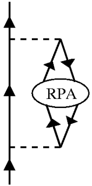
RANDOM-PHASE APPROXIMATION

$$V(\mathbf{r},\mathbf{r'},E) = V_{HF}(\mathbf{r},\mathbf{r'}) + \Delta V_{RPA}(\mathbf{r},\mathbf{r'},E)$$

RPA potential

$$\Delta V_{RPA} = \mathrm{Im}\left[V^{(2)}\right] + V^{RPA} - 2V^{(2)}$$

$$V^{RPA}(\mathbf{r},\mathbf{r}',E) = \lim_{\eta\to 0^+} \sum_{N\neq 0, ijkl} \sum\!\!\!\!\!\!\int_{\lambda} \chi_{ij}^{(N)} \chi_{kl}^{(N)} \times \left(\frac{n_\lambda}{E - \epsilon_\lambda + E_N - i\eta} + \frac{1 - n_\lambda}{E - \epsilon_\lambda - E_N + i\eta} \right) F_{ij\lambda}(\mathbf{r}) F^*_{kl\lambda}(\mathbf{r}')$$



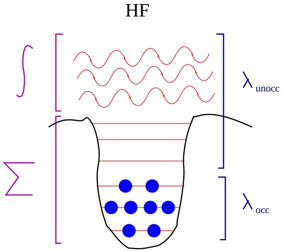
with

$$F_{ij\lambda}(\mathbf{r}) = \int d^3\mathbf{r}_1 \phi_i^*(\mathbf{r}_1) v(\mathbf{r},\mathbf{r}_1)[1-P]\phi_\lambda(\mathbf{r})\phi_j(\mathbf{r}_1)$$

- ϕ's are HF wave functions.
- We include both bound and continuum particles in constructing our intermediate state ϕ_λ.
- Excitations of the target described with RPA/D1S

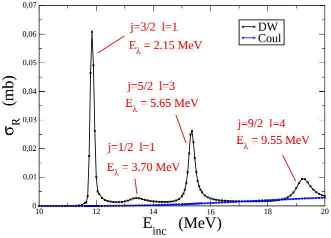
  Blaizot, et al., NPA 265, 315 (1976).

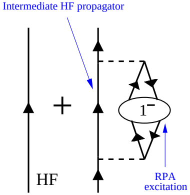
  Berger, et al., Comp. Phys. Com. 63, 365 (1991).

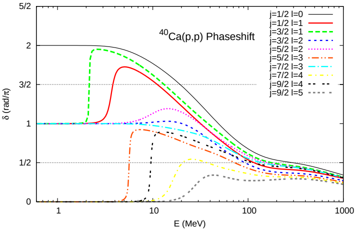


Effect of HF intermediate propagator

- p+^{40}Ca
- $V_{HF} + \mathrm{Im}(V_{RPA})$
- Coupling to the first 1^- $E_{1^-} = 9.7 MeV$



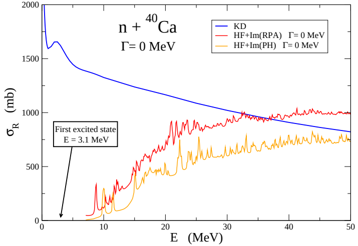




- Effect of resonances of the intermediate HF propagator.
- Enhancement of σ_R compared as with a Coulomb wave.

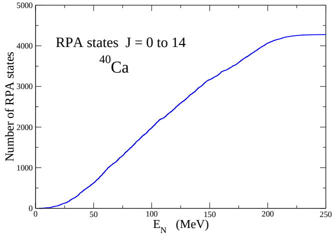
Effect of HF intermediate propagator

- σ_R from $V_{HF} + \mathrm{Im}(V_{RPA})$
- σ_R from $V_{HF} + \mathrm{Im}(V_{PH})$



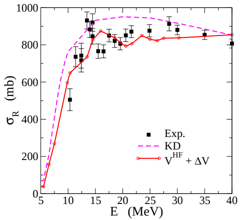
$\rightarrow$ Effect of the HF resonances on $\mathrm{Im}(V_{RPA})$

- Zero width calculation:
  - $\sigma_R = 0$ for incident energies below the energy of the first excited state of the target nucleus
- ^{40}Ca RPA states $J = 0 \rightarrow 8$

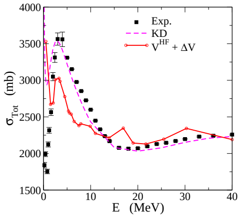


Averaged potential

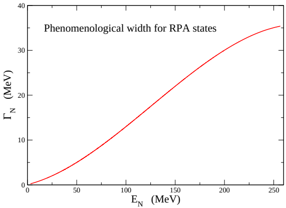
- $p + {}^{40}\mathrm{Ca}$



- $n + {}^{40}\mathrm{Ca}$



- Physical origin of width
  - Self-consistent scheme
  - $\eta \neq 0$ when HF propagator gets dressed by RPA
  - $E_N \rightarrow E_N + i\Gamma_N(E_N)$
    Damping (doorway state) & continuum



- Use of a phenomenological width (Harakeh and van der Woude)

Averaging...

$$S = \langle S \rangle + \widehat{S}$$

Averaged cross section

$$\begin{aligned}
\langle \sigma_E \rangle &= \frac{\pi}{k^2} \langle |1 - S|^2 \rangle \\
\langle \sigma_R \rangle &= \frac{\pi}{k^2} \langle 1 - |S|^2 \rangle \\
\langle \sigma_T \rangle &= \frac{\pi}{k^2} \langle 1 - Re[S] \rangle
\end{aligned}$$

Averaged potential

$$\begin{aligned}
\bar{\sigma}_E &= \frac{\pi}{k^2} |1 - \langle S \rangle|^2 \\
\bar{\sigma}_R &= \frac{\pi}{k^2} (1 - |\langle S \rangle|^2) \\
\bar{\sigma}_T &= \frac{\pi}{k^2} (1 - Re[\langle S \rangle])
\end{aligned}$$

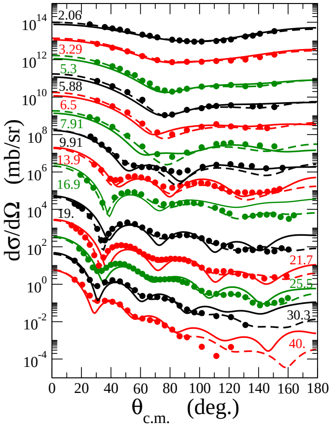
$$\begin{aligned}
\langle \sigma_E \rangle &= \bar{\sigma}_E + \sigma_{CE} \\
\langle \sigma_R \rangle &= \bar{\sigma}_R - \sigma_{CE} \\
\langle \sigma_T \rangle &= \bar{\sigma}_T
\end{aligned}$$

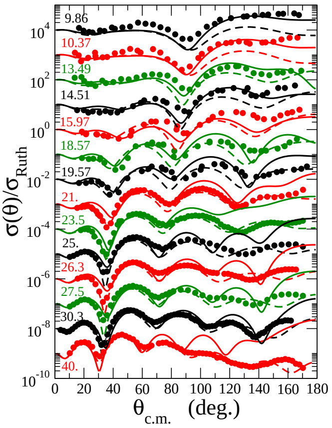
Compound elastic

$$\sigma_{CE} = \frac{\pi}{k^2} \langle |\widehat{S}|^2 \rangle$$

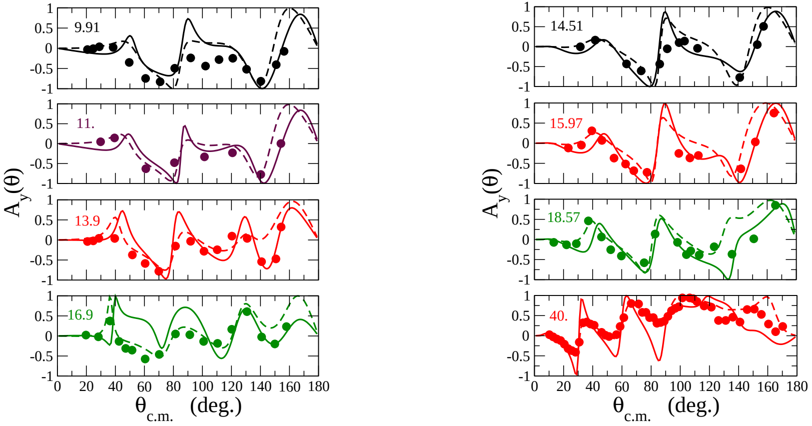
- TALYS: Hauser-Feshbach/ Koning-Delaroche
- particularly relevant for neutron scattering below 10 MeV

Elastic cross section n/p+^{40}Ca





Analyzing powers n/p+^{40}Ca



Conclusion

- Summary:
  - We take into account absorption coming from the coupling to RPA states.
  - Consistent scheme.
  - Tools to deal with non-local potentials (bound and continuum states, HF in coordinate space).
  - Exact treatment of the intermediate state with resonances.
  - Good agreement with experiment (cross section, analyzing power) for ^{40}Ca up to 30 MeV.
  - ^{48}Ca, ^{90}Zr, ^{132}Sn and ^{208}Pb in production
- Outlooks:
  - Bound single particle dressing.
  - Consistent width.
  - Consistent Compound elastic.
  - QRPA potential, deformed nuclei.
  - Inelastic scattering.