Compound Nucleus Contributions to the Optical Potential

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Nonelastic Channels

- Optical Potential for n+A Elastic Scattering:
  - monopole folding potential,
  - + dynamic polarisation potential from all non-elastic reactions.
- Direct Reactions,
  - Examples: collective inelastic states or pickup
  - All remove flux from the elastic channel
  - Effect on elastic scattering is an imaginary contribution to the optical potential, giving
  - Reaction Cross Section
- Full Calculation: DPP has Real & Imaginary Components
  - Energy dependence of these related by dispersion integrals.

Compound Nucleus States

- CN States are Long-lived Resonances
  - narrow peaks in an incident-energy spectrum.
- Remove Flux from the Elastic Channel, which Flux is emitted some long time later:
  - either back to the elastic channel,
  - or by γ-ray or particle emissions.
- After a long time,
  - No remaining information about the incident beam direction,
  - Decays are isotropic (subject to conserved quantum numbers)

The Optical Potential

- Defined to include the effects of all 'fast' absorption from the elastic channel
  - when averaged over some interval $I \gg D$, where D is the level spacing
  - So CN states give optical-model absorption
- This is to treat separately:
  - Shape Elastic
    - From the optical potential
  - Compound Elastic:
    - What only much later feeds back to the elastic channel.

Average Widths

- To calculate the optical potential, need information about (average) CN resonances.
- The ratio of the average width of the resonances $\langle\Gamma\rangle$ to D gives the reaction cross section loss in the elastic channel α:

$$1 - |S_{\alpha\alpha}^{\text{opt}}|^2 = 2\pi \langle\Gamma_\alpha\rangle / D$$

(This is the ratio needed for Hauser-Feshbach calculations)

- BUT: to calculate the $\langle\Gamma_\alpha\rangle / D$ ratio, microscopic details needed, either statistical, or schematic.

Schemes for finding $<\Gamma_\alpha>/D$

- $<\Gamma_\alpha>/D$ is the fraction, total-width/spacing.
- Consider doorway states
  - (those reached from first particle-hole step)
  - These will be 'fractioned' into all the final CN states,
  - BUT:
    - Initial doorways and final CN states have similar $<\Gamma_\alpha>/D$
  - SO:
    - try to model the doorway states so they have correct average physical widths $<\Gamma_\alpha>$ and spacings D

Coupled Channels Models

- Try to explicit couple elastic to CN states
  - Too many to do all of these, so:
  - Just focus on the particle-hole Doorway States
- Do coupled-channels calculations:
  - Either: pure particle-hole excitations in mean field,
  - Or: Correlated p-h states from Random Phase Approximation (RPA) model of excitations (so include some residual interactions in target)
- (Starting to) Unify Direct Reaction and Statistical Methods

Steps in OM calculation

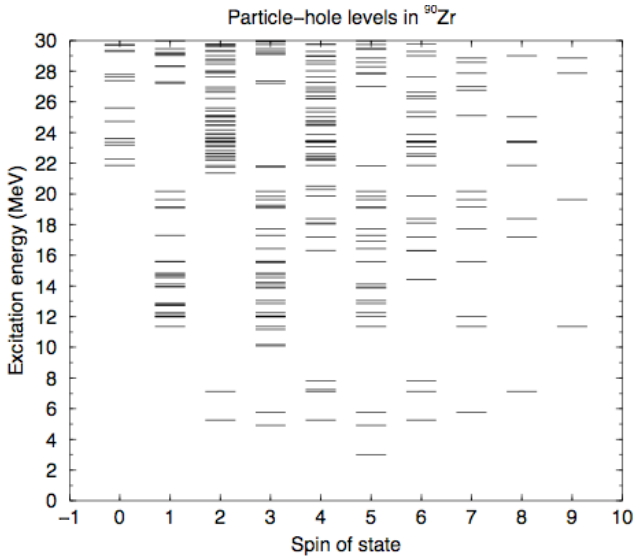
1. Nucleus ^{A}Z: here ^{90}Zr.
2. Hartree-Fock gs + RPA excitations
   - Transition densities gs $\rightarrow$ E*(f)
3. Folding with effective $V_{nn} \rightarrow V_{f0}(r;\lambda)$
4. Large Coupled-channels calculations
   - Extract S-matrix elements $S_{\alpha\alpha'}$
   - Hence:
     - Reaction cross sections $\sigma_R(L) = \pi\,(2L+1)\,[1-|S_{\alpha\alpha}|^2]/k^2$
     - Elastic $\sigma(\theta)$
5. Use partial reaction cross sections $\sigma_R(L)$ in HF models
6. (If desired) fit $\sigma(\theta)$ to find elastic optical potential

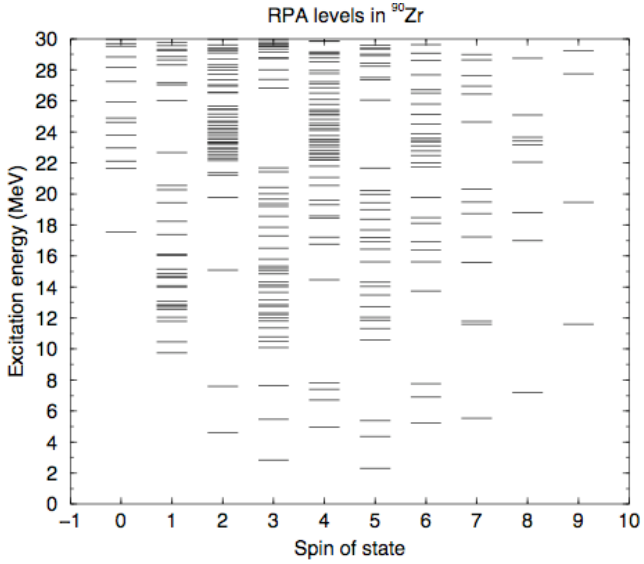
   [An optical potential = convenient way of generating $\sigma_R(L; E)$]

Particle-hole & RPA levels

- Spherical HF calculations from Marc Dupuis
- Using Gogny's D1S' force (V_{so}=−115 MeV)
- Harmonic oscillator basis,
  14 $\hbar\omega$ where $\hbar\omega$ = 13.70 MeV minimises the ^{90}Zr gs
- RPA calculation of spectrum
  - (removing spurious 1^- state that is cm motion)
  - Extract super-positions of particle-hole amplitudes for each state.

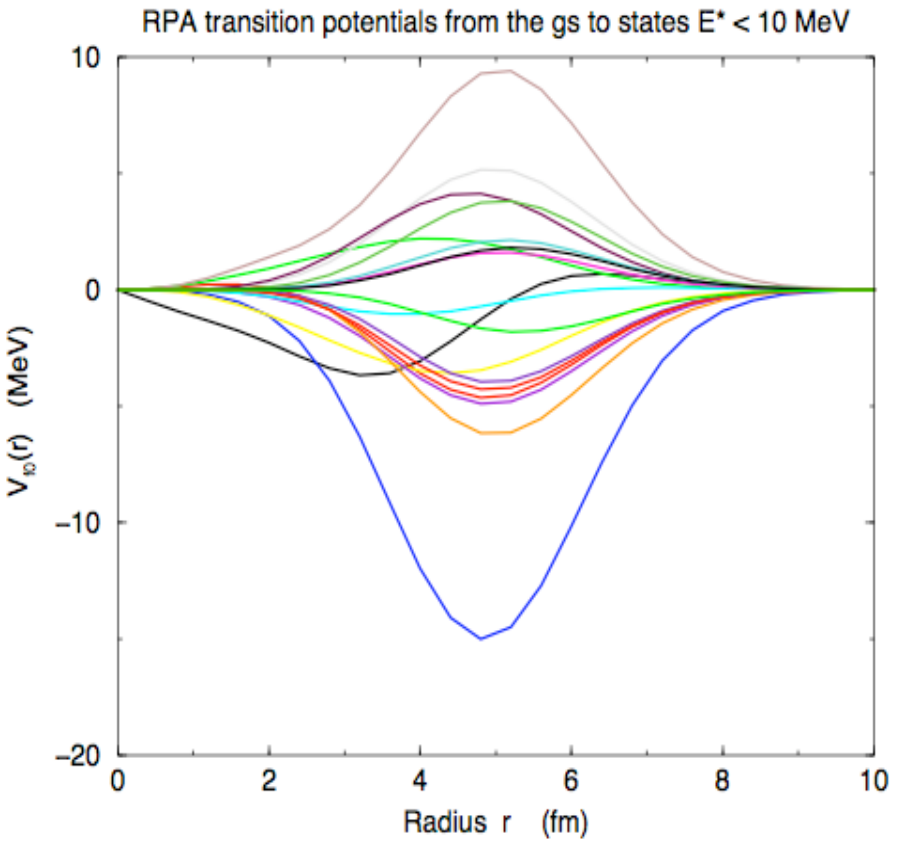
Note: this only a small fraction of all the levels!





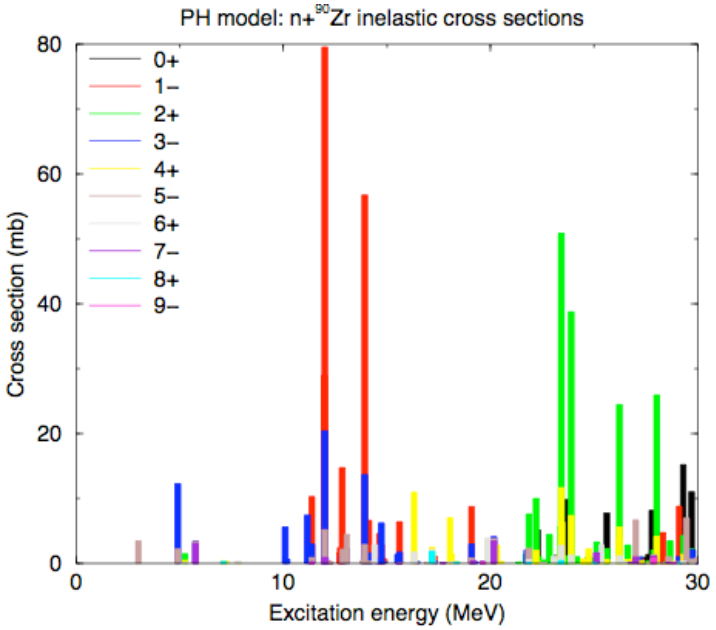
Folding with effective V_{nn} to get transition gs → E*(f)

- Use Love's effective V_{nn} derived from M3Y
  - (fit with Gaussians)
  - direct + approximate (ZR) exchange
- Folded with RPA transition densities using Fourier method
- Derived transition potentials $V_{f0}(r;\lambda)$ from gs to each excited state, of multipole λ

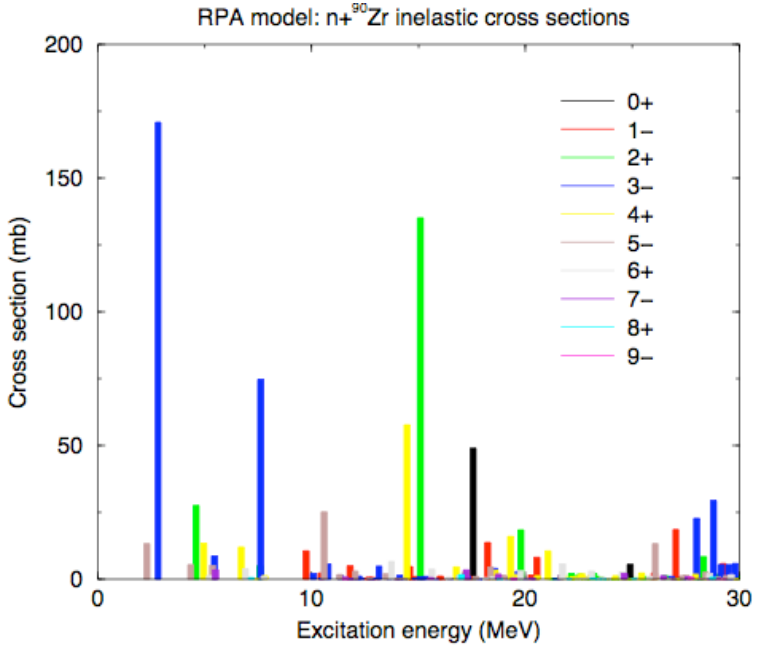


Coupled channels n+A*

- Add Woods-Saxon real monopole $V_0(r)$
  - NO imaginary part in any input
- Fresco Coupled inelastic channels at $E_{lab}(n)=40$ MeV
  - E* < 10, 20 or 30 MeV, with ph and RPA spectra.
  - Maximum 1277 partial waves.
- RPA moves 1^- strength (to GDR), and removes c.m. motion and enhances collective 2^+, 3^-

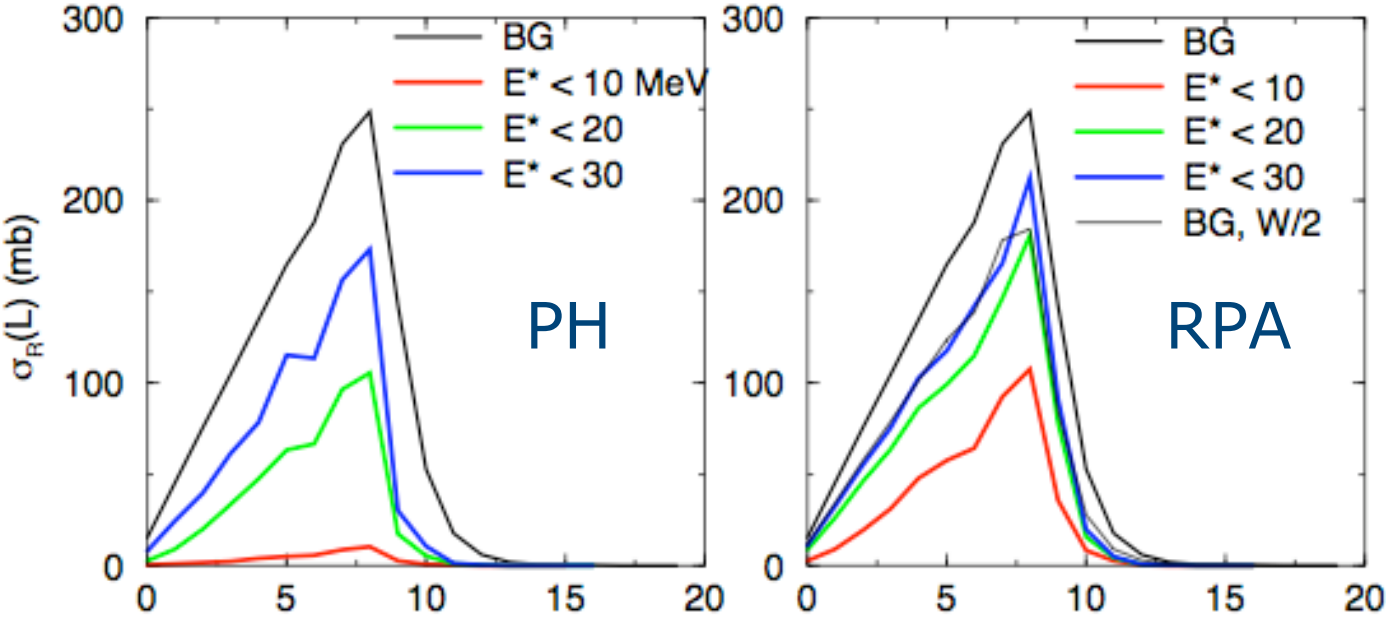


(Note change of scale!)



Predicted Cross sections

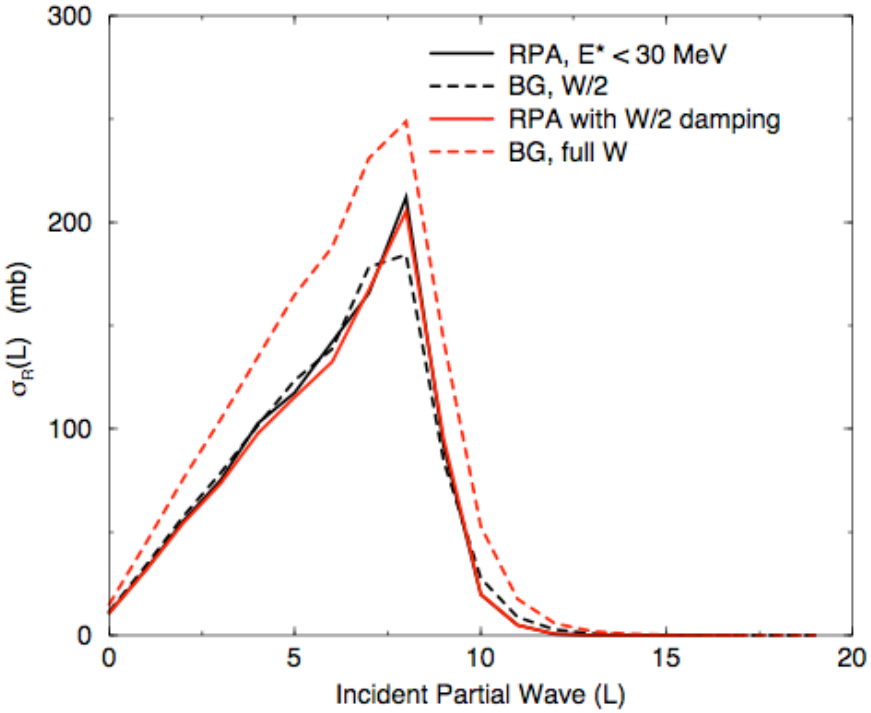
- Calculate reaction cross section $\sigma_R(L)$ for each incoming wave L
  - Guidance: compare with $\sigma_R(L)$ from fitted optical potential such as Becchetti-Greenlees (black lines)
- Result: with RPA and all 30 MeV of spectrum, we obtain about HALF of 'observed' reaction cross section.
- Optical Potentials can be obtained by fitting to elastic S_L or $\sigma_{el}(\theta)$



$n+^{90}Zr$ at 40 MeV

Damping of Doorway States

- Doorway States couple to further ph states:
  the 2p2h states
  (giving 3p2h, including incident nucleon)
- So: Doorways damped just like the incident 1p state!
- Try using observed 1p damping for each of the doorway states?
  - (ignoring escape widths of the RPA/1p1h states)



NOT a large effect in this approx.
Unless excited states damped More

Improving the Accuracy

- RPA model has Low-Lying Collective + Giant Resonance States.
  - Is this structure Accurate?
- We should couple Between RPA states
  - Known to have big effect in breakup reactions
- Re-examine Effective Interaction V_{nn}
  - Especially its Density-Dependence

Resonance Averaging

- At lower energy these CC calculations will give resonances, from closed inelastic channels.
  - Must Average theoretical curves over resonances
  - Or use Complex Energy. For interval I:
    - $\langle S(E) \rangle = S(E + iI)$
  - Note:
    CC calculations with only doorway states have only SMALL level densities:
    - Much Smaller than Observed CN-resonance level density.

Conclusions

- We can now Begin to:
  - Use Structure Models for Doorway States, to
  - Give Transition Densities, to
  - Find Transition Potentials, to
  - Do large Coupled Channels Calculations, to
  - Extract Reaction Cross Sections & Optical Potentials
- Still Need:
  - More systematic calculation of Doorway Widths
  - Higher Level-Densities of resonance, & their Averaging.
- (Starting to) Unify Direct Reaction and Statistical Methods