Microscopic particle-hole amplitudes for low-energy reactions.

Ian Thompson, Jutta Escher, Frank Dietrich, Vesselin Gueorguiev and Daniel Gogny
Nuclear Theory & Modelling, Lawrence Livermore National Laboratory,
Ludovic Bonneau, Marc Dupuis and Toshihiko Kawano
Theoretical Division, Los Alamos National Laboratory
Progress Report

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. Coupled-channels calculations
   • Reaction cross sections; Elastic $\sigma(\theta)$
5. Fit to find elastic optical potential
6. Other reactions:
   $(\alpha,\alpha')$, $(^3He,\alpha)$ microscopic transitions
Nucleus $^{90}$Zr

- Spherical HF calculations by Marc Dupuis
- Using Gogny's D1S' force ($V_{so} = -115$ MeV)
- Harmonic oscillator basis,
  $14 \ h_\omega$ where $h_\omega = 13.70$ 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.
Folding with effective $V_{nn}$ to get transition $gs \rightarrow E^*(f)$

- Use Love’s effective $V_{nn}$ derived from M3Y
  - (fit with Gaussians)
  - direct + approximate (ZR) exchange
- Folded with RPA transition densities by Frank Dietrich using Fourier method
- Derived transition potentials $V_{f0}(r;\lambda)$ from $gs$ to each excited state, of multipole $\lambda$
Coupled channels \( n+A^* \)

- Add Woods-Saxon real monopole \( V_0(r) \)
  - NO imaginary part in any input
- Fresco Coupled inelastic channels at \( E_{\text{lab}}(n)=40 \) 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 \( 2^+, 3^- \)
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 a large fraction of 'observed' reaction cross section.
- Optical Potentials fitted to elastic $S_L$ or $\sigma_{el}(\theta)$: see Arbanas talk

![Graphs showing predicted cross sections](image-url)
Inelastic ($\alpha,\alpha'$) for spherical targets

J. Escher

- **Goal**: Calculate cross sections for highly-excited $^{90}$Zr states
- **Start**: with ph description, weak-binding approximation, phenomenological OMPs, schematic treatment of spreading widths
- **In progress**: Systematic investigation of improved nuclear structure input

**Example**: Weak-binding vs. bin-function description shows level of uncertainty in the description of unbound final states.

Example: Comparison of ph calculation with experiment. Calculation with RPA transition densities (w/F.S. Dietrich) to be finalized...

$^{90}$Zr($\alpha,\alpha'$) at $E_\alpha=140$ MeV
(\(^3\text{He},\alpha'\)) pickup from deformed targets
V. Gueorguiev, P.D. Kunz, F.S. Dietrich, J. Escher

- Goal: Calculate cross sections for highly-excited \(^{156}\text{Gd}\) states
- Initial calculations use single-particle states in a deformed WS potential, phenomenological OMPs, schematic treatment of spreading widths
- Starting point for work on deformed systems...

**Results:** Distribution of excited states in \(^{156}\text{Gd}\), produced via neutron-removal from \(^{157}\text{Gd}\). Radii of circles indicate strengths of pickup cross sections.
Nucleon direct + semidirect capture
L. Bonneau, T. Kawano, LANL.

- **Compound-Nucleus mechanism:**
  incident energy equally shared among all degrees of freedom (dominant below 5 MeV)

- **Direct-Semidirect mechanism:**
  projectile scattered into a bound state of the target either directly (direct part) or through the excitation of the giant dipole resonance (semidirect part)

- **Microscopic single-particle bound states** \( | b \rangle \) for even-even targets in the Hartree-Fock-BCS model:
  no input parameters aside from the effective nucleon-nucleon interaction (of the Skyrme type)

**Calculated results:**

\[
\begin{align*}
\sigma_{DSD} & \propto \sum_{b,M,...} |\mathcal{M}_D + \mathcal{M}_{SD}|^2 \\
\mathcal{M}_D & \propto \langle \Psi_f^{(b)} | \hat{O}_{E1} | \Psi_i \rangle \\
\mathcal{M}_{SD} & \propto \sum_s \frac{\langle \Psi_f^{(b)} | \hat{O}_{E1} | \Psi_s \rangle \langle \Psi_s | \hat{H}_{p-v} | \psi_i \rangle}{E_{\gamma} - E_s + i\Gamma_s/2}
\end{align*}
\]

\( \hat{O}_{E1} \): electric dipole operator
\( \hat{H}_{p-v} \): particle-vibration coupling

- |\( \psi_0 \rangle \rangle\):
  GS vibrational core
- |\( I_sM_sK_s \rangle \rangle\):
  excited vibrational core
- |\( I_fM_fK_f \rangle \rangle\):
  rotational state
- |\( |b \rangle \rangle\):
  scattering state
- |\( |\Psi_f^{(b)} \rangle \rangle\):
  bound state
- |\( |\Phi_i \rangle \rangle\):
  GS vibrational core

Articles and Preprints


2. Inelastic alpha scattering from a spherical nucleus: Particle-hole vs. RPA approach, J.E. Escher and F.S. Dietrich, in preparation


Plans for Next Year

1. Calculate monopole folded potentials
   • Fit to bound single-particle levels in the mean field?
2. MPI Parallelising of Fresco coupled channels (enable 3.)
3. Calculation of couplings between excited states
   • (Suspicion: this reduces reaction cross sections)
4. Good extraction of elastic optical potentials
   • Explore L- and parity-dependence
5. Estimate spreading width from ph↔2p2h couplings
   • Add as diagonal imaginary part to ph excited states.
Plans for Next Year (cont.)

6. Systematic examination of range of targets
   • Reproduce shell effects in optical potentials?

7. Theoretical reproduction of resonances?
   • Averaging (cross sections, potentials) over resonances.

8. Applications to Excitation cross section calculations:
   1. Identify proper description for (highly-) excited states reached by scattering and transfer reactions.
   2. Move towards a microscopic description of spreading widths and compare to phenomenological descriptions.
   3. Identify (and begin to implement) appropriate descriptions for reactions with deformed targets (rare earth and actinide nuclei).
Thompson, Escher, postdoc

- We will perform a systematic calculation in nucleon-nucleus collisions of particle-hole excitation cross sections, first ignoring pp- and hh-correlations and the summed first order contributions will be compared with reaction cross sections. **Done**
- They will develop ways to use second and higher-order ph- excitations to calculate their contributions to the optical potential, especially to its imaginary part. **Not yet done**
- They will also work on improving the predictions of reaction cross sections in collaboration with Arbanas (ORNL). **Done for optical potentials**
- The continuum particle states will be included in the ph-couplings and compare, using quasi-bound wave functions, resonant bins, and the Gamow shell model expansions (Escher+Arbanas) **Some comparisons done**
- They will begin systematic links to structure calculations by folding RPA transition densities to give transition potentials, for use in one-, two- and all-order calculations. **Done**
- Also they will try a direct use of structural information given as correlated expansions on a single-particle basis. **Not yet done**
- They plan to begin implementing a distributed coupled-channels solver, spreading the computation load for even a single Jπ coupled-channels set over multiple nodes. **First part done, second beginning**
- Thompson in collaboration with Nunes (MSU) will use coupled channels tools for regular nuclear breakup. **Ongoing**