Coupled-Channels Effects in Optical Potentials for deformed nuclei, and in Semi-direct Mechanisms for neutron capture

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Topics

- Convergence issues for rotational nuclei
- Validity of the adiabatic limit & of near-even approx.
- Previous actinide optical potentials for neutrons
- A new optical potential fit for actinide nuclei
- Uncertainties in extracting compound cross section
- Further coupled-channels effects in capture
  - Beyond schematic-DWBA for semi-direct captures.
Convergence issues for rotational nuclei

$E_n = 0.1 \text{ MeV},$  
4 open channels

$E_n = 1.0 \text{ MeV},$  
12 open channels

Note the scale!

Get essential same results even if set excitation energies $E^*=0!$
Sets of 5 to 13 channels

Sets of 11 to 17 channels

Converges to almost unit ratio.

**Note:** this unity is for sum over $J^\pi$: not for separate $J^\pi$. 

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Adiabatic Limit (all excitation energies $E^*=0$ MeV)

Adiabatic limit is:

- Zero excitation energies for the ground state band $E^*=0$
- Equivalent to large (infinite) moment of inertia of target
- Target then does not rotate during the neutron reaction.

Can then prove:

- $\sigma_{\text{CN}} = \text{average over all nuclear orientations of the CN production for each orientation.}$
  - for all nuclei (even or odd; any K)
- This also holds in the PWBA limit (Plane Wave Born Approximation).

Dietrich, Kawano & Thompson, PRC 85, 044611 (2012)
Adiabatic Approximation is Exceptionally Good!

Even at neutron energies much less than E* excitations:

- This implies:
  - Validity of spectator approximation for target spin
  - Correct to average transmission coefficients over target spins (with \( m \)-state-count weighting)
  - CN production independent of both I,K
  - Can predict any transition \( IK \rightarrow I’K’ \) from knowing all \( 00 \rightarrow J0 \) transitions!

See Lagrange et al, NSE (1982).
Previous rotational calculations

- We conclude that even-even nuclei need coupled-channels sets of $s=6$ levels (with $g_s$).
- Even-odd nuclei require up to 12 levels for accuracy.
- TALYS: default calculations are
  - ‘maxrot=2’ (levels in addition to the $g_s$: $s=3$)
- FLAP2.2 actinide potential fitted with $s=3$
- Soukhovitskii fitted his potentials
  - Using ‘saturated coupling’ of maxrot=4 ($s=5$)
- Clear need to re-evaluate calculations and re-evaluate optical potentials.
Previous actinide optical potentials

Soukhovitskii (2004):

- best actinide potentials to date
- His s=5 calculations indeed converged for most observables: mainly $\sigma_{TOT}$, $\sigma_{el}(\theta)$, and $\sigma_{inel}(\theta)$.
- However: they are not fully converged for absorption / CN-production: $\sigma_{CN}$.

Again need to re-examine the determination of CN-cross section from other observables.
New optical potential fit for actinides

- Improve ‘FLAP 2.2’ from Frank Dietrich (LLNL)
  - Parameters are piecewise-linear functions of neutron energy.
  - Soukhovitskii has analytic functions:
    - not so easy to adjust the various energy regions;
    - We want a fit independent of this.
  - So we start with a deformed Koning-Delaroche global potential
  - Fit $^{238}$U, then $^{232}$Th, and then other actinides.

- Make a ‘FLAP 3.0’ parameter set
FLAP 3.0 potential fit for actinides (a)


Green: Soukhovitskii (2004) with KD formula for Fermi energies. $(\beta_2=0.223, \beta_4=0.056)$

Red: new FLAP3.0 $(\beta_2=0.213, \beta_4=0.043$ from re-analysis of inelastic cross sections)

Results for neutron+$^{238}$U scattering.
FLAP 3.0 potential: more elastics (b)
FLAP 3.0 potential: total, CN (c)

Total

CN production
FLAP 3.0 potential: low-E neutron (d)

$S_0$, $S_1$ and $R'$ from Mughabghab

Work in Progress!
Uncertainties in extracting $\sigma$(CN)

Note again the large variations in $\sigma$(CN) even when $\sigma$(TOT) is similarly fitted:


Red: new FLAP3.0
Related:
Semi-direct capture mechanisms

- Ideally: want a unified treatment of
  - two-step capture mechanisms
  - other coupled-channels processes

- Semi-direct E1 capture is when:
  1. GDR inelastically excited,
  2. leaving neutron in final bound state,
  3. GDR later decays, emitting the E1 gamma-ray.

- Direct and semi-direct interfere coherently.
  - GDR collectivity is strong: should be coupled-channels
Semi-direct capture mechanisms

- Calculation of capture $^{208}$Pn(n,γ) via giant-dipole resonance (GDR)
- Comparison with CUPIDO, which uses on-shell form of Green’s function.
- Slightly different interference shapes.
- CC framework is more general.

![Graph showing capture cross section vs. neutron energy](image)
Collective transitions in capture

- Neutron-nucleus scatterings require coupled-channels calculations.
  - Rotation models for all known band, even beyond
  - Vibrational models for 1- or 2-phonon excitations

- For consistency, should include these couplings also in the final neutron bound states.

- Still is some debate about imaginary parts $W$ of optical potentials in incoming & final channels.
  - **Incoming**: $W/2$ related to resonance averaging interval
    - OR: to the ‘floor’ between resonances.
  - **Final**: $W/2$ gives spreading of doorways into the discrete (bound) compound microstates.
Role of $2^+$ state in $^{56}\text{Fe}(n,\gamma)$ captures: direct contribution only

Real incoming potentials: resonances

Complex incoming potentials: smoothed

Direct contribution should be less than ‘floor’ between resonances. This favors non-spherical models (red lines).
Conclusions

- We need to pay good attention to:
  - Convergence of inelastic scattering in rotational models
  - Uncertainties (and covariances!) in extraction of CN-production cross sections from other observables
  - Developing a new actinide potential: e.g. FLAP3.0

- We can benefit from:
  - Good physical accuracy of adiabatic model for rotational excitations.
  - Use of near-even-even approximation for odd nuclei
  - Coupled-channels treatments of 2-step capture processes