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

NEMEA-7/CIELO Workshop

Nov 6, 2013

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LLNL-PRES-645406

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Topics

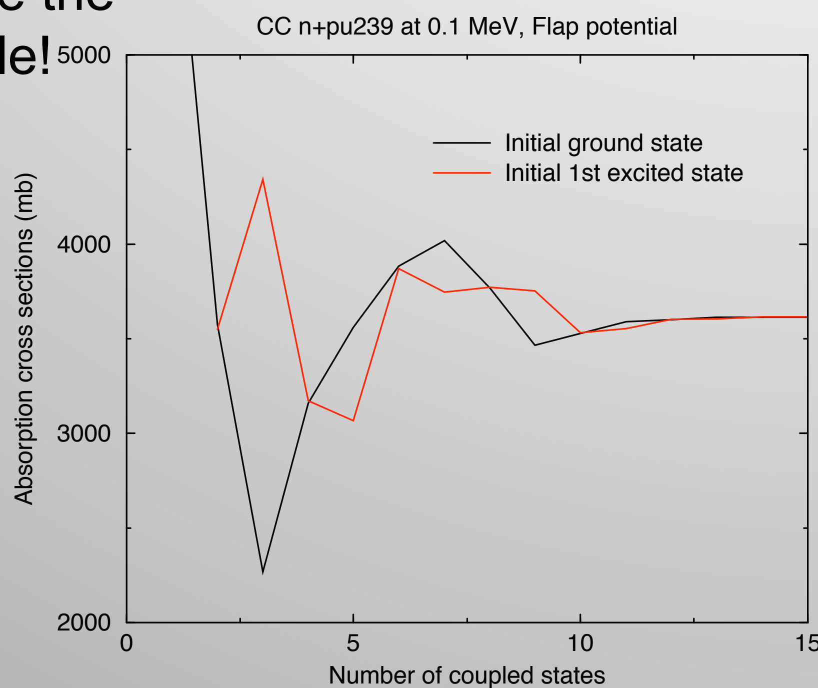
- Convergence issues for rotational nuclei
- Validity of the adiabatic limit & of near-even approx.
- Previous actinide optical potentials for neutrons
- A new optical potential fit for actinide nuclei
- Uncertainties in extracting compound cross section
- Further coupled-channels effects in capture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

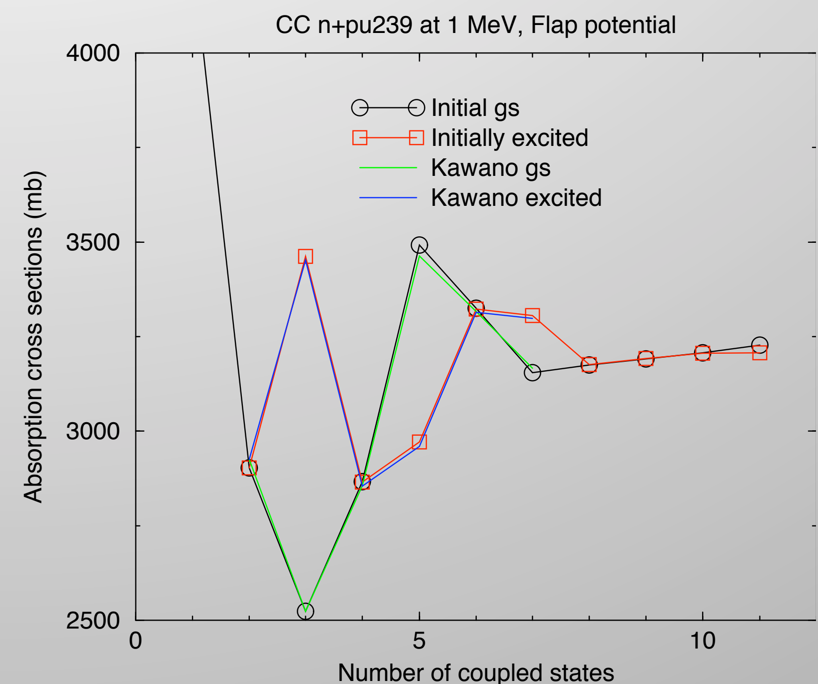
Convergence issues for rotational nuclei

E_n = 0.1 MeV,
4 open channels

E_n = 1.0 MeV,
12 open channels

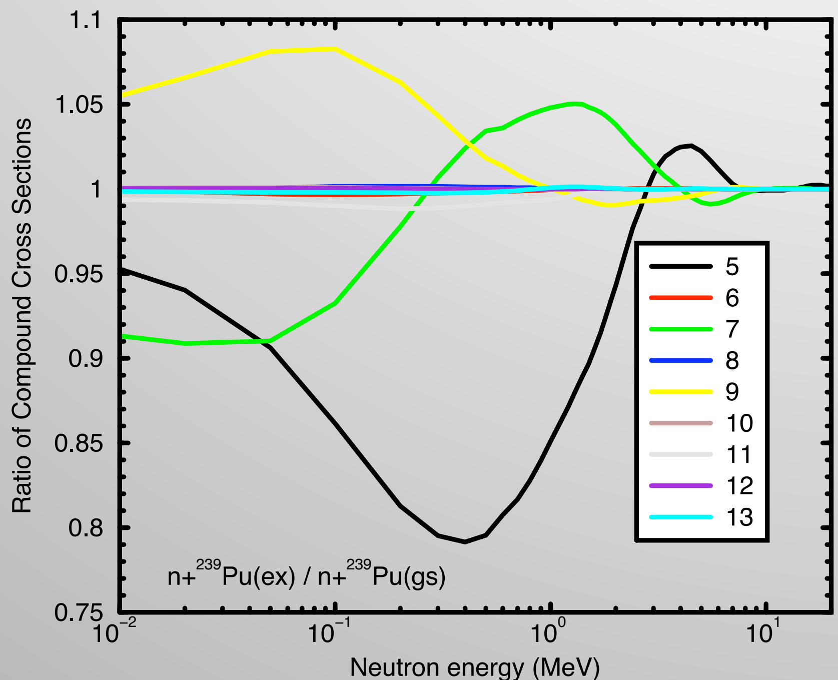
Note the scale!



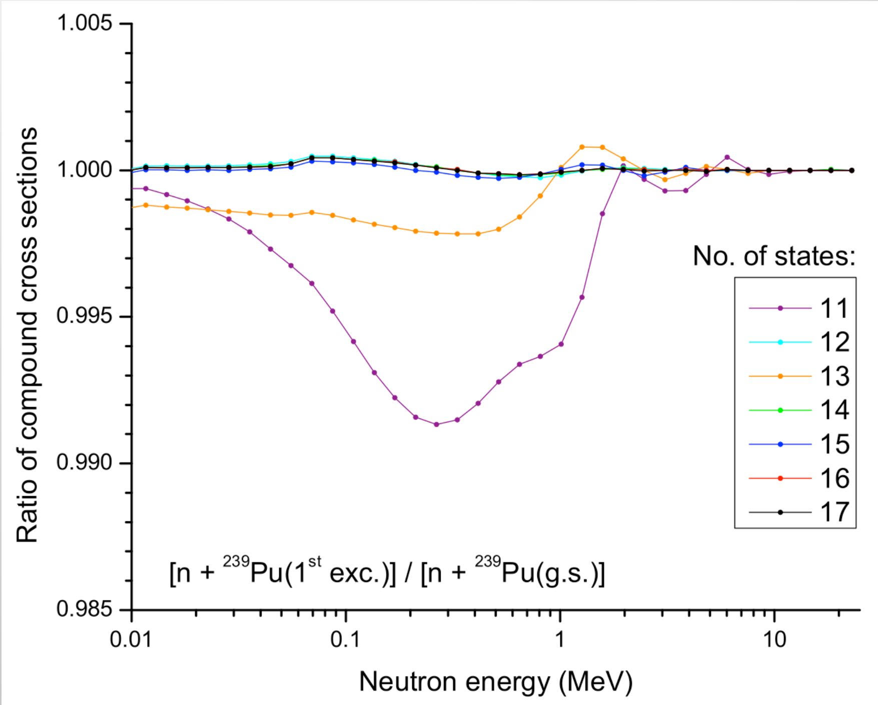


Get essential same results even if set excitation energies E*=0!

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^{π}: not for separate J^{π}.

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:

- σ_{CN} = 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.

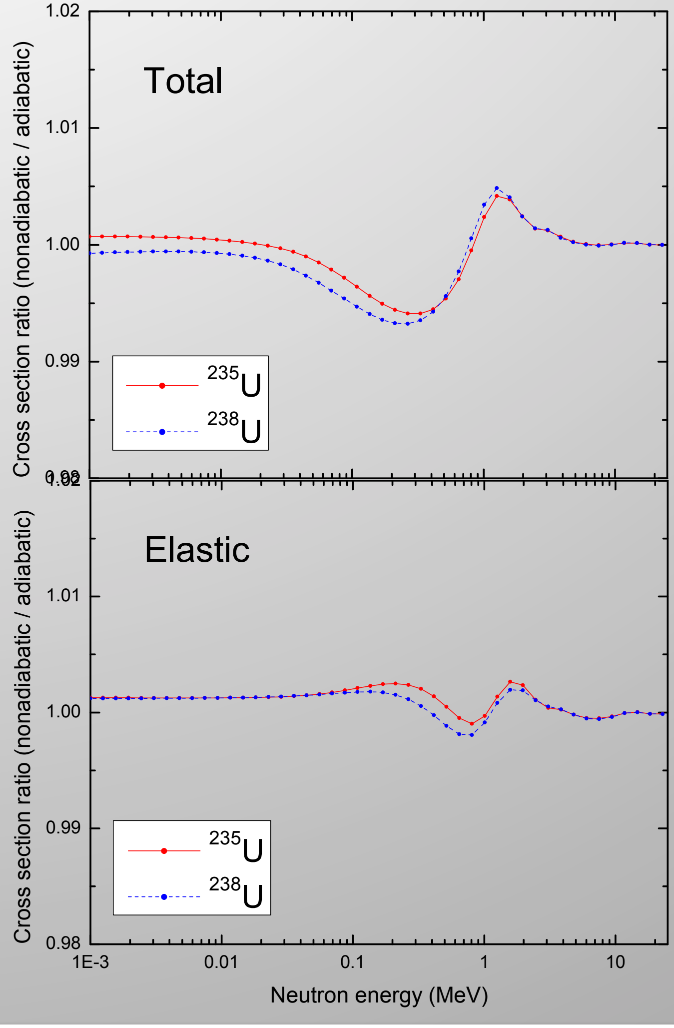
Dietrich, Kawano & Thompson, PRC **85**, 044611 (2012)

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➔I'K' from knowing all 00➔J0 transitions! See Lagrange et al, NSE (1982).

n+^{235,238}U, ratio nonadiabatic/adiabatic



Previous rotational calculations

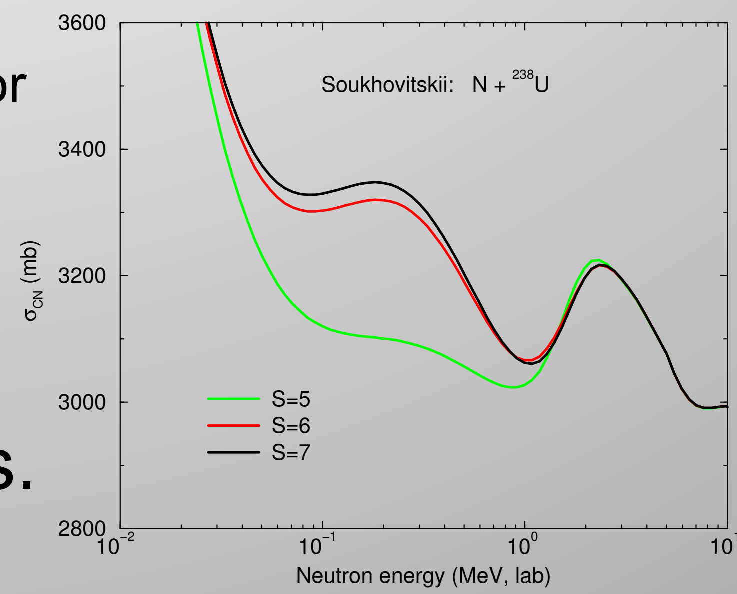
- We conclude that even-even nuclei need coupled-channels sets of s=6 levels (with gs).
- Even-odd nuclei require up to 12 levels for accuracy
- TALYS: default calculations are
  - 'maxrot=2' (levels in addition to the gs: s=3)
- FLAP2.2 actinide potential fitted with s=3
- Soukhovitskii fitted his potentials
  - Using 'saturated coupling' of maxrot=4 (s=5)
- **Clear need to re-evaluate calculations <u>and</u> 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 σ_{TOT}, $\sigma_{el}(\theta)$, and $\sigma_{inel}(\theta)$.
- <u>However</u>: they are <u>not</u> fully converged for absorption / CN-production: σ_{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

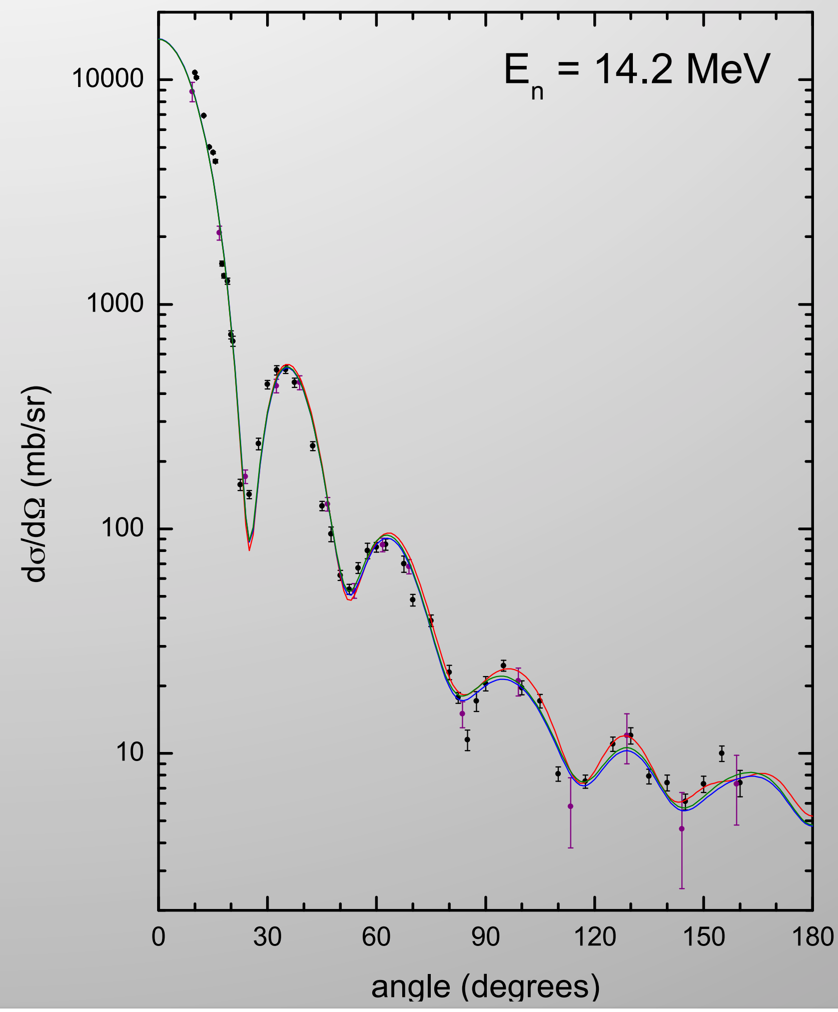
FLAP 3.0 potential fit for actinides (a)

Blue: Soukhovitskii (2004).

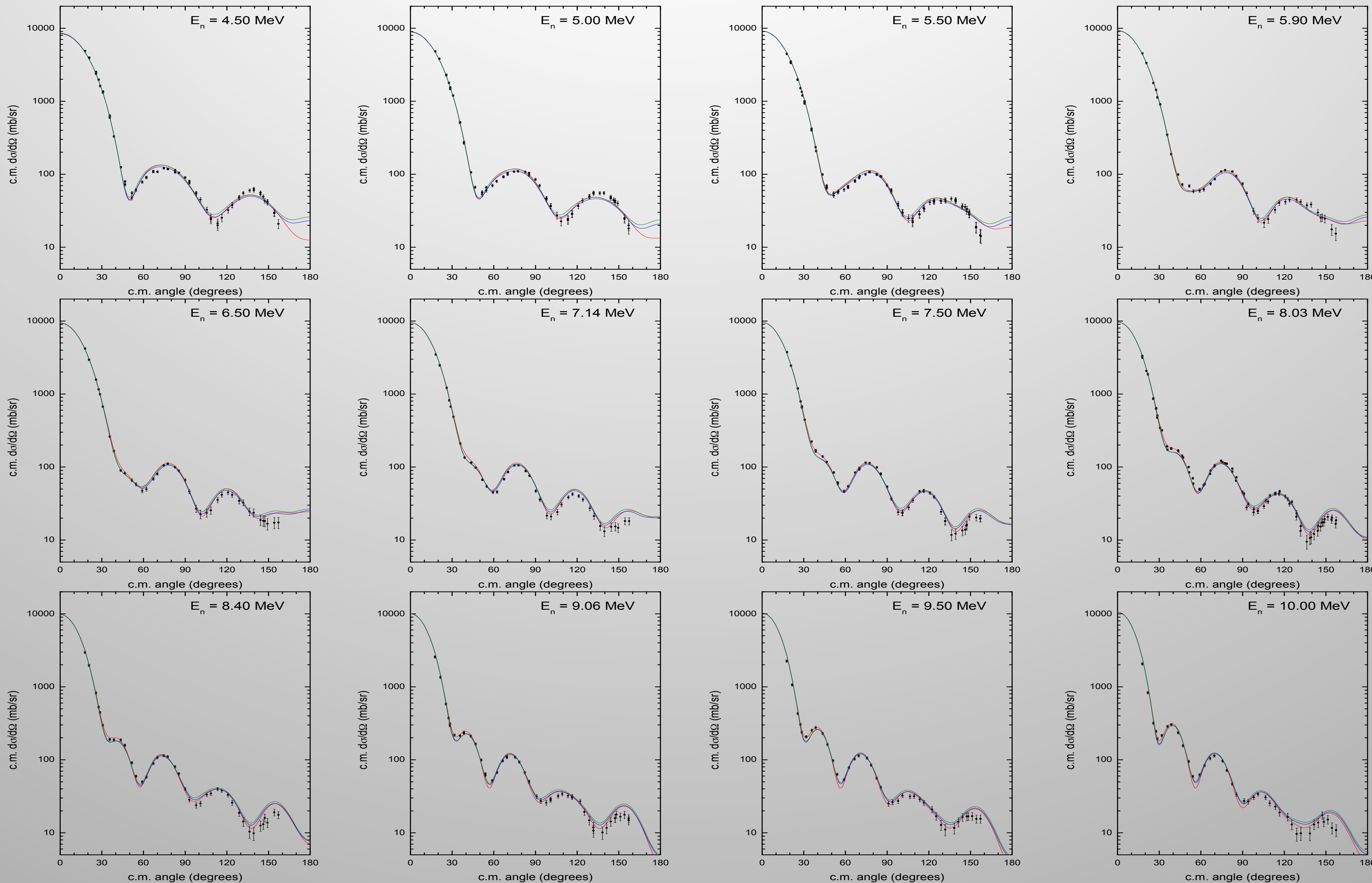
Green: Soukhovitskii (2004) with KD formula for Fermi energies. (β_2=0.223, β_4=0.056)

Red: new FLAP3.0 (β_2=0.213, β_4=0.043 from re-analysis of inelastic cross sections)

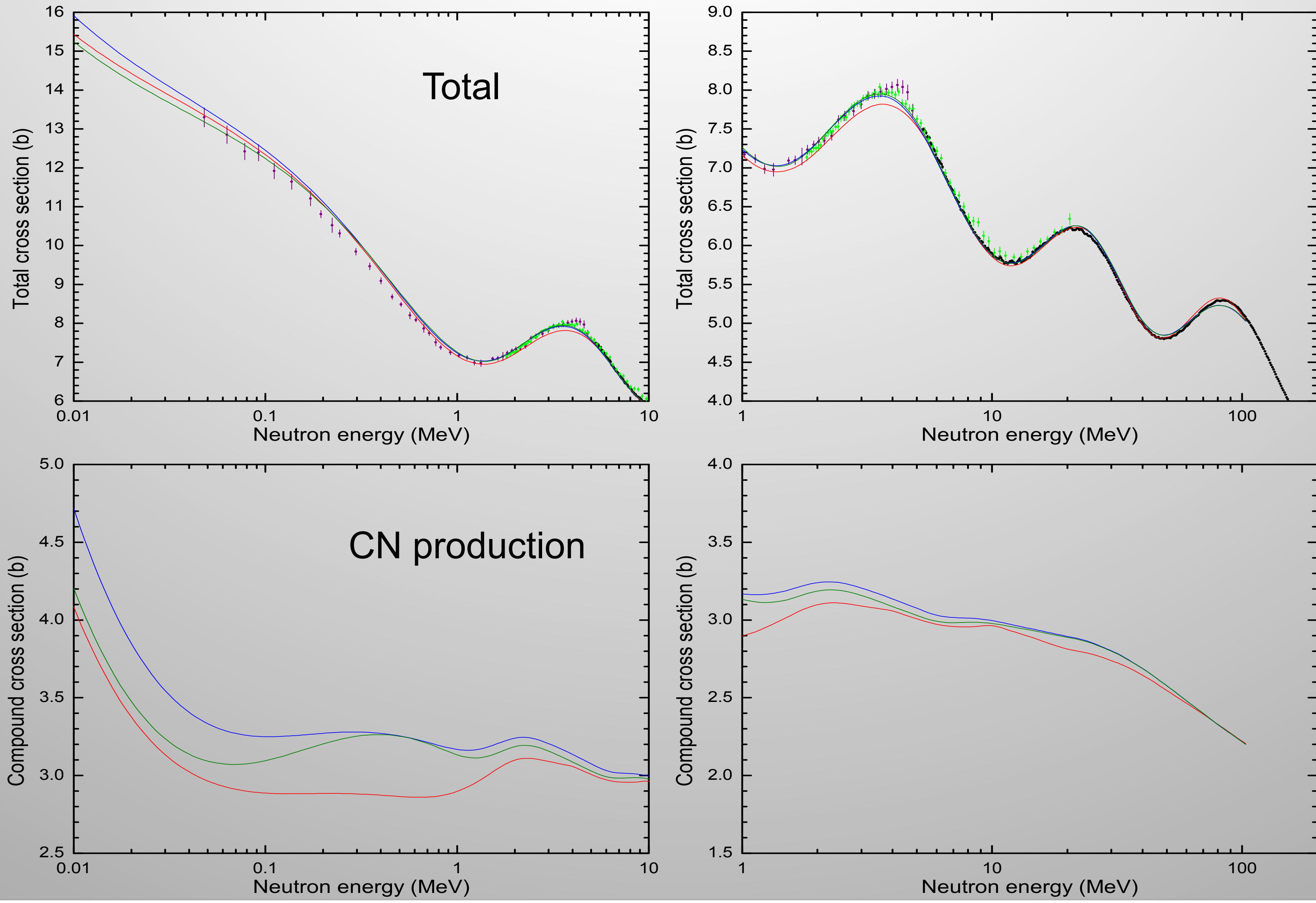
Results for neutron+^{238}U scattering.



FLAP 3.0 potential: more elastics (b)



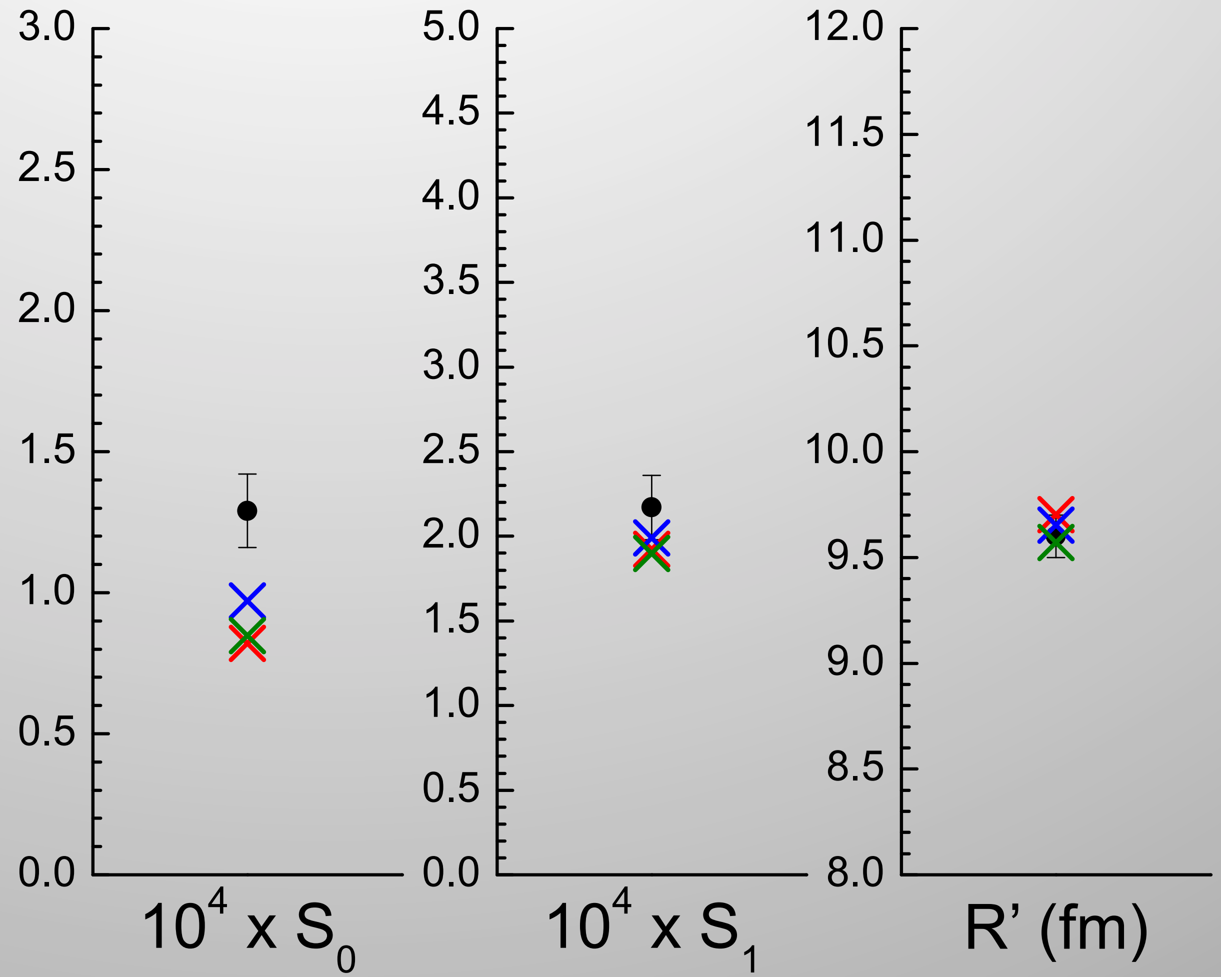
FLAP 3.0 potential: total, CN (c)



FLAP 3.0 potential: low-E neutron (d)

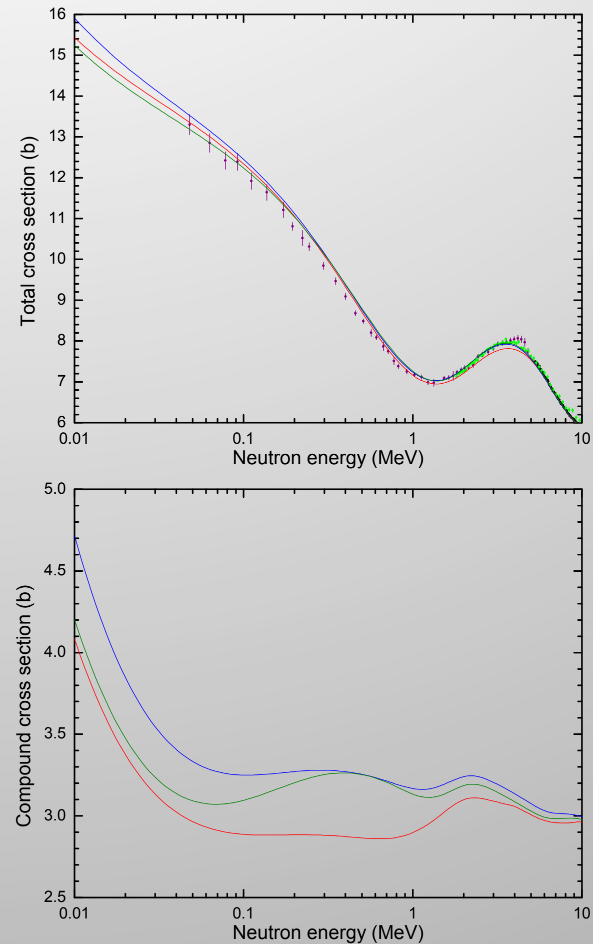
S_0, S_1 and R'
from
Mughabghab

Work in Progress!



Uncertainties in extracting σ(CN)

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



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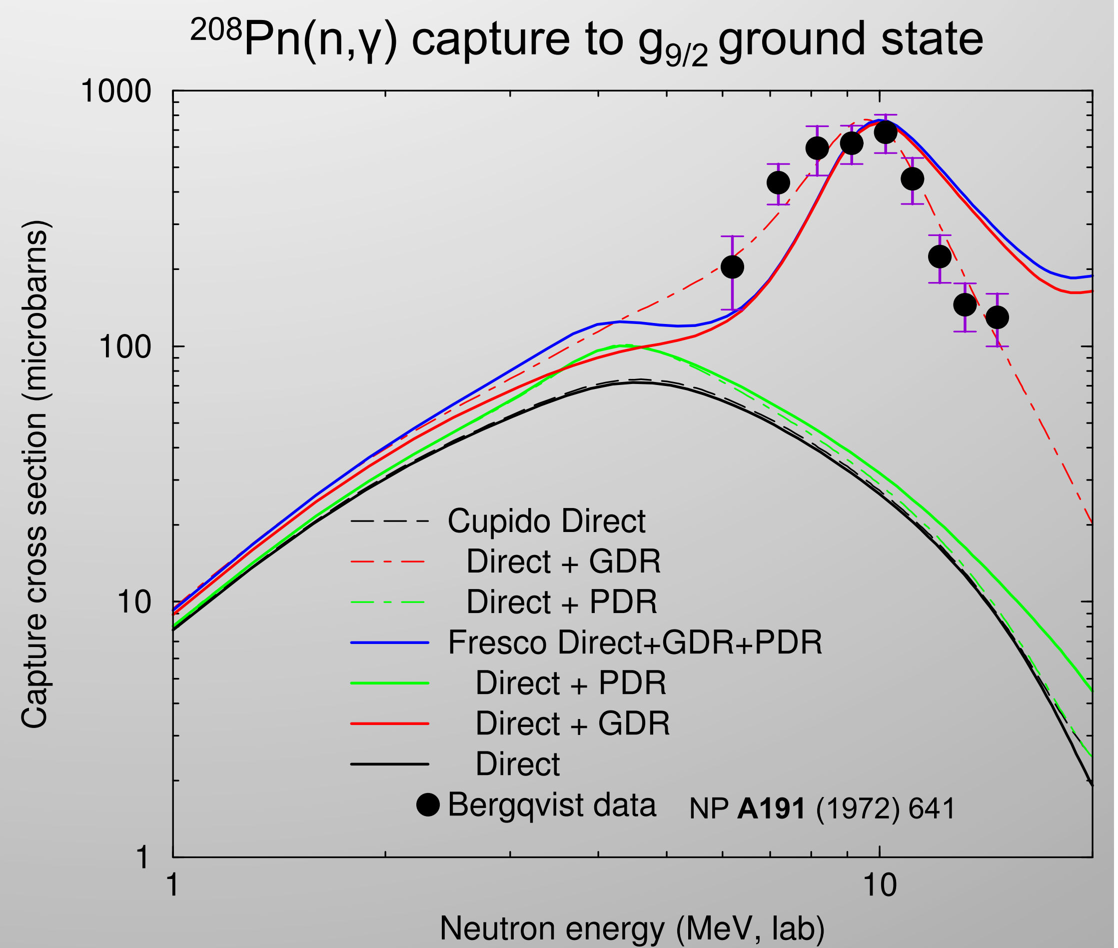
Related:
Semi-direct capture mechanisms

- 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.



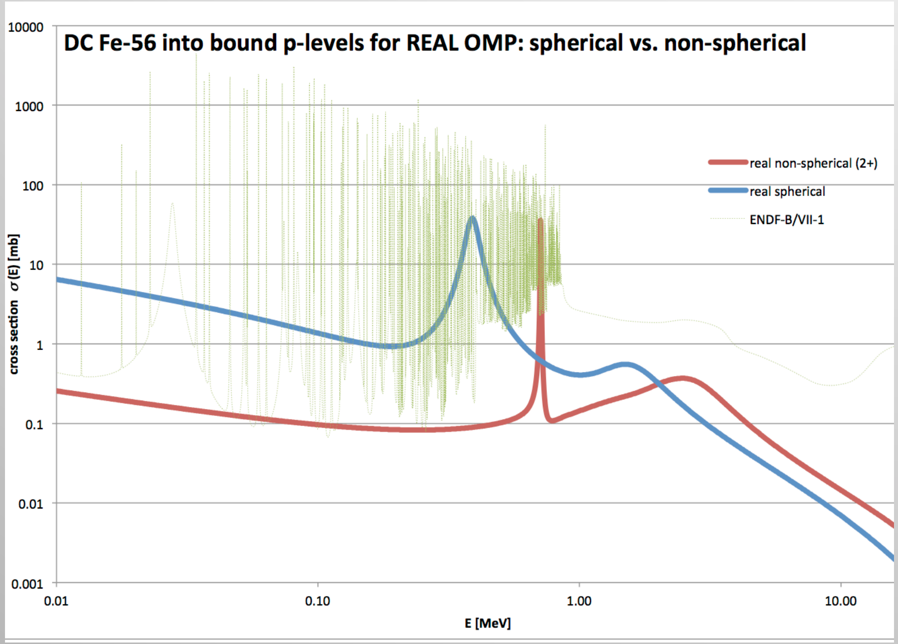
Collective transitions in capture

- 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.

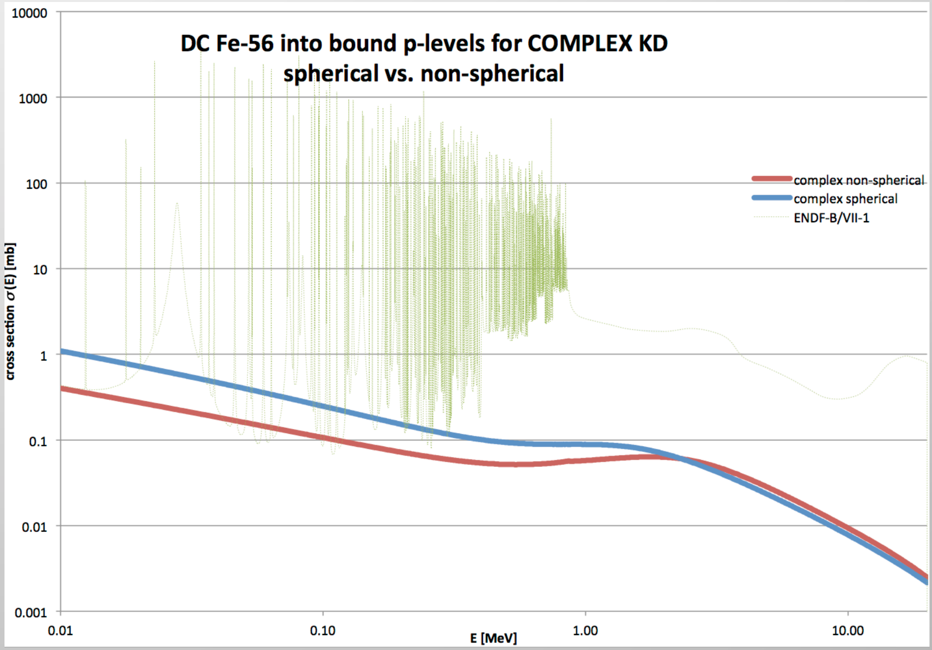
Role of 2$^+$ state in $^{56}Fe(n,\gamma)$ captures: direct contribution only

Preliminary, from Goran Arbanas

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

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