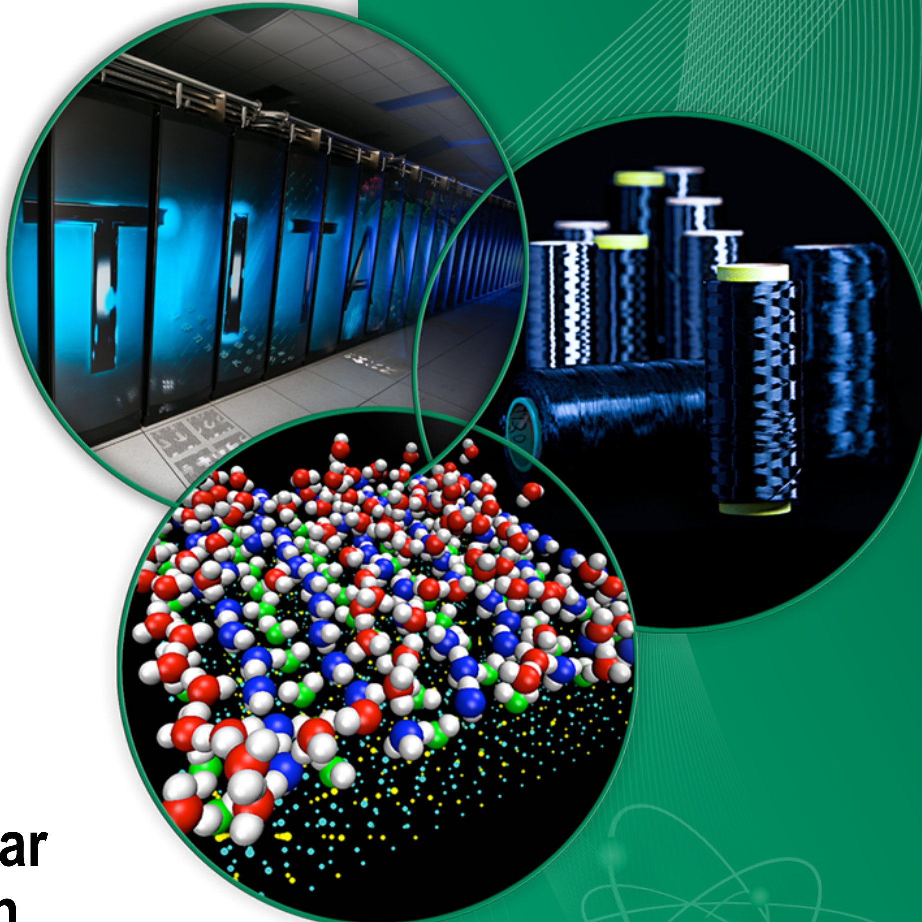
Coupled-Channel Computation of Direct Neutron Capture on Non-Spherical Nuclei



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Fourth Joint Meeting of the Nuclear Physics Divisions of the American Physical Society and The Physical Society of Japan

Hilton Waikoloa Village, HI, October 7-11, 2014

Direct Neutron Radiative Capture (n,γ)

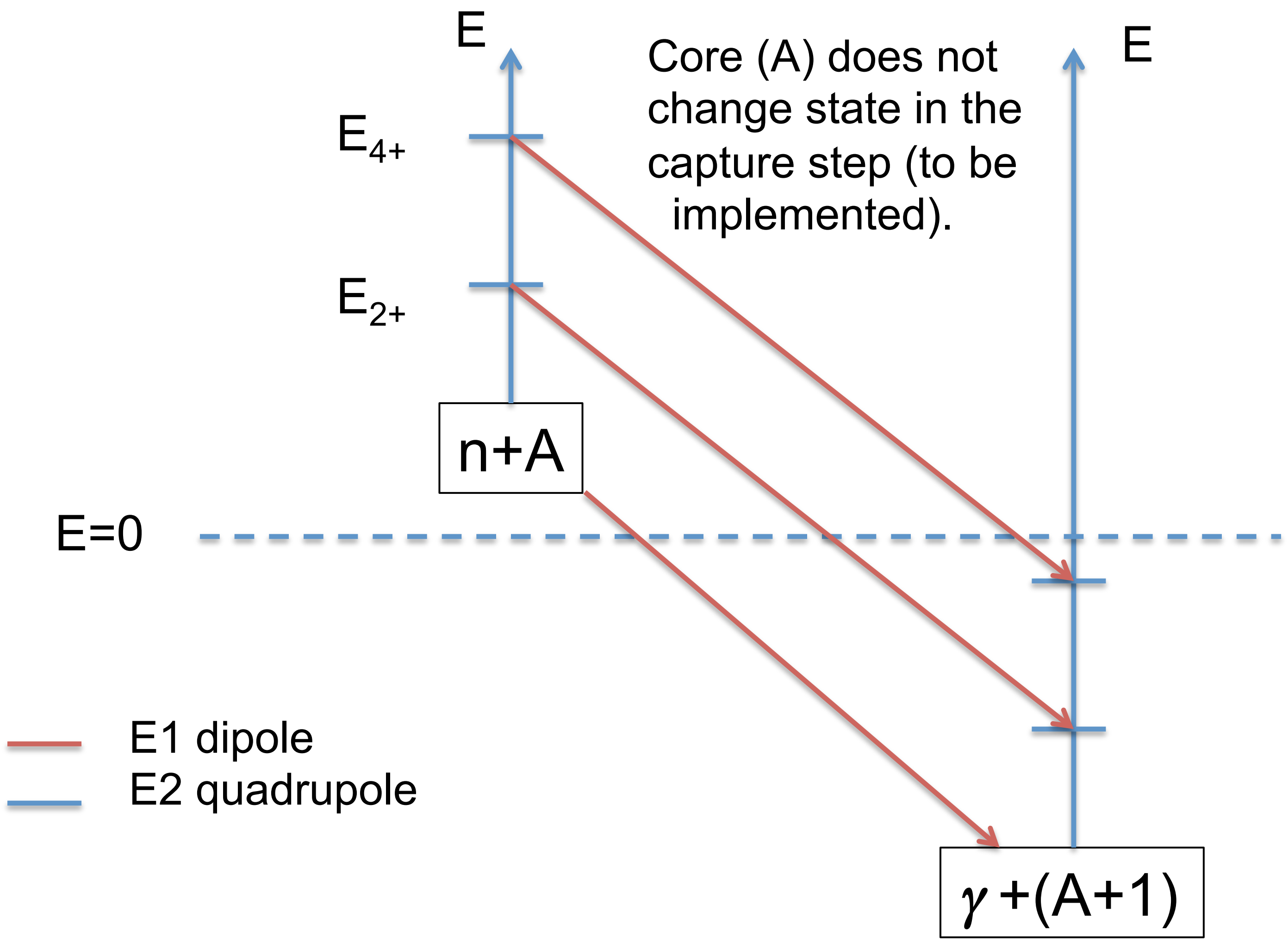
- Useful for studies of structure and reactions
- Needed for astrophysical nucleosynthesis models
  - Especially for light, and neutron rich nuclei where it may be greater than compound (statistical) neutron capture
- Needed for data evaluations of light and medium mass nuclei
- R-matrix resonance parameter fitting for resolved resonances

Direct Neutron Radiative Capture (n,γ)

- The effect of non-spherical shapes on direct capture has previously to this work been studied only in the incoming channels *or* the outgoing channels (bound states), but not in both
- We outline a coupled-channel approach to that self-consistently computes effects of non-spherical shape in incoming *and* in outgoing partitions
- We compute direct capture with and without the effect of deformation for the even calcium isotopes: Ca-40,42,44,46,48
  - By coupling 2+ and 4+ states with non-zero deformation lengths

Schematic Coupled Channel Model

- Initial and final partitions couple to 2+, 4+ states



Advantages of Ca even mass isotopes

- Wide range of deformational strengths and 2+ excitation energies
- Thermal capture cross sections known to better than 10%, and
  - Thermal neutron: measured prompt γ-ray energies and branching ratios
- Mostly E1 capture: 82%, 93% 98% 96% 100% for Ca-40,42,44,46,68
  - Good for testing models of direct capture
- Mostly direct capture at the thermal neutron energy
  - Compound resonant capture measured but small.
  - Its contribution can be computed via R-matrix formalism
  - Small fraction of s-wave neutron E1 capture is compound resonant

Theory of Direct Capture

- Siegert's theorem (1937):
  - Expresses EM operator in terms of charge density form
- Coupled channels (FRESCO)
  - I.J. Thompson, F.M. Nunes, "Nuclear Reactions for Astrophysics", (2009)
- Core excitations in incoming (n+core) or outgoing (γ+(n+core)) partitions:
  - 2+, 4+ state of a rotational band with deformation lengths from TALYS
  - Core remains in the same state (0+,2+,or 4+) during the capture step

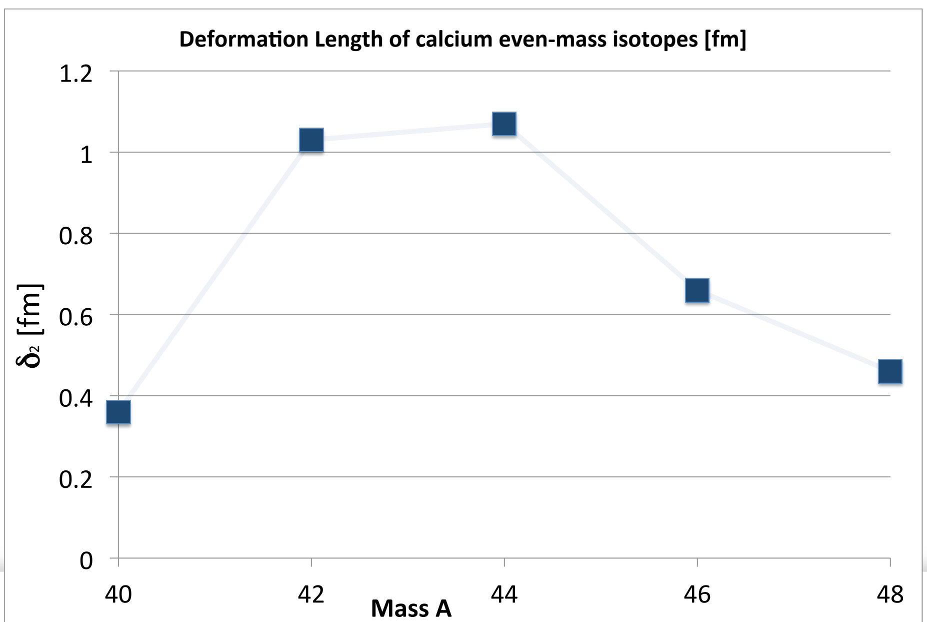
$$\mathbf{T}_{\gamma\alpha_i} = -\frac{1}{k}\frac{k}{\hbar c}\frac{q}{\mathrm{i}}\sqrt{\frac{8\pi\hbar c(J+1)}{Jk}}\sum_{\alpha}\langle \mathrm{i}^J F_J \phi_b | \psi_{\alpha\alpha_i}\rangle \qquad (4.7.16)$$

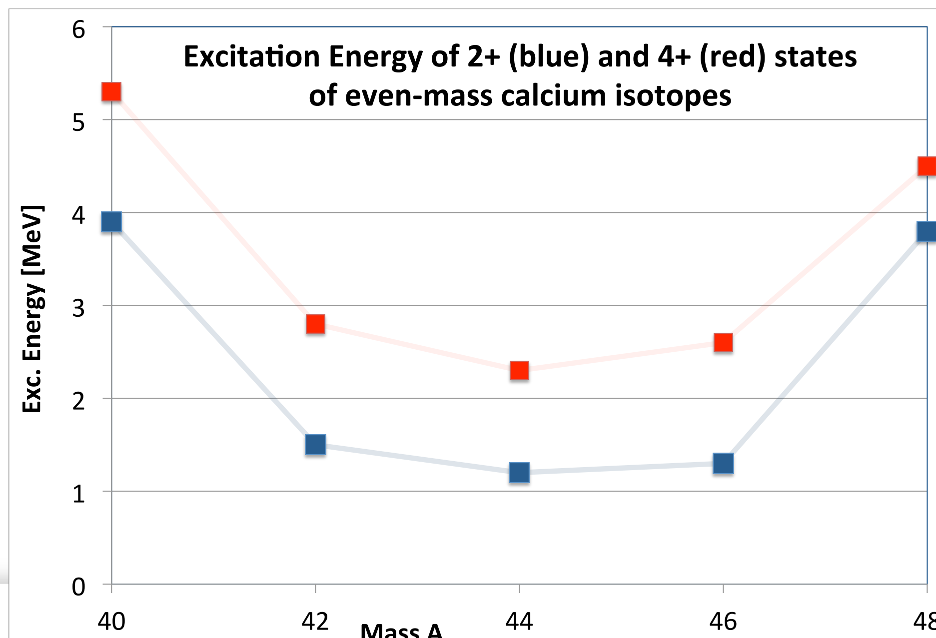
$$\sigma^J_{\mathrm{cap}} = \frac{4\pi}{k_i^2}\frac{1}{(2I_p+1)(2I_t+1)}\frac{c}{v_i}\sum_{J_{\mathrm{tot}}}(2J_{\mathrm{tot}}+1)\,|\mathbf{T}^{J_{\mathrm{tot}}\pi}_{\gamma\alpha_i}|^2. \quad (4.7.20)$$

  - Later we may implement core transitions in the capture step itself

FRESCO Calculation Input

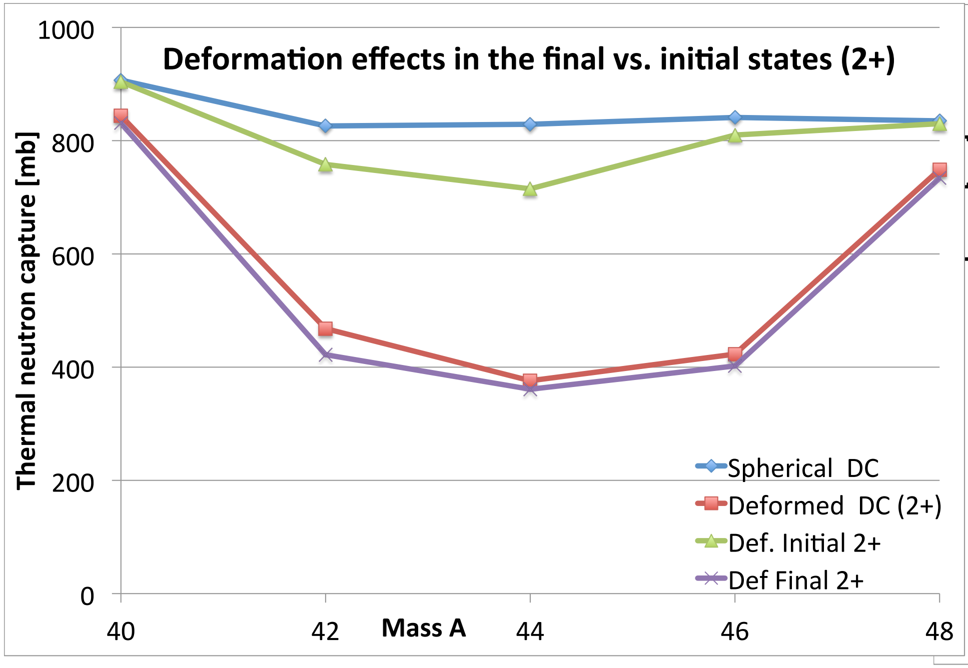
- Koning-Delaroche complex optical potential at E=0 MeV
  - Good for thermal neutron capture and sufficient for low-energy
- Deformation length parameters from TALYS database from B(E2)
- Compute direct capture for Ca-40,42,44,46,48
  - No deformation; 2+; {2+,4}, in initial and final channels
  - Deformation 2+; {2+,4+}; in initial channel only, or final channel only

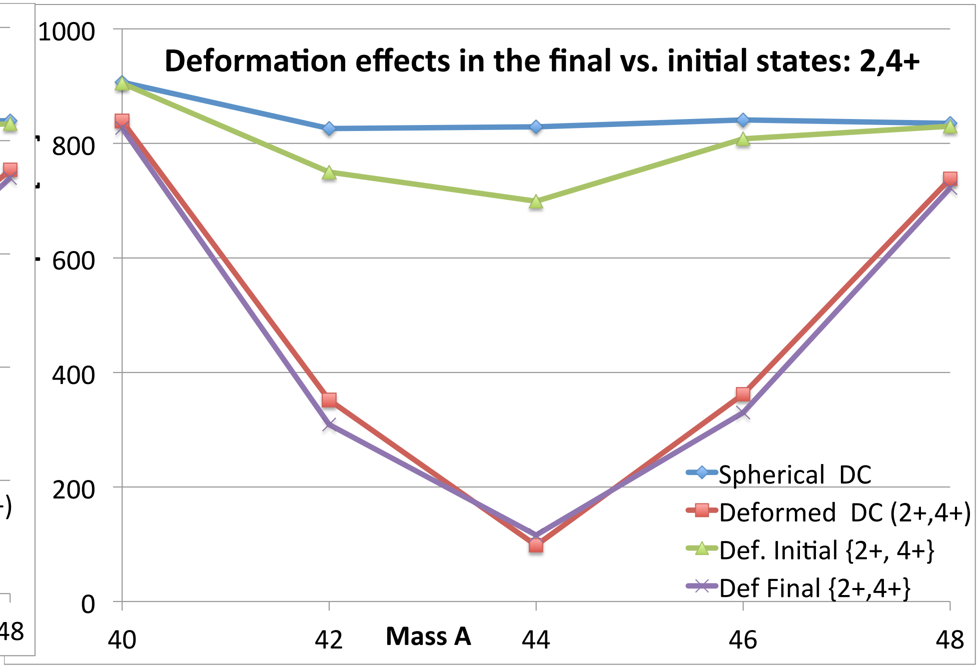




Deformation in initial vs. final states

- The effect of deformation in the final neutron bound state is greater than in the initial neutron scattering state
  - Assumed by Boison and Jang, Nucl. Phys. A189 (1972) 334-352
  - Using bound spectroscopic factors (SF) from Kahane et al. (1987)
  - Plots below are for thermal neutron capture

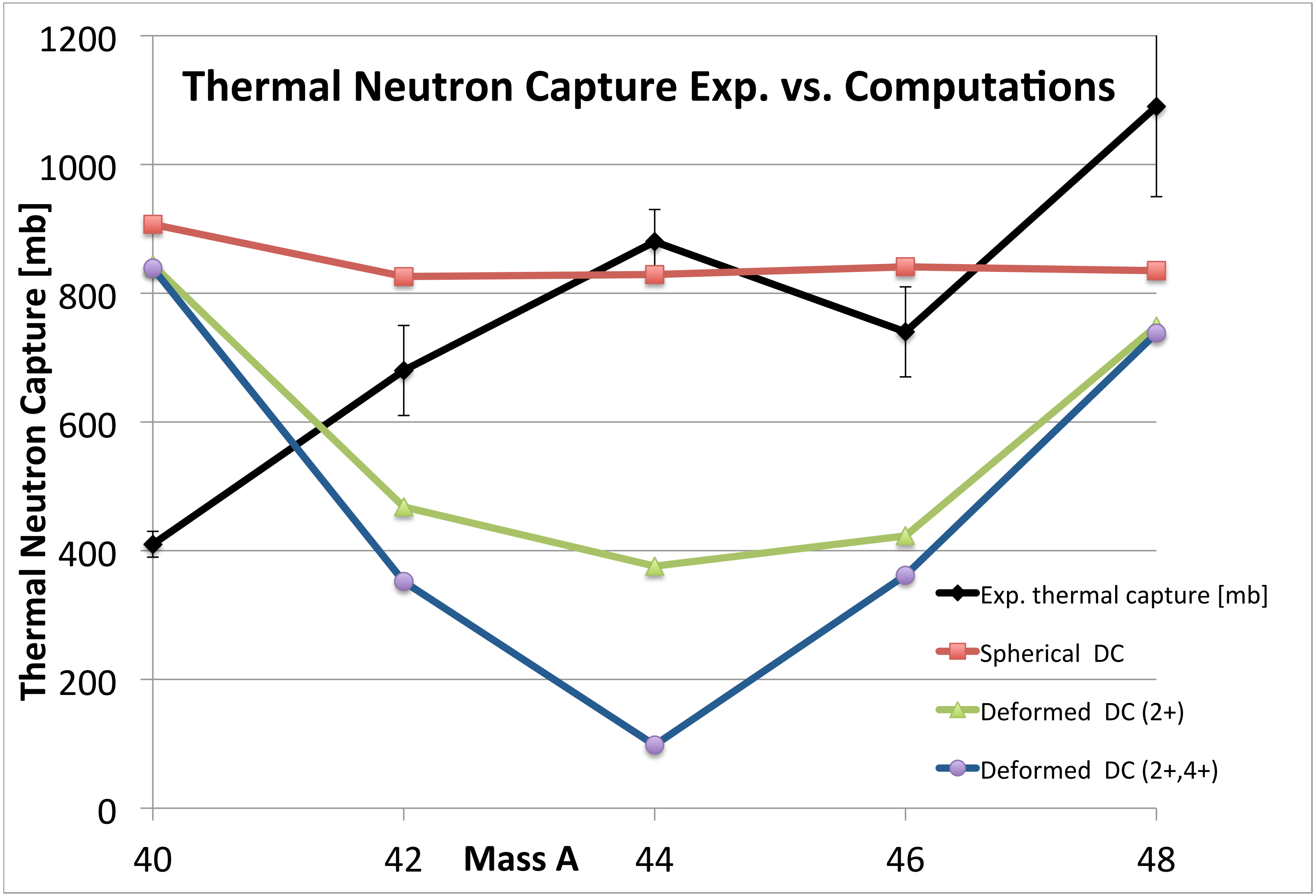




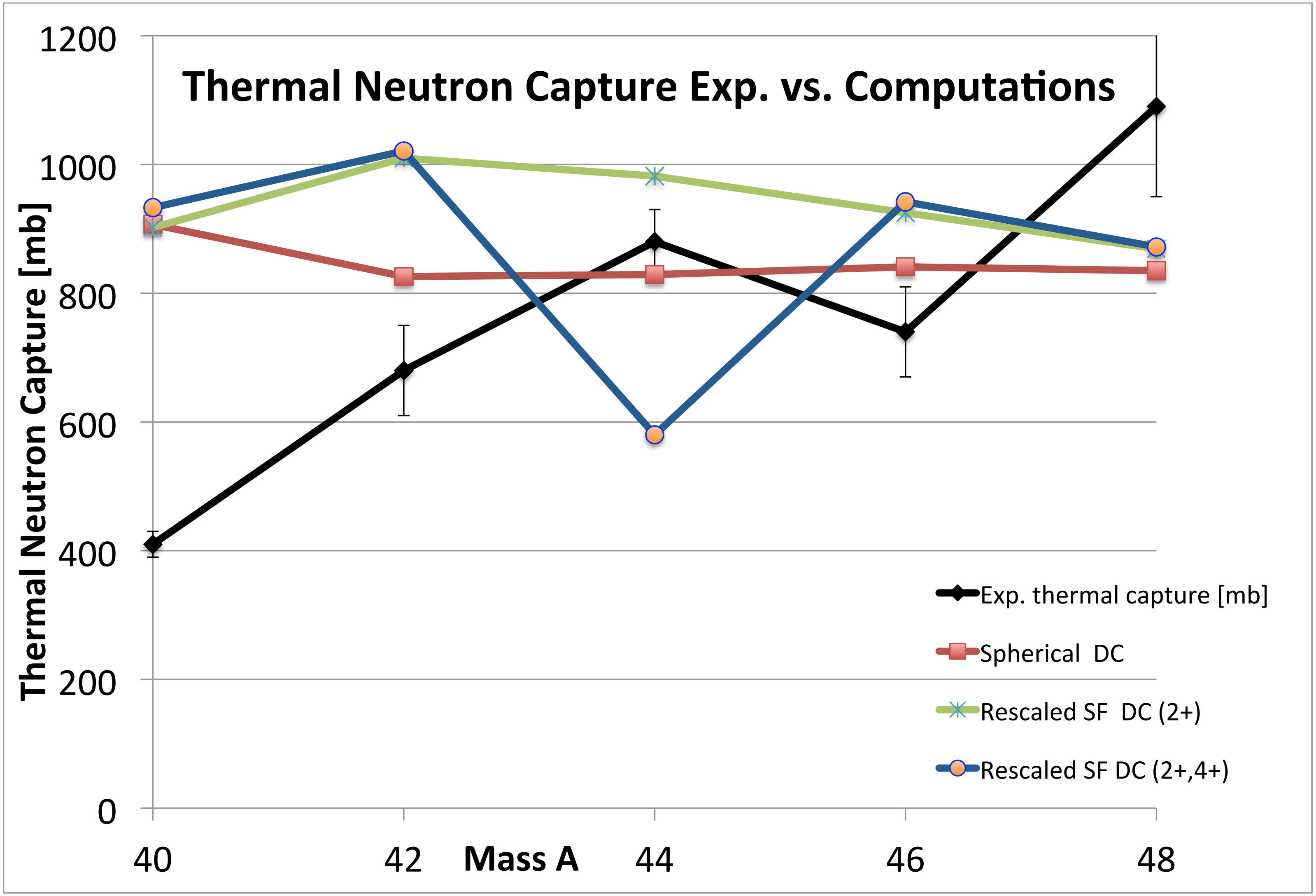
Experimental determination of SF's

- SF were determined by fitting (d,p) cross sections w/o deformation (spherical potentials)
- But, in bound states, the fraction of the core in its GS diminishes with coupling to 2+ and 4+ core states. This upsets (d,p) fits.
- We compensated, *approximately*, by rescaling overall SF in order to make the GS component the same as was fitted before
- Most of the direct capture occurs into the core in the GS, so a decrease in the fraction of the core in the GS decreases capture
- Later, should revisit (d,p) reactions with couplings to (2+, 4+) states

Thermal capture results vs. data

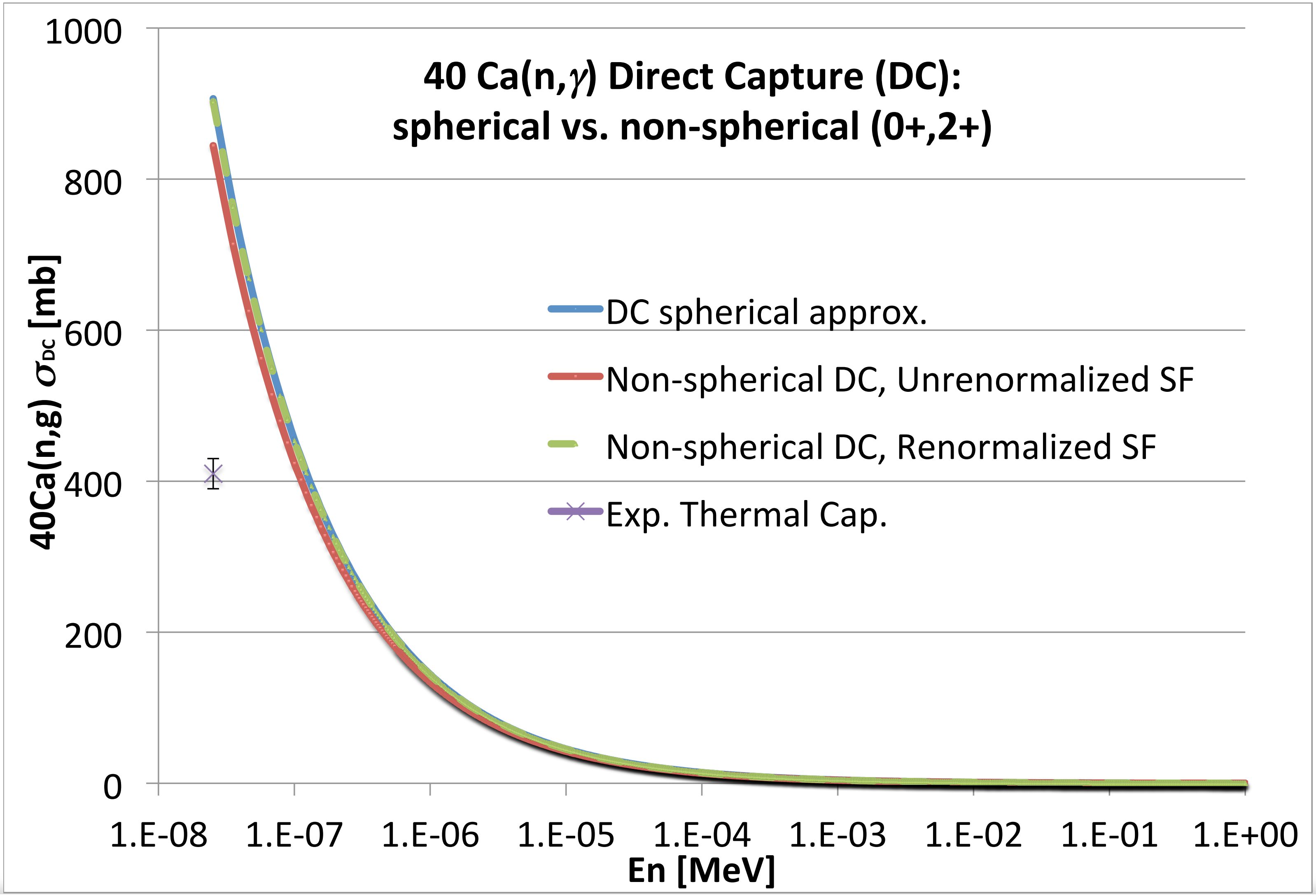


Thermal capture results vs. data



40Ca(n,g) spherical vs. CC (0+,2+)

- Computations of capture over-predict thermal cap. by a factor of 2



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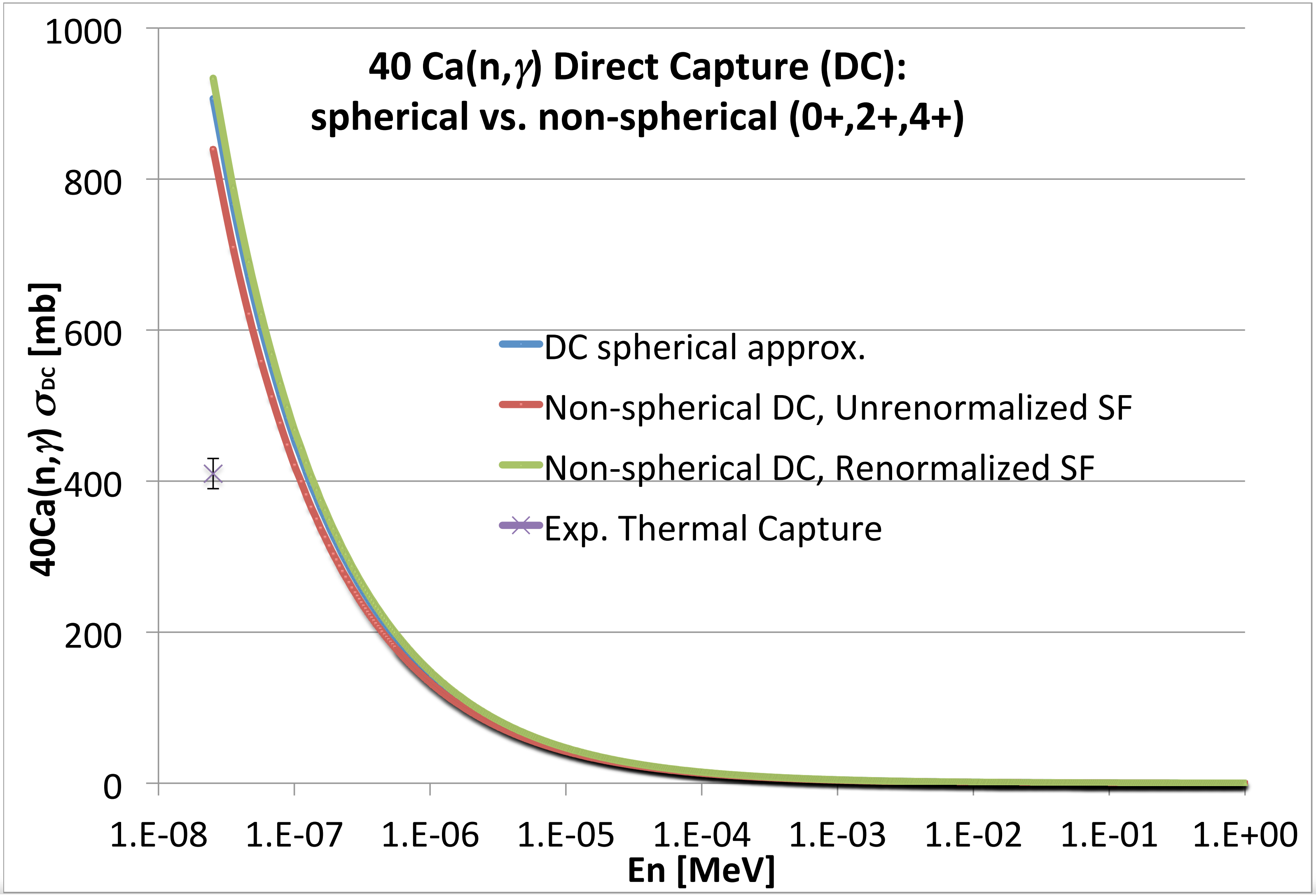
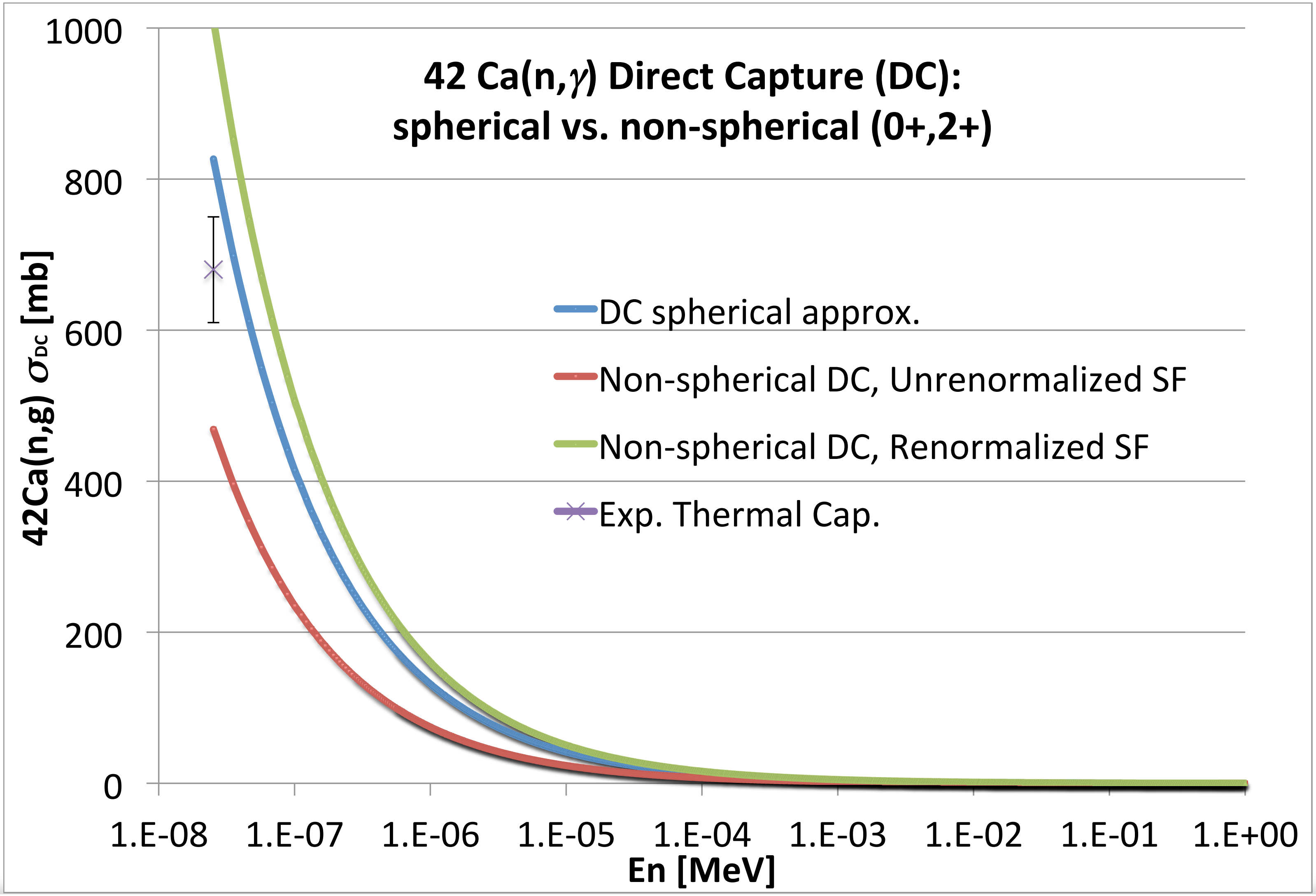


42Ca(n,g) spherical vs. CC (0+,2+)

- DC with rescaled SF is larger than thermal capture expt.



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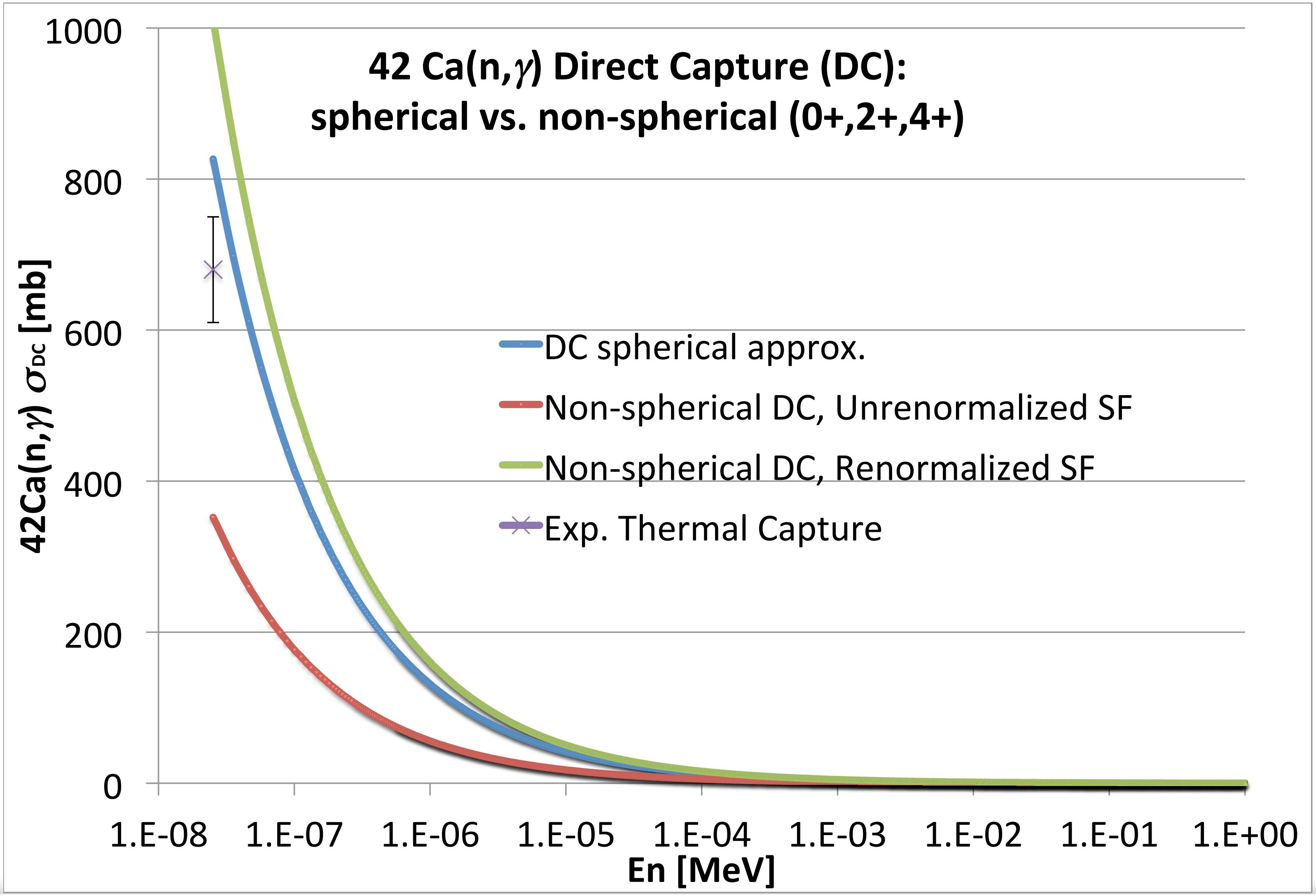
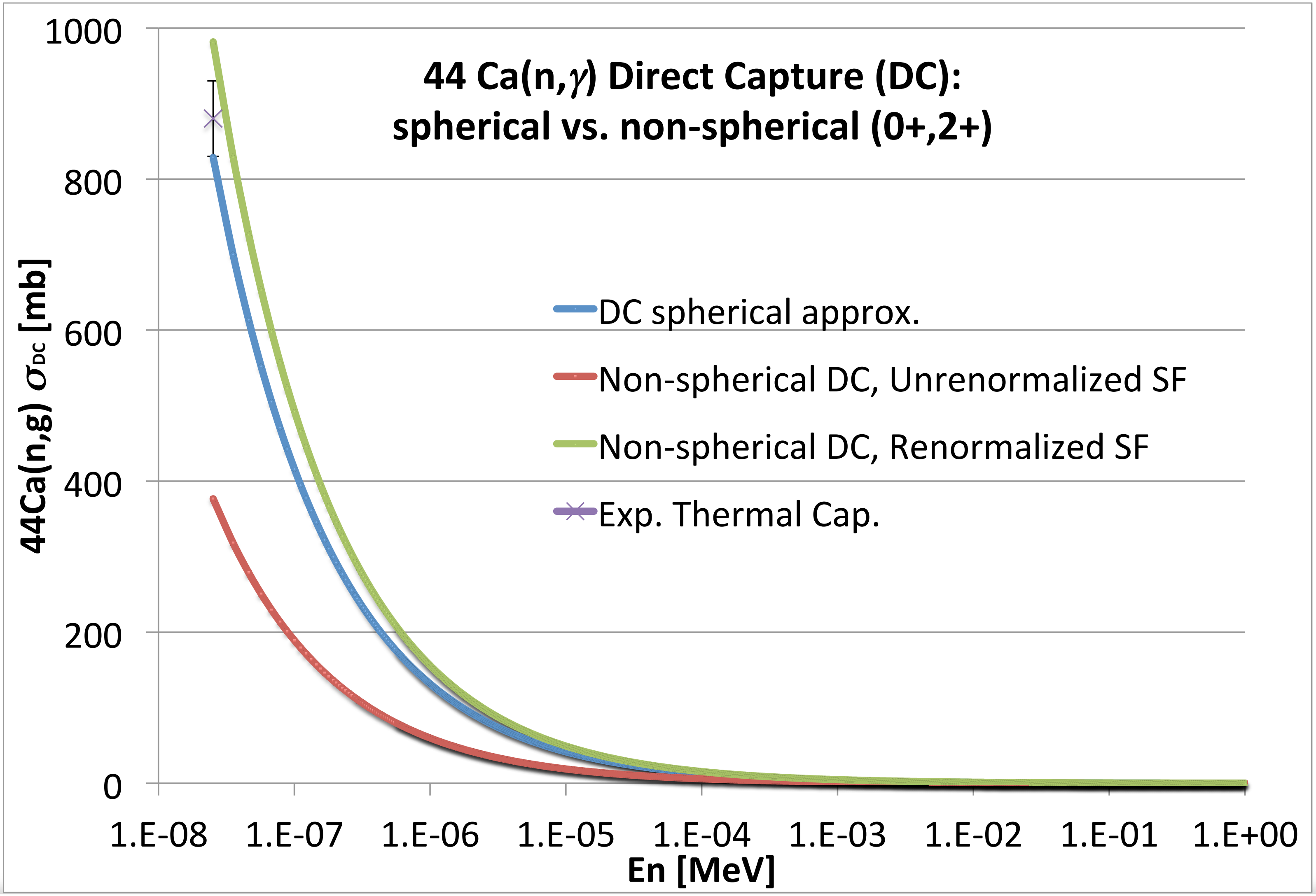


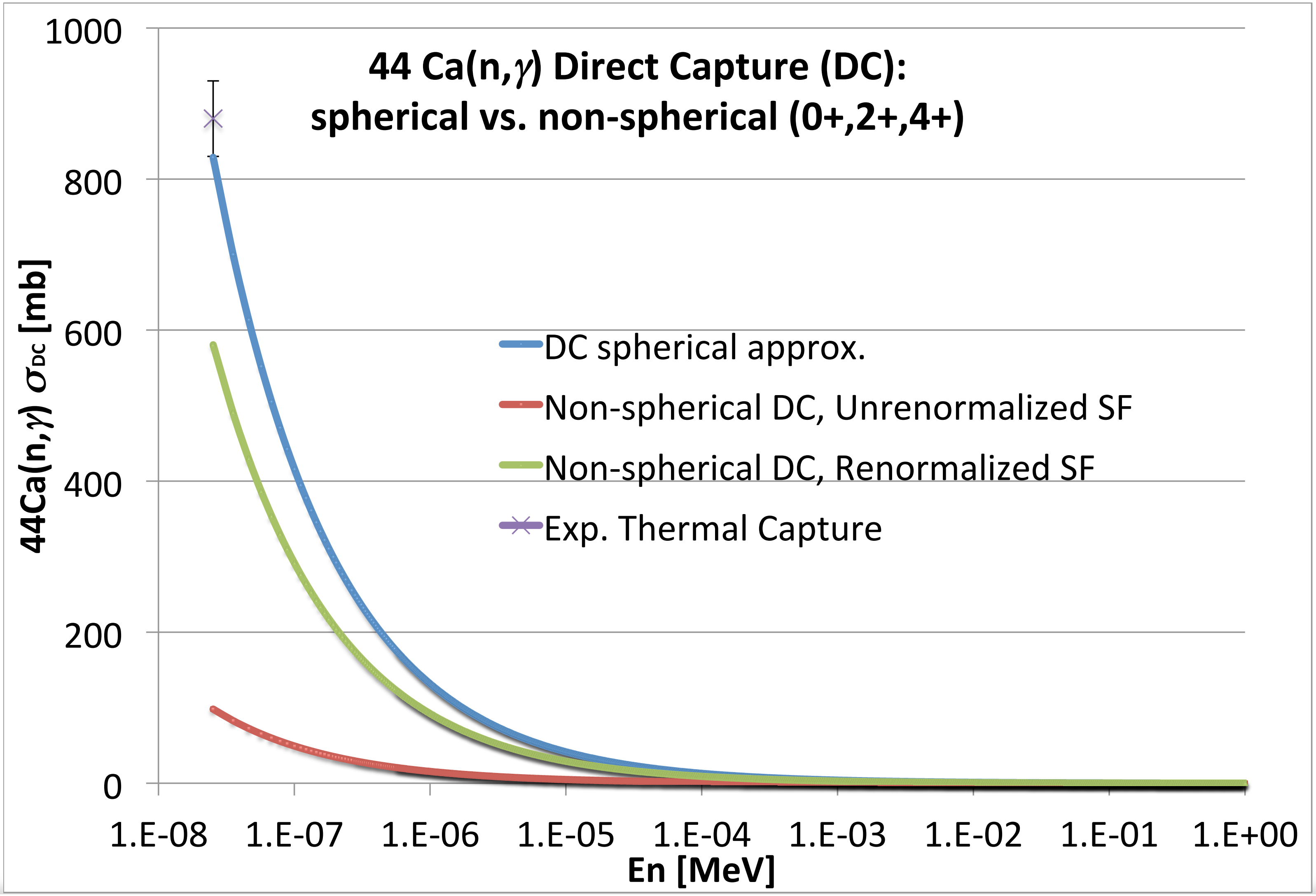
44Ca(n,g) spherical vs. CC (0+,2+)

- Renormalization of SF yields capture compatible with experiment



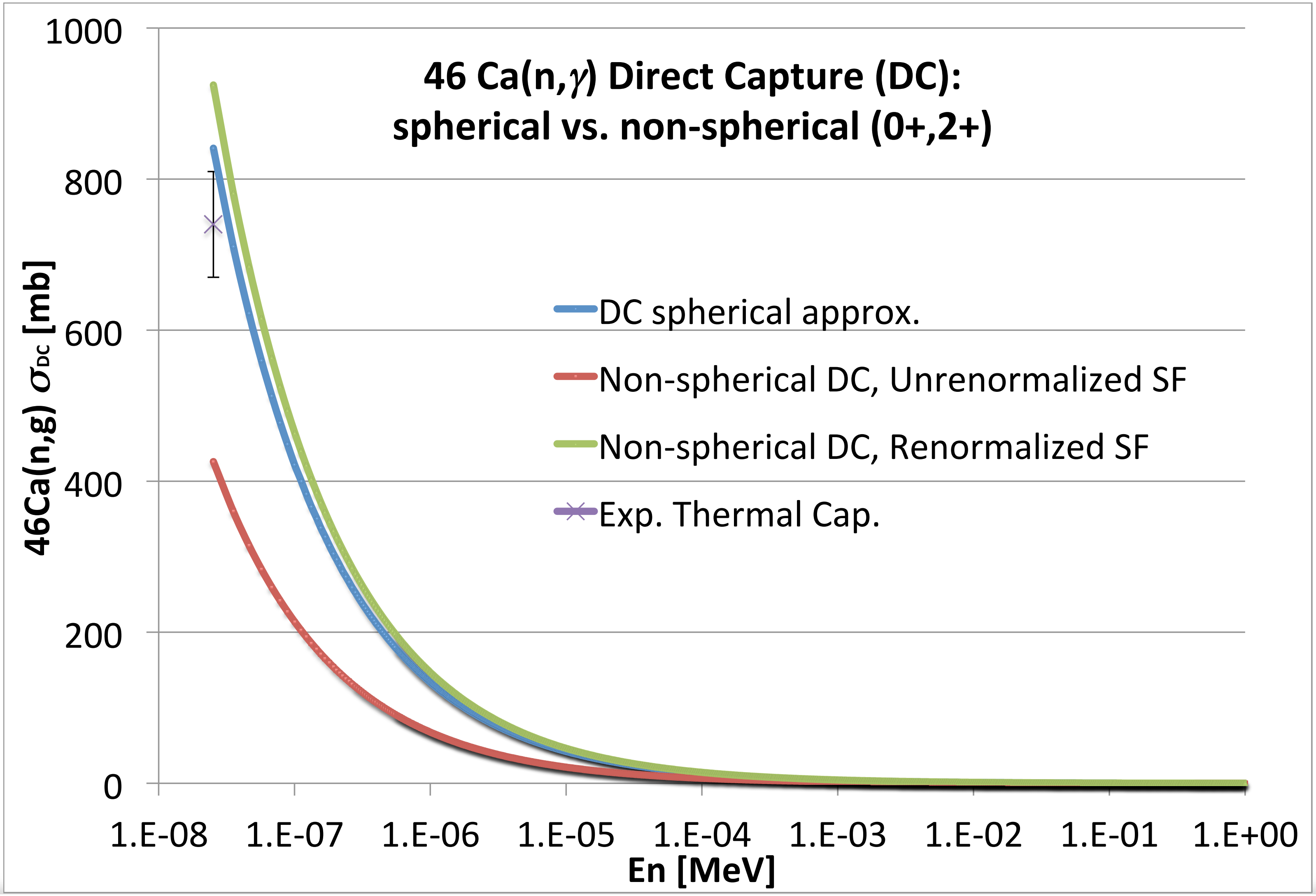
44Ca(n,g) spherical vs. CC (0+,2+,4+)

- Renormalization of SF yields thermal capture smaller than expt.



46Ca(n,g) spherical vs. CC (0+,2+)

- Rescaling of SF yields thermal capture larger than expt.



46Ca(n,g) spherical vs. CC (0+,2+,4+)

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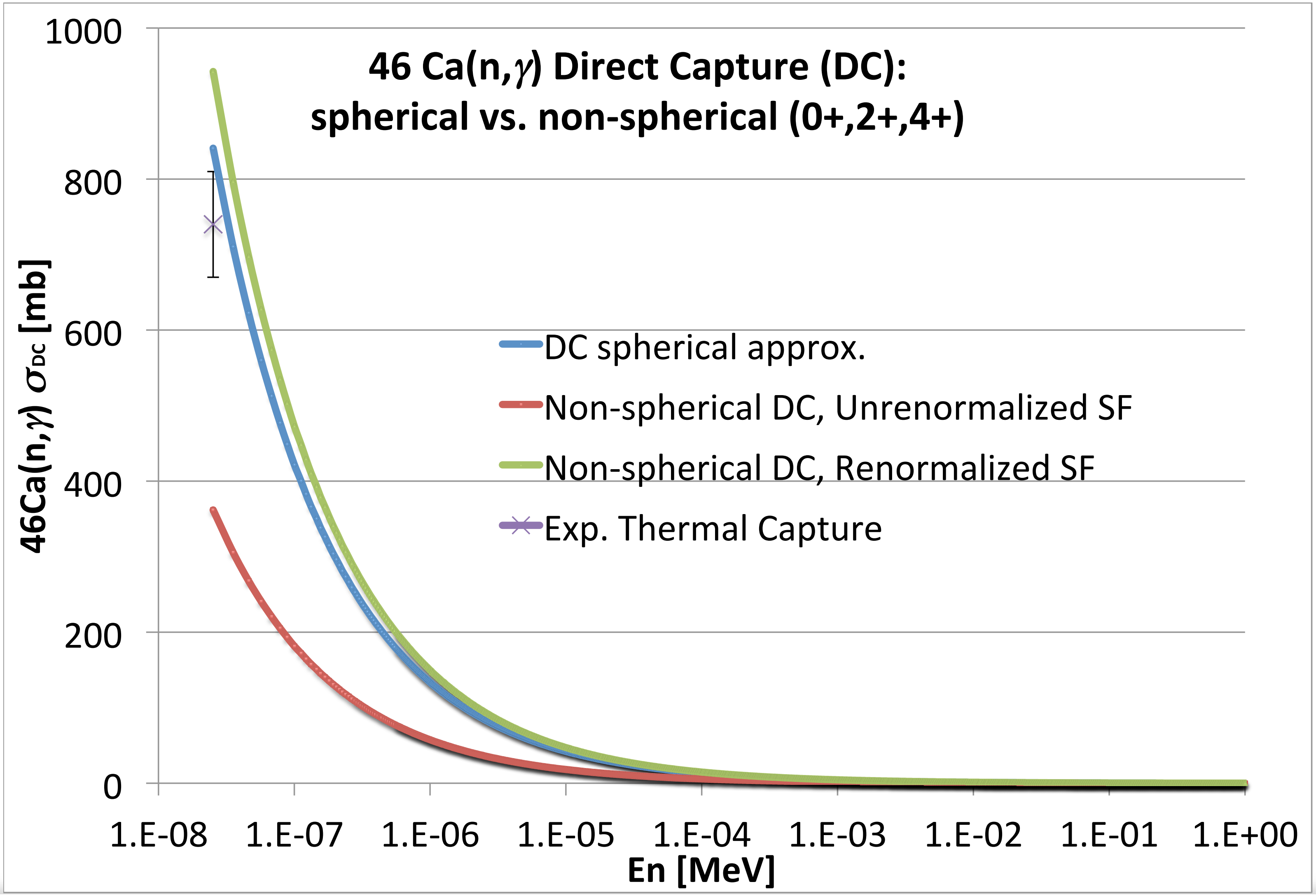
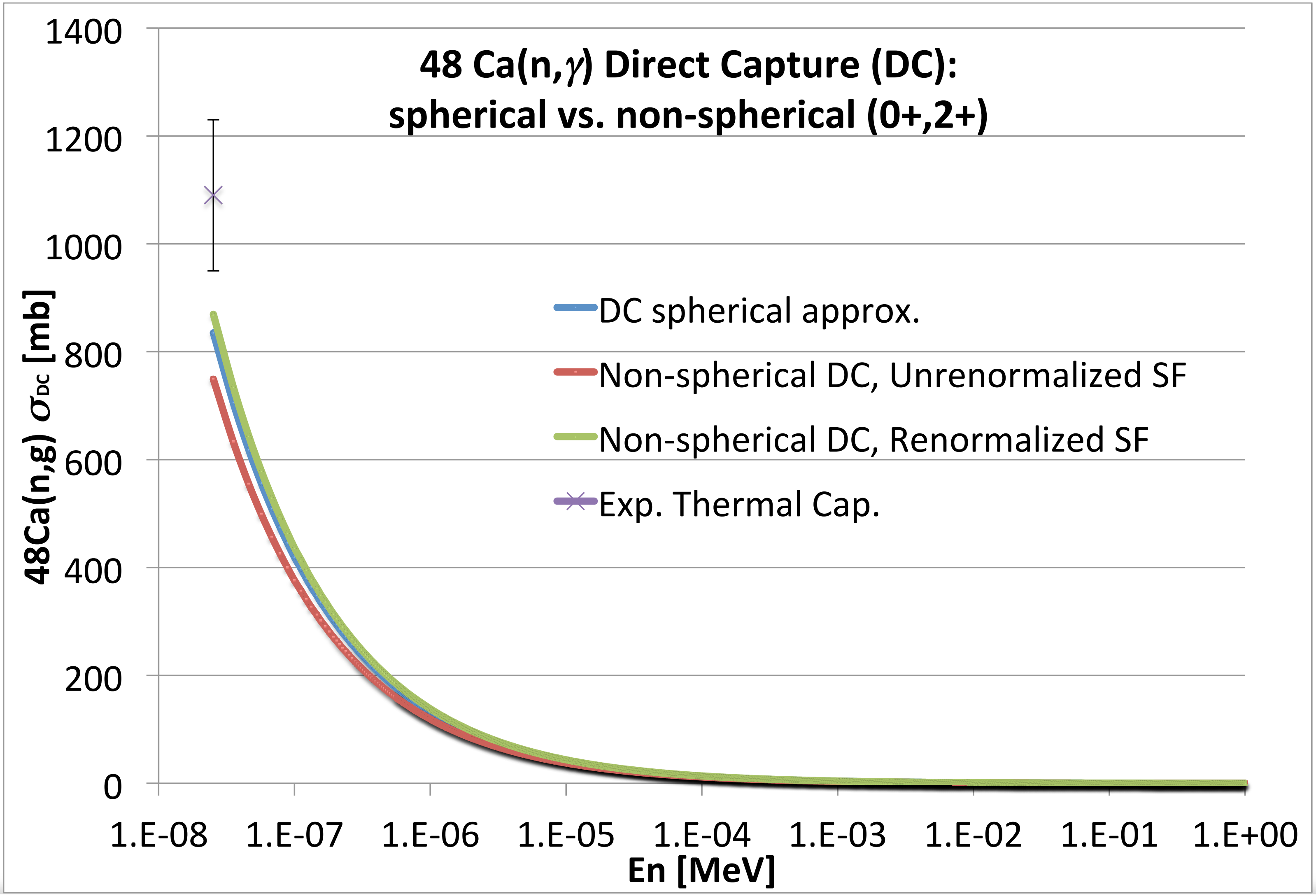


48Ca(n,g) spherical vs. CC (0+,2+)

- All methods yield thermal capture cross sections smaller than expt.



48Ca(n,g) spherical vs. CC (0+,2+,4+)

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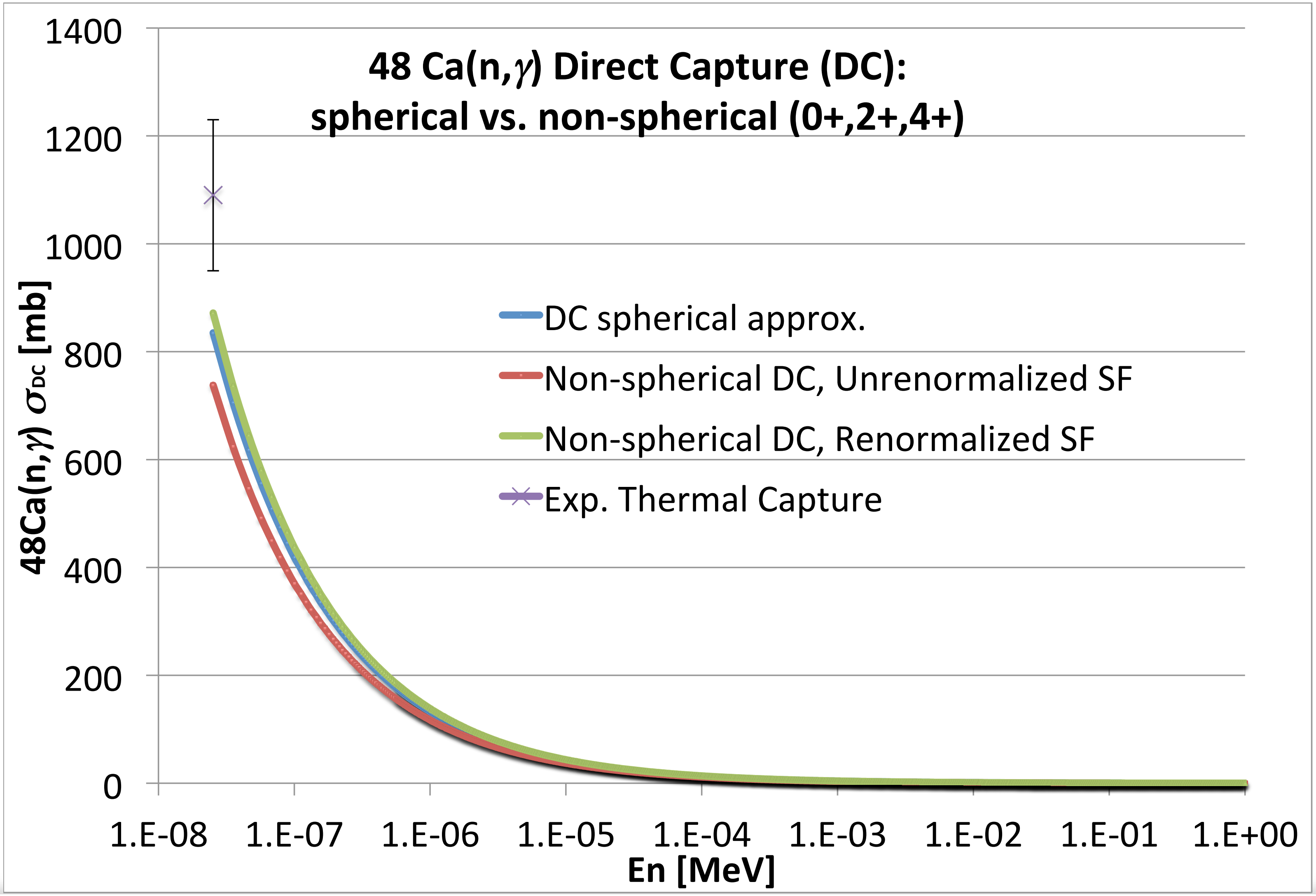


Conclusions

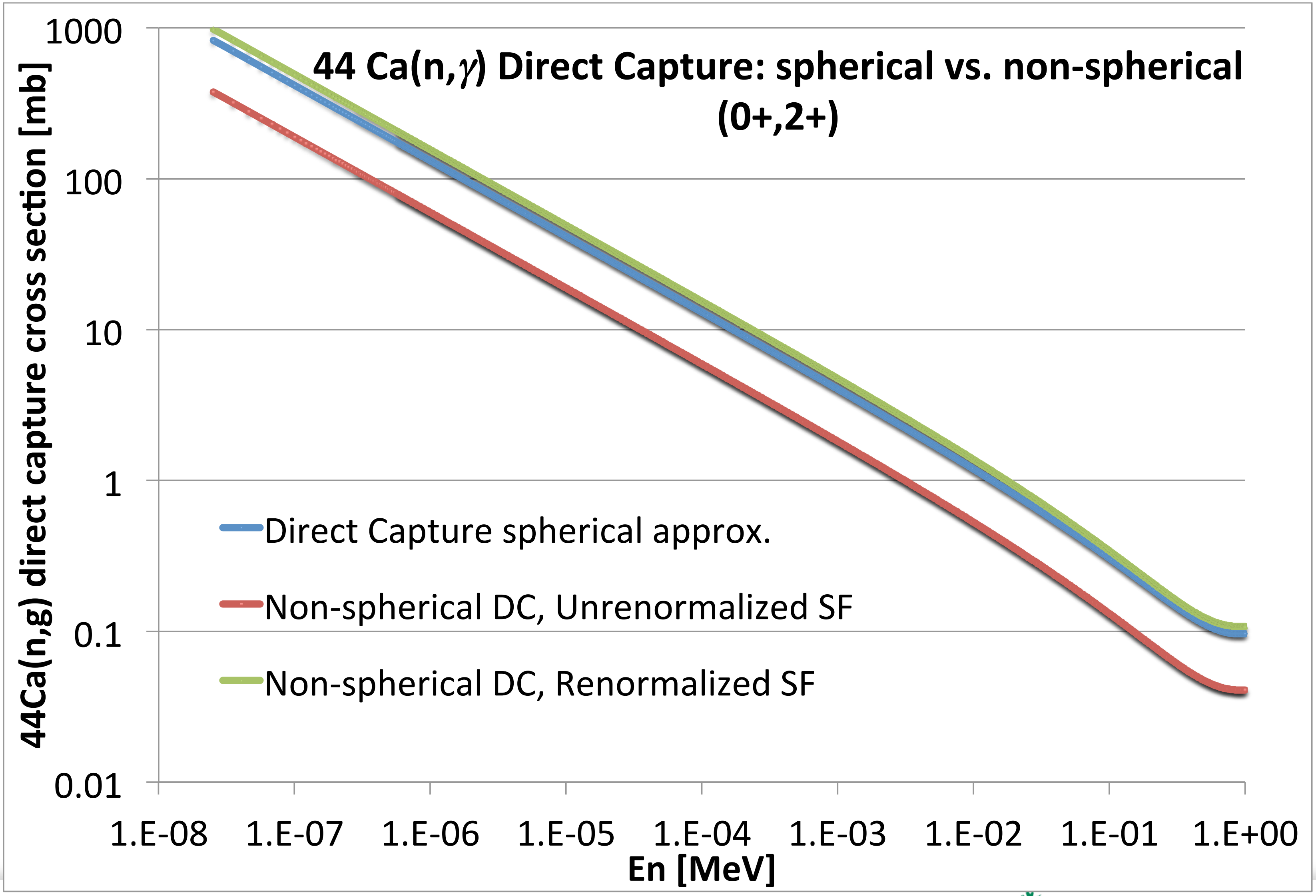
- These quadrupole-core couplings have strong effects on capture away from closed shell.
  - Even if spherical models come close to the data
- Effect of non-spherical shapes are larger for final (bound) state
  - Bound states become fractionated among core states (0+,2+,4+)
  - This fractionation diminishes fraction of the core in GS and direct capture
- To restore the original experimental spectroscopic amplitudes some renormalization of bound states may be necessary

Future research (TORUS Collaboration)

- Allow for core (de-)excitations in the capture step itself
  - Findings may yield insight on the SF renormalization method
- Revisit (d,p) reactions with couplings to (2+, 4+) states
  - It may affect values and interpretation of SF

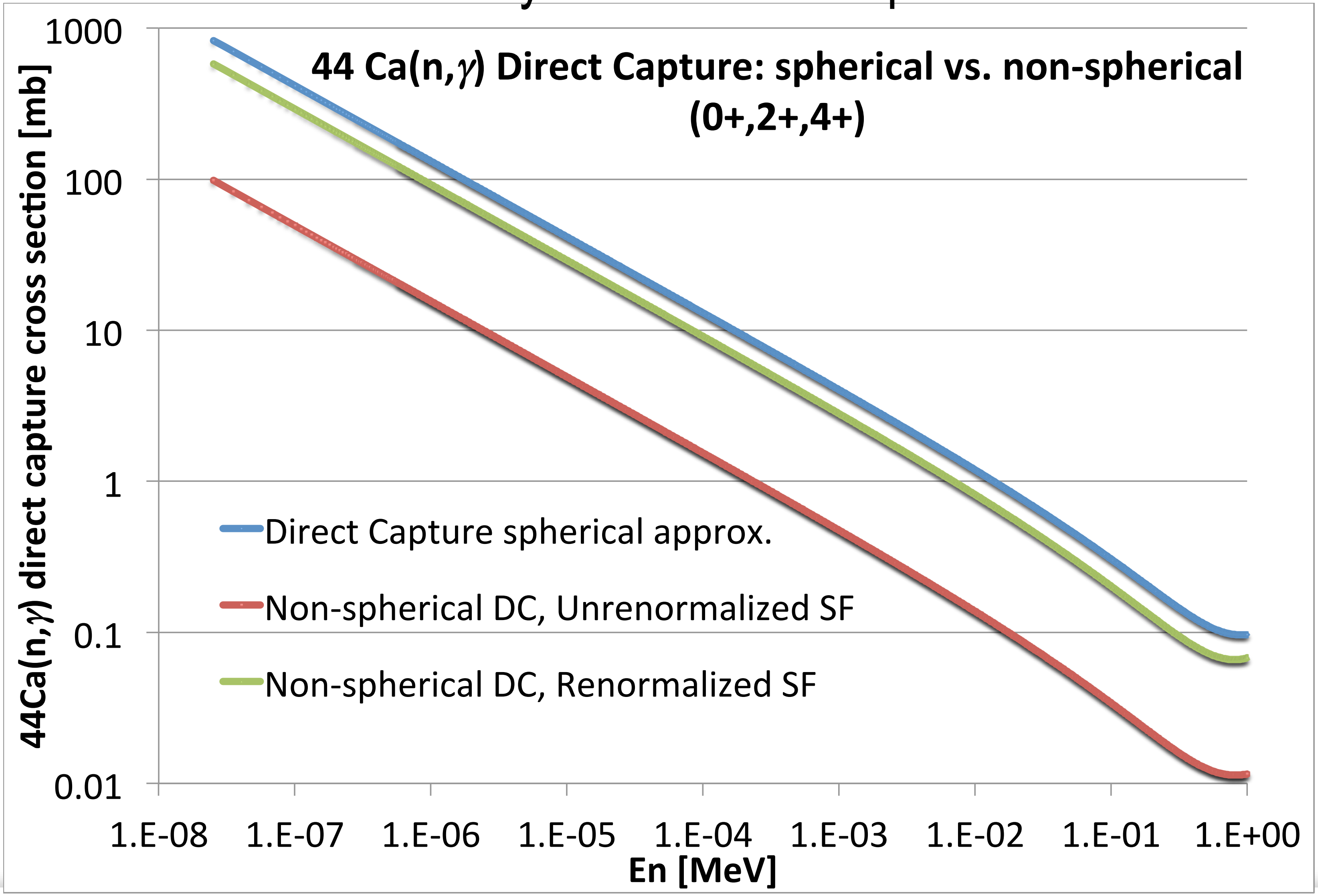
44Ca(n,g) spherical vs. CC (0+,2+)

- Renormalization of SF yields capture compatible with experiment



44Ca(n,g) spherical vs. CC (0+,2+,4+)

- Renormalization of SF yields thermal capture too small



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