Higher-Order Contributions to Capture Processes

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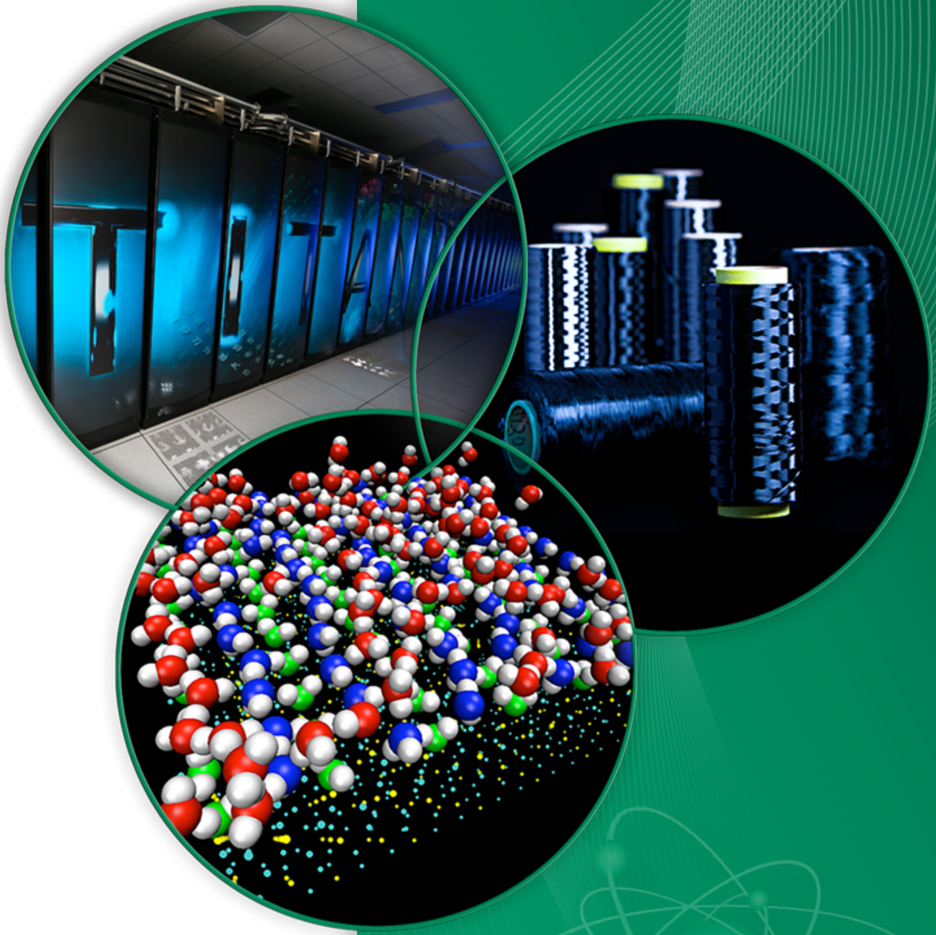


TORUS Collaboration Meeting

Michigan State University, East Lansing, MI

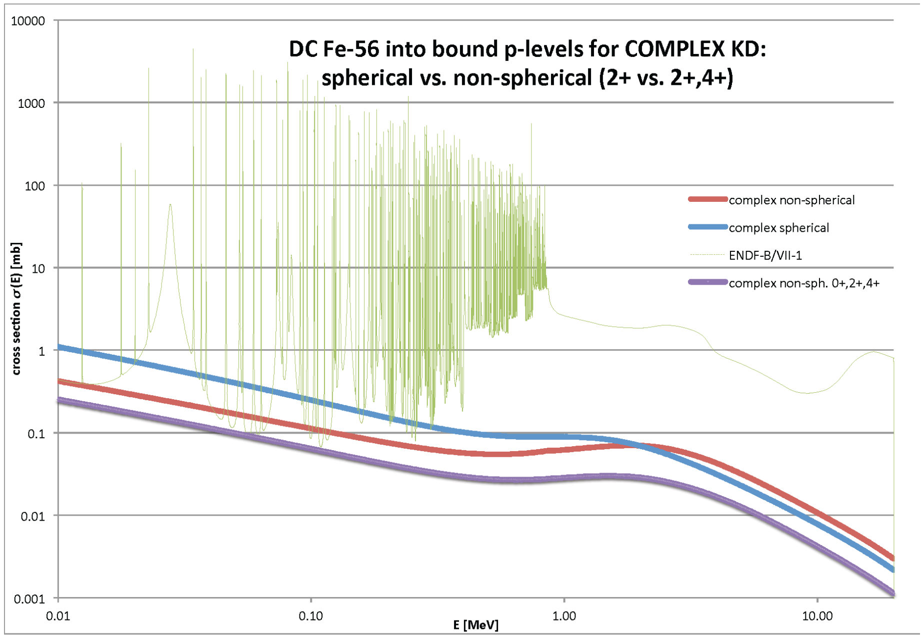
June 9, 2014

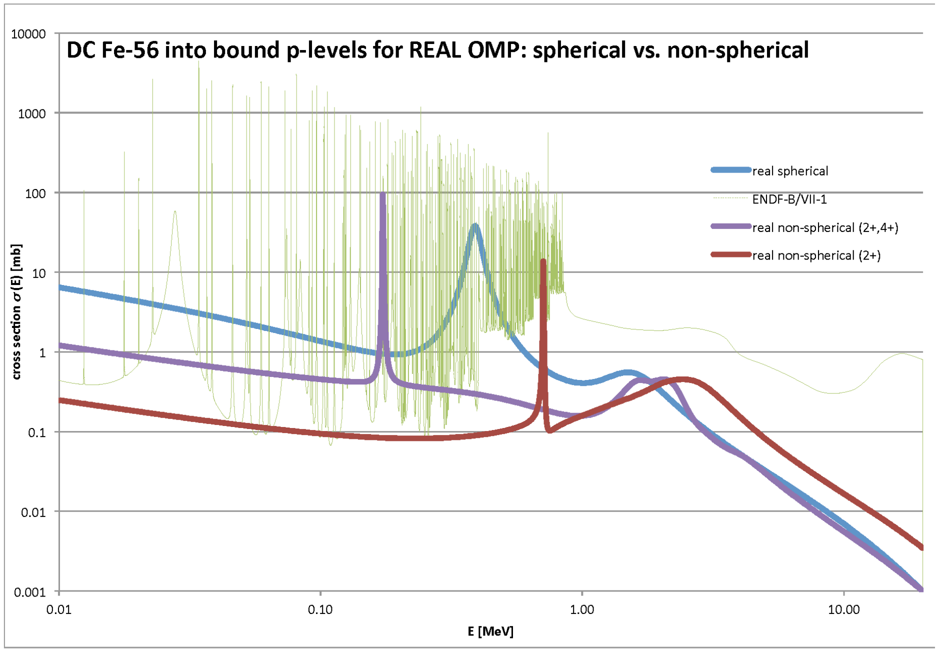
Overview

- Computation of capture via collective rotational states (2+, 4+)
  - Higher-order than direct capture
  - Fe-56 (n,g); relevant to CIELO collaboration
- Study of Nickel MACS (Rituparna Kanungo/TRIUMF)
  - Direct capture & compound resonance (*s*- & *p*-wave) capture important
- Study of 130Sn(n,γ)131Sn from (γ,n)
  - B. Manning computed (n,g) G.S. from Adrich's (γ,n) data; detailed balance
  - Compute total (n,γ) from (γ,n) γ-strength function using TALYS
- Quantifying the improvement to MACS that could be hoped for from an improved theory (relative to Hauser-Feshbach) of (n,γ):
- Gamow-Shell Model computation of (n,g) near 132-Sn
  - Need effective interaction for tin isotopes (late 2014, or 2015)

Direct (n,γ) + coupling to (2+, 4+)

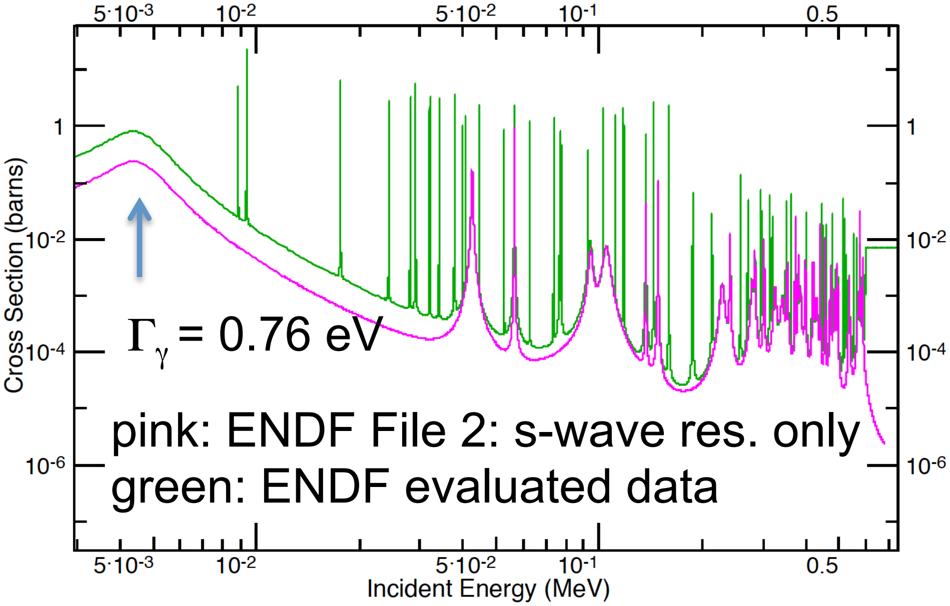
- Used FRESCO to consistently couple to 2+ and 4+ states
  - In the incoming and the outgoing states
  - Prior to this work only incoming or outgoing but not both
  - Initiated a study of Ca-{40,42,44,46,48} isotopes
  - Computed Fe-56 because relevant to CIELO int.'l collab. nuclear data
    - 0+ (G.S.), 2+, 4+ rotational band states (but not clear for 6+, 8+…)
    - Real vs. Complex Koning-Delarche Opt. Pot. (cf. floor of capture data)





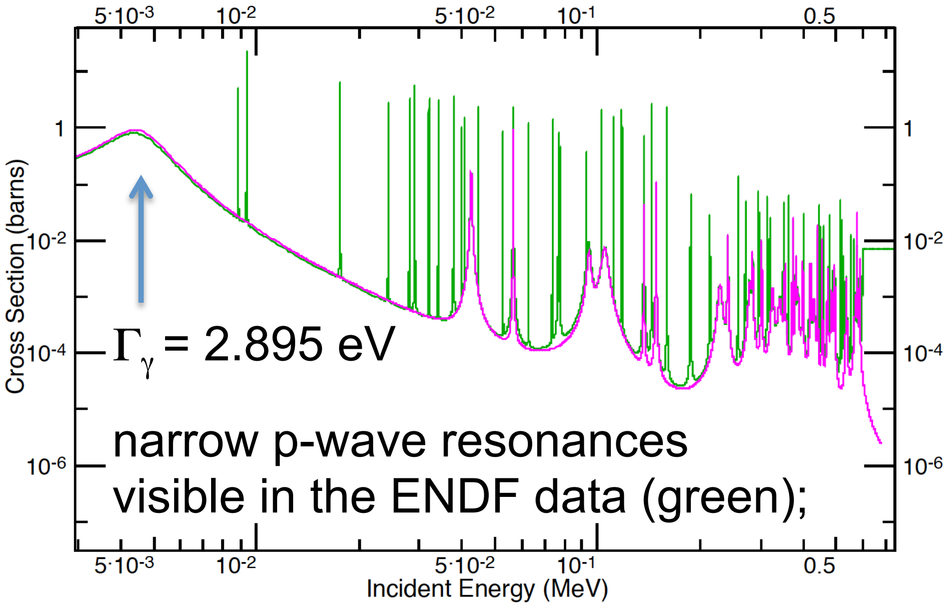
^{62}Ni(n,γ)^{63}Ni: Direct vs. Resonant capture

- Direct Capture (DC) issues:
  - 3s1/2 zero-energy “resonance” of real (e.g. Woods-Saxon) pot. for A~55-60
  - May yield unrealistic (too large) DC cross section
- Resonant capture (RC) issues:
  - γ-ray width of the 4.6 keV resonance underestimated:
    - (0.76 vs. 2.895) eV (plotted below)→ 30 keV MACS: (5.2 vs. 14.2) mb; 9 mb too small!
  - *p*-wave resonances were omitted from MACS: another 10 mb missing!



Γ_γ = 0.76 eV

pink: ENDF File 2: s-wave res. only
green: ENDF evaluated data



Γ_γ = 2.895 eV

narrow p-wave resonances
visible in the ENDF data (green);

^{62}Ni(n,γ)^{63}Ni: Direct vs. Resonant capture

\ MACS 30 keV	Rauscher [mb]	This work	Measured
Resonant (RC)	5.2 ± (5%)	24.2 ± (5%)	n/a
Direct (DC)	5.5 ± 0.8	0.4 ± (20%)	n/a
Total	10.5 ± 0.8	24.8± (>5%)	25.8±1.8(stat)±1.9(sys)

- DC in this work computed by CUPIDO (Dietrich, LLNL):
  - for the real part of the Koning-Delaroche optical potential
    - Its s-wave “resonance” occurs near A~55, so possibly safer than Rauscher’s potential
  - Analogous computation of MACS on 58,60Ni supported by high-res. data
    - Guber et al., Phys. Rev. C 82, 057601 (2010) (DC computation by Arbanas/CUPIDO)
    - A decreasing trend of DC for {58,60,62}Ni {1.36, 0.54 0.4} mb observed:
      - Expected from a general formula for E1 s-wave neutron capture:
      - SF*(BE+E_n)^3 ← both SF and BE slowly decreasing as neutron number increases
    - The above may boost confidence into our DC computations.
- RC in this work: corrected Γ_γ of 4.6 keV res. + p-wave resonances

“Rauscher”: Rauscher and Guber, Phys. Rev. C **71**, 059903(E) (2005)
“Measured”: Alpizar-Vicente et al., Phys. Rev. C 77, 015806 (2008)

Estimating errors of Hauser-Feshbach (HF)

- HF uses optical potential transmission coefficients
  - Yields energy-averaged cross-sections (*gross* structure)
    - Energy-averaging interval is on the order of 1 MeV
- What if we had an *intermediate* structure theory?
  - s.t. yields energy-averaged cross sections averaged over ~0.1 MeV
    - Corresponding to the width of nominal doorway states; e.g. 2p-1h states
- Performed a numerical estimate by energy-averaging ^{62}Ni(n,γ) data
  - Followed by Maxwellian averging for KT= 30 keV; cf. TALYS HF MACS

Preliminary

E-avg. interval [MeV]	MACS [mb] kT=30 keV
0.0	24.2
0.1	24.7
0.2	20.3
0.5	8.8
1.0	7.0

TALYS Γ_γ-strength	renormalized	unrenor.
Kopecky-Uhl Lorentz.	31	8
Brink-Axel Lorentzian	29	35
Hartree-Fock BCS	n/a	13
Hartree-Fock-Bogol.	n/a	13
Goriely's hybrid model	30	12

  - The improvement in accuracy may be appreciable in this case

Intermediate Struct. Theory of Reactions

- How would an ideal Intermediate Structure Theory improve MACS
  1. Compute MACS of the Hauser-Feshbach (OMP) vs. MACS of the data
  2. Compute MACS of the averaged data 100 keV vs MACS of
- KKM formally extended to intermediate structure (UNEDF)
  - Via doorway projection operators

Atomic Data and Nuclear Data Tables **76,** 70–154 (2000)

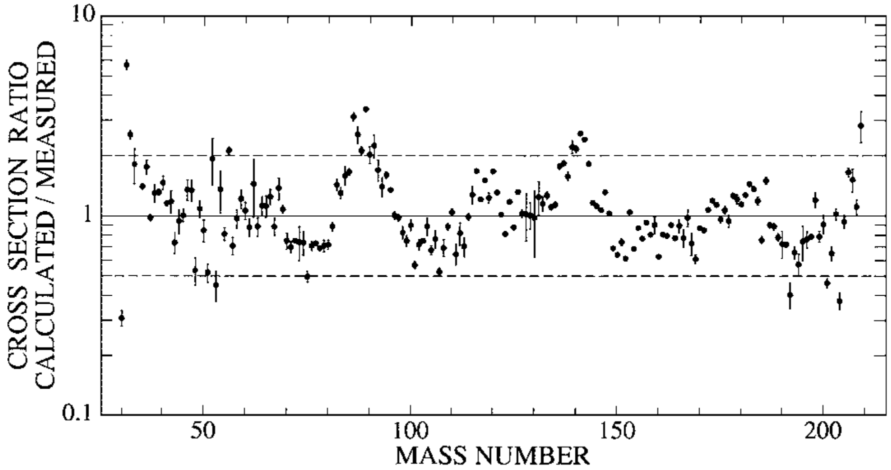
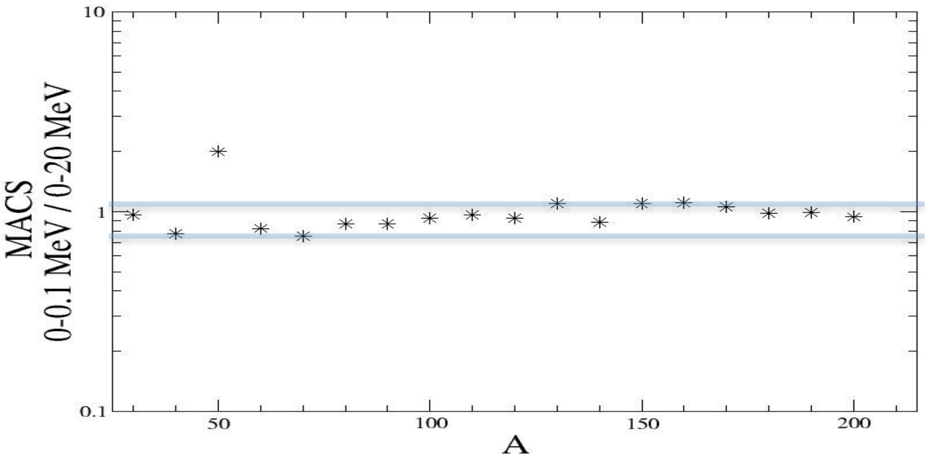
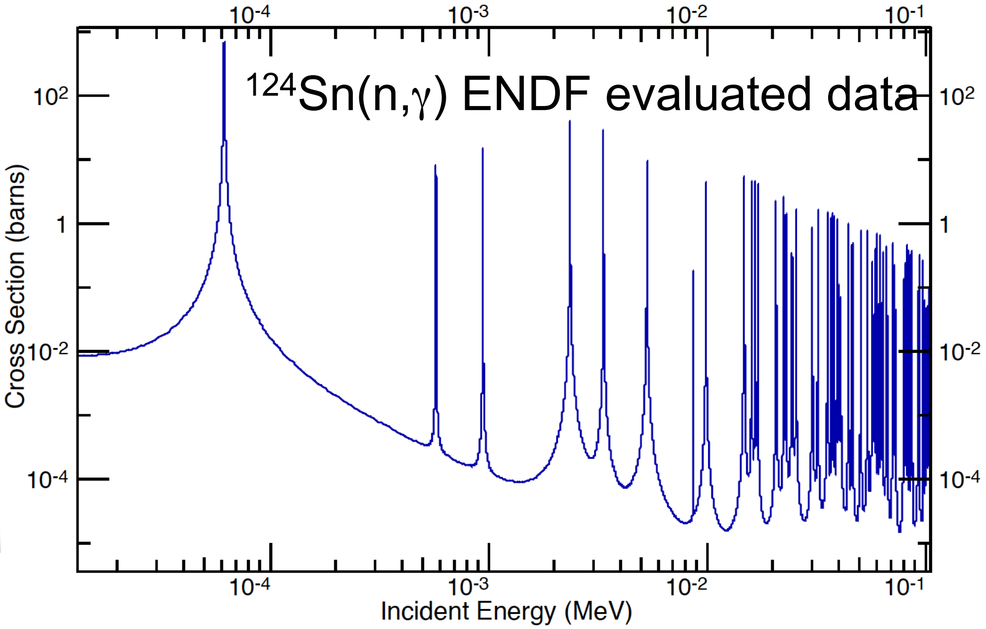


FIG. 3. Comparison of Maxwellian-averaged (n, γ) cross sections for 30 keV thermal energy calculated with the statistical model code NON-SMOKER [3] with experimental data. The dashed lines are drawn to illustrate that the calculations tend to overestimate the cross sections near magic neutron numbers by up to a factor two, but are much more reliable elsewhere.



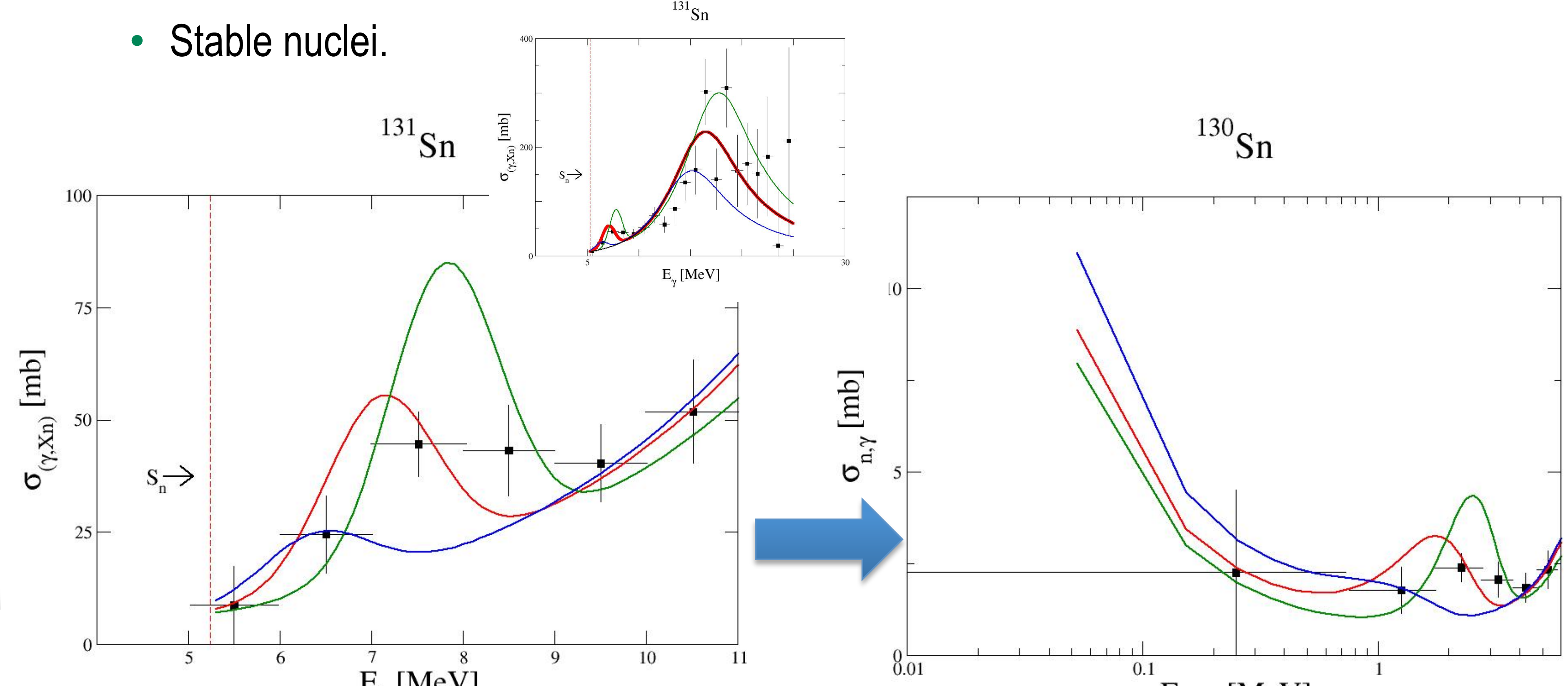
DC vs RC near closed shell nuclei

- Motivated by our computation of ^{130,132}Sn(n,γ) Direct Capture (DC)
  - ^{132}Sn(n,γ): DC >> RC is generally accepted
  - ^{130}Sn(n,γ): DC << RC is estimated by Hauser-Feshbach models
    - But not confirmed experimentally
    - For ^{48}Ca and ^{208}Pb data suggest DC >> RC (in support of 132Sn DC >> RC above)
    - For ^{46}Ca and ^{206}Pb data suggest DC << RC; does this imply ^{130}Sn(n,γ) DC<<RC too?
    - ^{124}Sn(n,γ) (the heaviest stable tin) plotted; shows many compound resonances
      - Its kT=30keV MACS is ~10 mb
      - consistent with some HF models
      - but still inconclusive Re: ^{130}Sn(n,γ)
  - Could an intermediate structure model give answer?



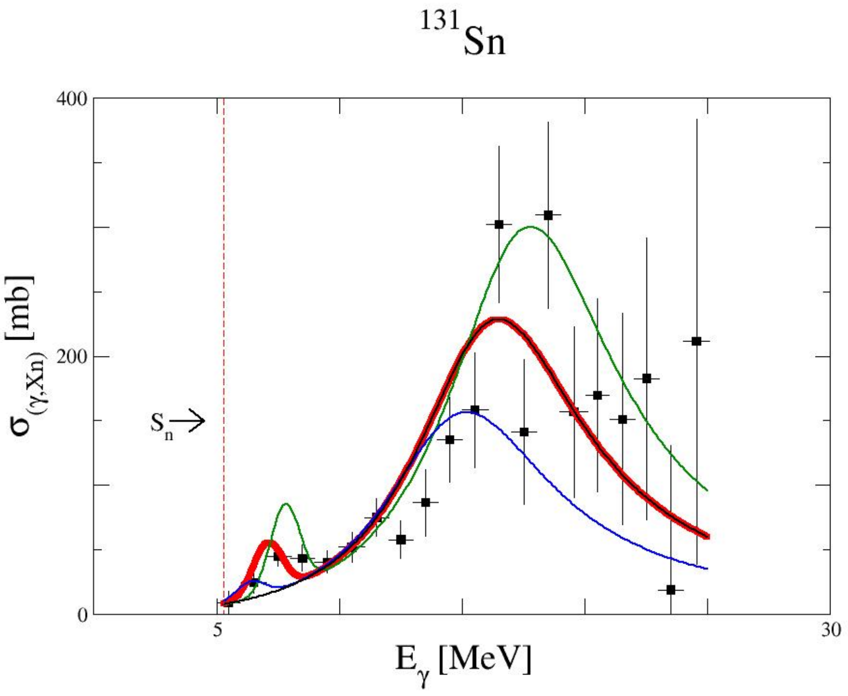
^{130}Sn(n,γ)^{131}Sn$_{g.s.}$ from ^{131}Sn$_{g.s.}$(γ,n)^{130}Sn

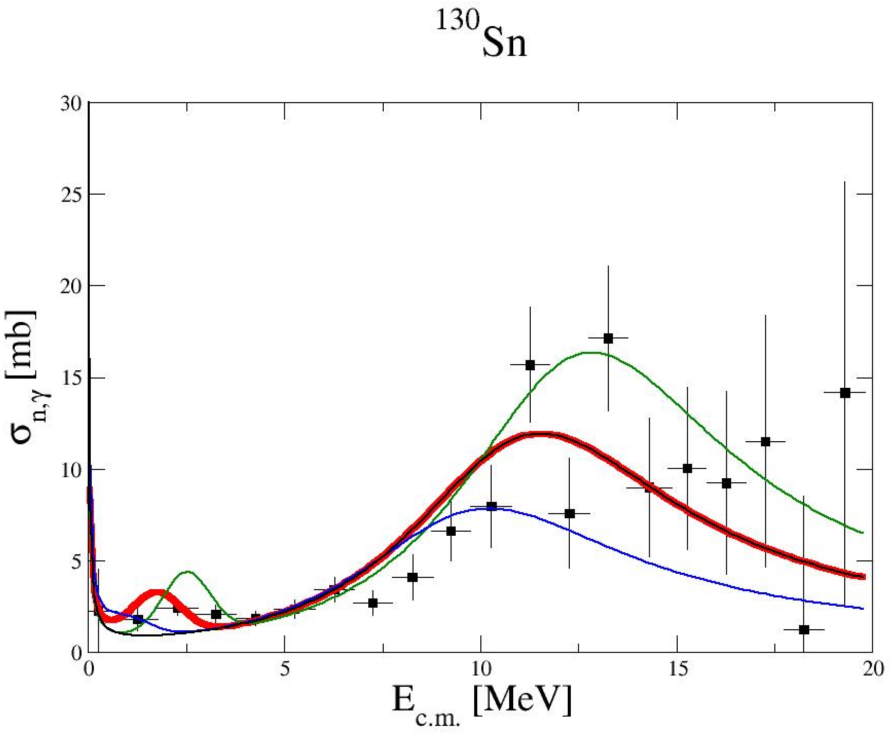
- Using principle of detailed balance (g.s. only)
  - (γ, n) a surrogate reaction for (n, γ); usually applied to lighter nuclei
  - Adrich (2005) ^{131}Sn$_{gs}$(γ, n) data yields ^{130}Sn$_{gs}$(n, γ) E_n<1.2 MeV, ~ 10 x DC
    - even with large uncertainties; and without pygmy dipole resonance
  - A. Tonchev (TUNL) monochromatic laser (1-3)% energy variance
    - Stable nuclei.



(n,γ) from (γ,n) γ-strength function method

- Goriely, Hillaire, Koning (TALYS)
  - γ-strength function method to compute (n,γ) from (γ,n) & (γ,γ’) data
  - Total capture cross section (not just capture c.s. to g.s.)
  - Correspondence in progress. References
    - R. Raut, S. Goriely, et al., Phys. Rev. Lett. 111, 112501 (2013): ^{85}Kr(n,γ) ← ^{86}Kr(γ,n)
    - H. Utsunomiya, S. Goriely et al., Phys. Rev. C 84 055805, (2011): $^{118-124}$Sn


^{131}Sn


^{130}Sn

Proposal for (n,γ) in Gamow Shell Model

- Higher order (2p1h, 3p2h,) components in bound/resonant states
  - More complex than direct capture toward compound resonant capture
    - Comparison with Hauser-Feshabch

$$\frac{d\sigma_{fc}}{dE_\gamma d\Omega_\gamma} = \frac{1}{\phi_{\text{inc}}} \frac{2\pi}{\hbar} \frac{E_\gamma^2}{(\hbar c)^3} |T_{fc}|^2 \delta(E - E_f)$$

- Coupled channels

$$T_{fc} = \langle \Psi_f^{(A)} | H_\gamma | \Phi_c \rangle$$

- Proposal is nearly finalized
  - Pending effective interaction

$$|\Phi_c\rangle = \int_0^{+\infty} \mathcal{A}|\{|\Psi_c^{(A-1)}\rangle^{J_c} \otimes |r\ \ell_c j_c \tau_c\rangle\}^{J_A}_{M_A}\rangle u_c(r) r^2\ dr$$

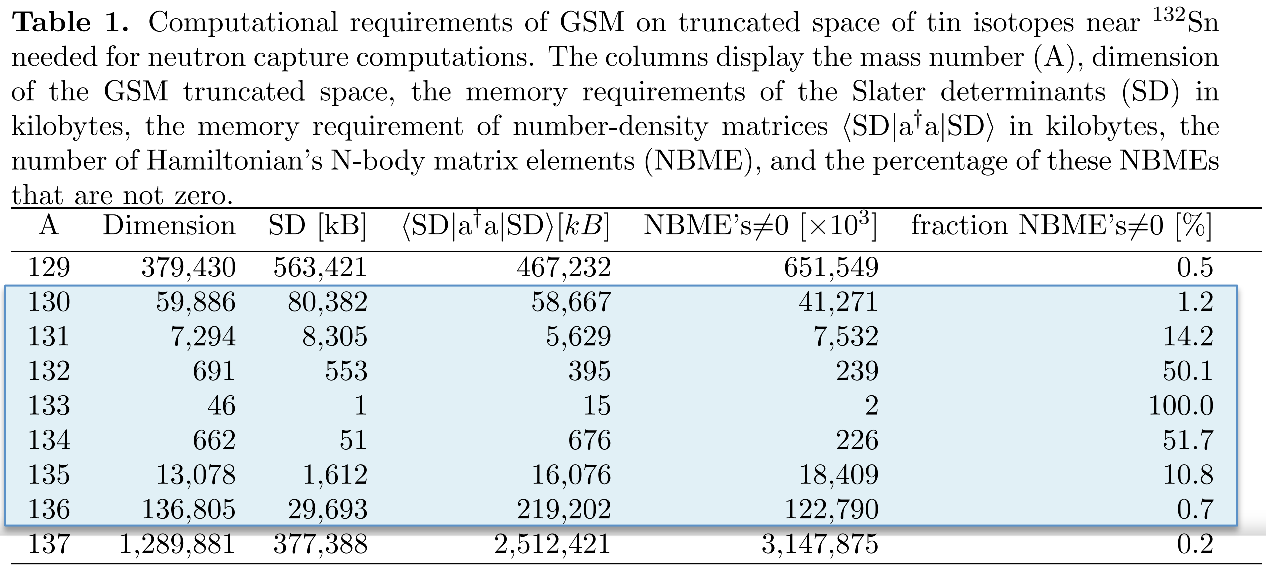


Table 1. Computational requirements of GSM on truncated space of tin isotopes near ^{132}Sn needed for neutron capture computations. The columns display the mass number (A), dimension of the GSM truncated space, the memory requirements of the Slater determinants (SD) in kilobytes, the memory requirement of number-density matrices $\langle$SD$|a^\dagger a|$SD$\rangle$ in kilobytes, the number of Hamiltonian's N-body matrix elements (NBME), and the percentage of these NBMEs that are not zero.

A	Dimension	SD [kB]	$\langle$SD$\|a^\dagger a\|$SD$\rangle[kB]$	NBME's≠0 [$\times 10^3$]	fraction NBME's≠0 [%]
129	379,430	563,421	467,232	651,549	0.5
130	59,886	80,382	58,667	41,271	1.2
131	7,294	8,305	5,629	7,532	14.2
132	691	553	395	239	50.1
133	46	1	15	2	100.0
134	662	51	676	226	51.7
135	13,078	1,612	16,076	18,409	10.8
136	136,805	29,693	219,202	122,790	0.7
137	1,289,881	377,388	2,512,421	3,147,875	0.2

Review and Outlook

- Direct neutron capture on non-spherical nuclei was modeled by rotational band states 2+, 4+ in incoming and outgoing partitions, and their effect, computed by Fresco, was significant for ^{56}Fe.
- The improvement to stellar MACS that could be achieved by an ideal intermediate structure reaction theory over Hauser-Feshbach
  - The upper-limit promising, but a realistic theory would not do quite as well
- Used detailed balance and Adrich's ^{131}Sn(γ,n) to estimate the lower limit of compound resonant capture on ^{130}Sn(n,γ)^{131}Sn$_{g.s.}$
  - It appears to be greater than the Direct Capture component
  - Exploring the prospect of using g-strength function to compute total compound resonant capture, to all states (not just the g.s.)
- Gamow Shell Model; an intermediate structure theory of reactions?
  - An attempt to apply it to ^{132}Sn(n,γ) is planned for 2015