Giant dipole and pygmy contributions to capture processes

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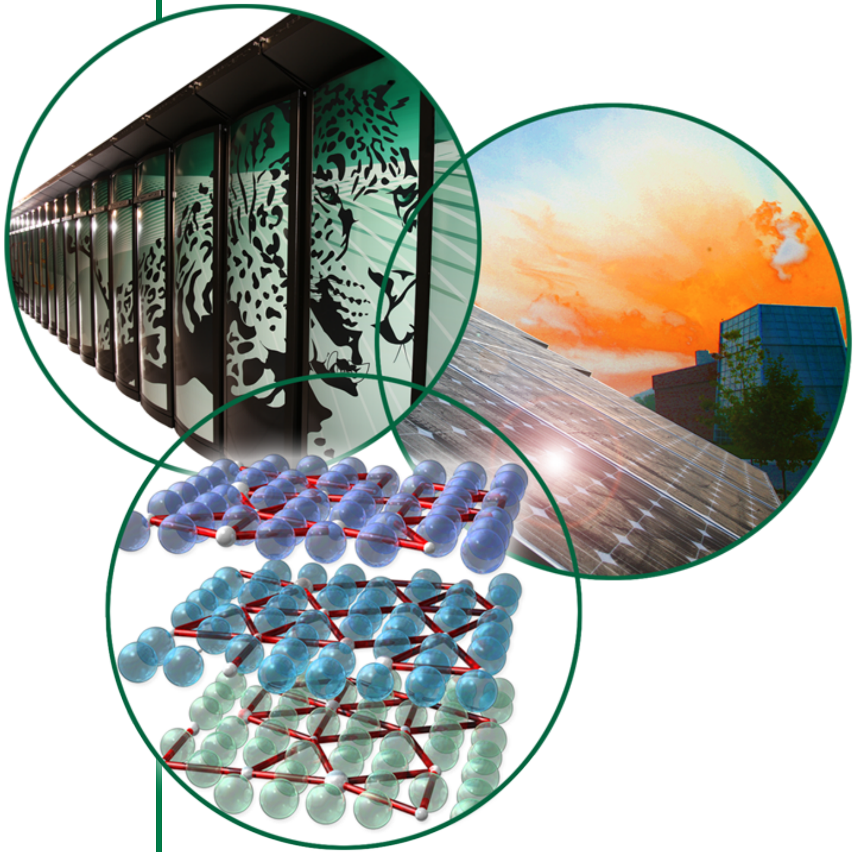

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Main Contributions to captures

- Direct capture (D) (i.e. one-step)
  - Important at low energies on light, or neutron rich nuclei
  - Potential model needs ANC from a (d,p) reaction
- Semidirect (SD) capture (i.e. two-step)
  - Via GDR, PDR, GQR or other doorway states
  - Dominates at, and around, $E_b + E_{GDR}$
  - D + SD contributions interfere; their amplitudes add
- Compound capture (i.e. many-step)
  - Via (complex) compound nuclear states
  - Competes with the above at all energies, and dominates for low-energy gammas of stable nuclide

DWBA Implementation of DSD

$$T_{\mathrm{if}}^{(\lambda)} = \langle \Psi_{\mathrm{i}} | O_\lambda | u_{\mathrm{f}} \psi_0 \rangle \qquad H = H_0 + H_n + V_{\mathrm{coll}}$$

$$|\Psi_{\mathrm{i}}\rangle = |\chi_{\mathrm{i}} \psi_0\rangle + \frac{1}{E - H_0 - H_n} V_{\mathrm{coll}} |\chi_{\mathrm{i}} \psi_0\rangle$$

$$T_{\mathrm{if}}^{(\lambda)} = T_{\mathrm{D}} + T_{\mathrm{SD}}$$

$$T_{\mathrm{D}} = \langle \chi_{\mathrm{i}} | O_\lambda | u_{\mathrm{f}} \rangle$$

$$T_{\mathrm{SD}} = \langle \chi_{\mathrm{i}} \psi_0 | V_{\mathrm{coll}} \frac{1}{E - H_0 - H_n} O_\lambda | u_{\mathrm{f}} \psi_0 \rangle$$

Fresco:

$$T_{\mathrm{SD}} = \langle \chi_{\mathrm{i}} \psi_0 | V_{\mathrm{coll}} | \psi_{\mathrm{D}} \rangle \frac{1}{E - E_{\mathrm{D}} - H_{\mathrm{n}}} \langle \psi_{\mathrm{D}} | O_\lambda | u_{\mathrm{f}} \psi_0 \rangle$$

Cupido:

$$T_{\mathrm{SD}} = \langle \chi_{\mathrm{i}} \psi_0 | V_{\mathrm{coll}} | u_{\mathrm{f}} \psi_{\mathrm{D}} \rangle \frac{1}{E - E_{\mathrm{D}} - E_{\mathrm{b}}} \langle u_{\mathrm{f}} \psi_{\mathrm{D}} | O_\lambda | u_{\mathrm{f}} \psi_0 \rangle$$

Direct-Semidirect Capture in Coupled Ch.

- T-matrix: a coherent sum of *direct* and *semidirect* parts

$$T_{\mathrm{fi}}(E,E_\gamma) = \langle \Psi_{\mathrm{f}}(E,E_\gamma) | O^{\mathrm{n}}_\lambda + O^{\mathrm{c}}_\lambda | \Psi_{\mathrm{i}}(E) \rangle$$

- Incoming and outgoing wave functions

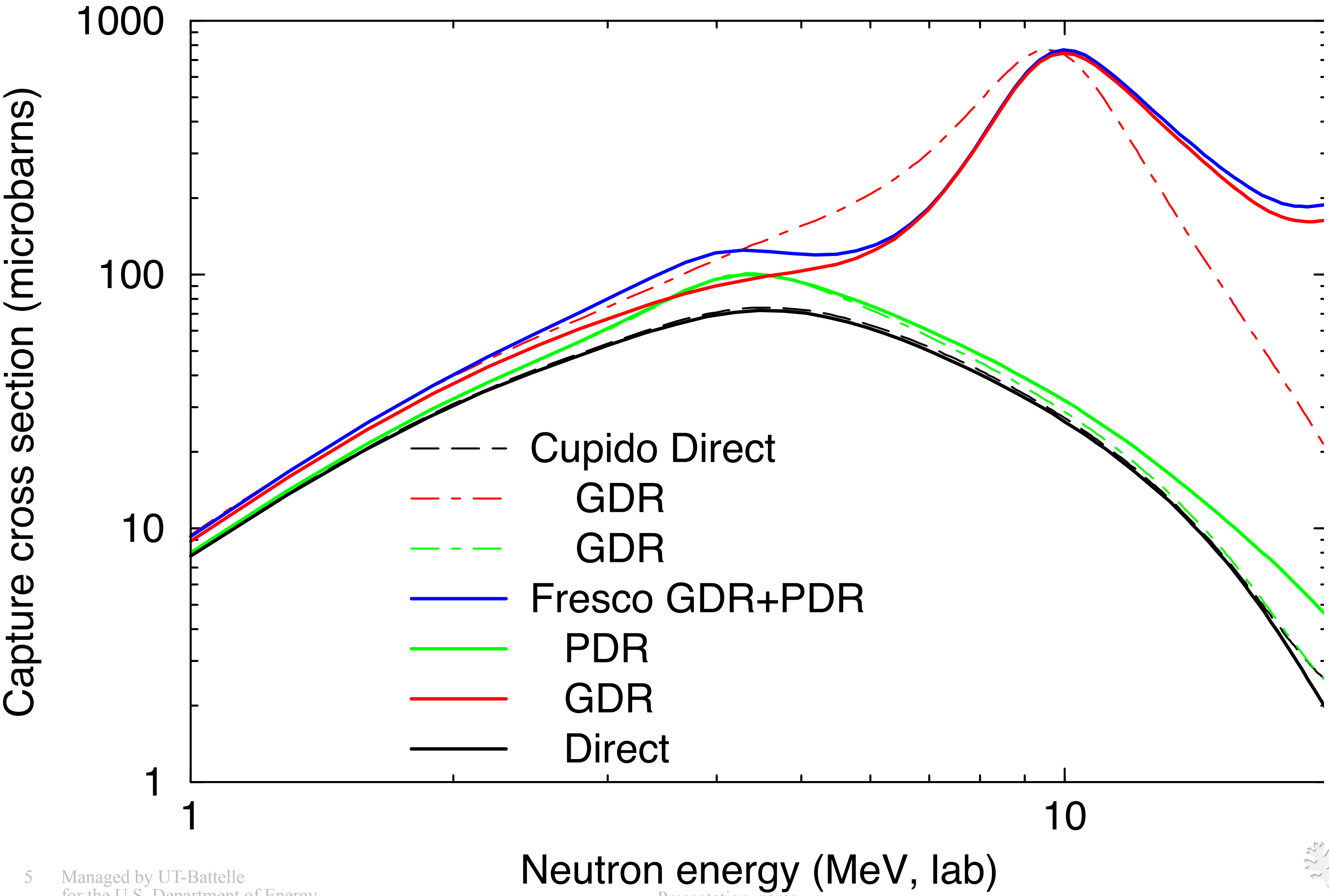
$$\begin{aligned} \Psi_{\mathrm{i}}(E) &= \chi^{E}_{\mathrm{n}}(r_{\mathrm{n}})\phi_{\mathrm{gs}}(\xi) + \chi^{E-E_{\mathrm{d}}}_{\mathrm{d}}(r_{\mathrm{n}})\phi_{\mathrm{d}}(\xi) \\ \Psi_{\mathrm{f}}(E,E_\gamma) &= [\chi^{E-E_\gamma}_{\mathrm{b}}(r_{\mathrm{n}})\phi_{\mathrm{gs}}(\xi) + \chi^{E-E_{\mathrm{d}}-E_\gamma}_{\mathrm{e}}(r_{\mathrm{n}})\phi_{\mathrm{d}}(\xi)]\zeta_\gamma(r_\gamma) \end{aligned}$$

- Inserting yields four terms

$$T_{\mathrm{fi}} = \boxed{\langle \chi_{\mathrm{b}} | O^{\mathrm{n}}_\lambda | \chi_{\mathrm{n}} \rangle} + \langle \chi_{\mathrm{e}} | O^{\mathrm{n}}_\lambda | \chi_{\mathrm{d}} \rangle + \boxed{\langle \chi_{\mathrm{b}} | \chi_{\mathrm{d}} \rangle \langle \phi_{\mathrm{gs}} | O^{\mathrm{c}}_\lambda | \phi_{\mathrm{d}} \rangle} + \langle \chi_{\mathrm{e}} | \chi_{\mathrm{n}} \rangle \langle \phi_{\mathrm{d}} | O^{\mathrm{c}}_\lambda | \phi_{\mathrm{gs}} \rangle$$

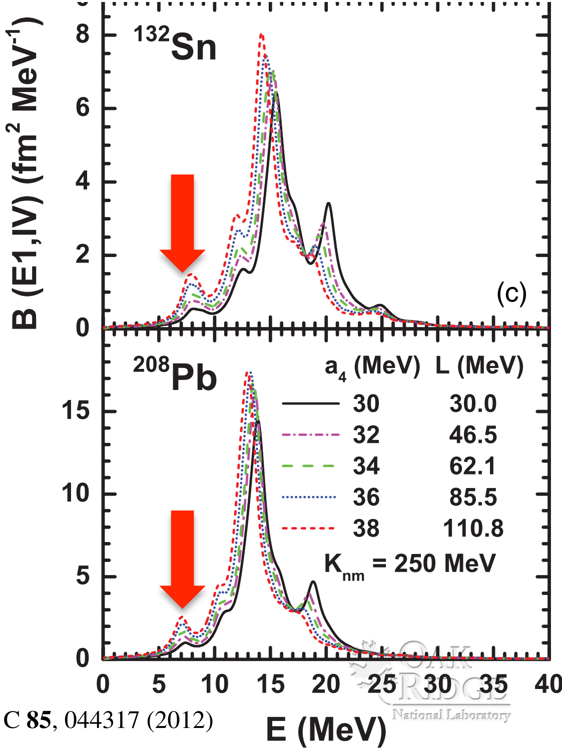
Dominant terms

DSD(G+P)DR 208Pb(n,g): various methods



Unresolved issues in DSD via GDR & PDR

- Various models provide formal expressions for GDR coupling
- GDR coupling strength conventionally adjusted to fit data
  - Sometimes w/o a clear physical motivation
  - E.g. a large ***imaginary*** GDR coupling is necessary to fit the DSD data
- Various physical interpretation of PDR e.g.:
  - Excess neutron oscillate around N=Z core
  - Toroidal motion around the N=Z core



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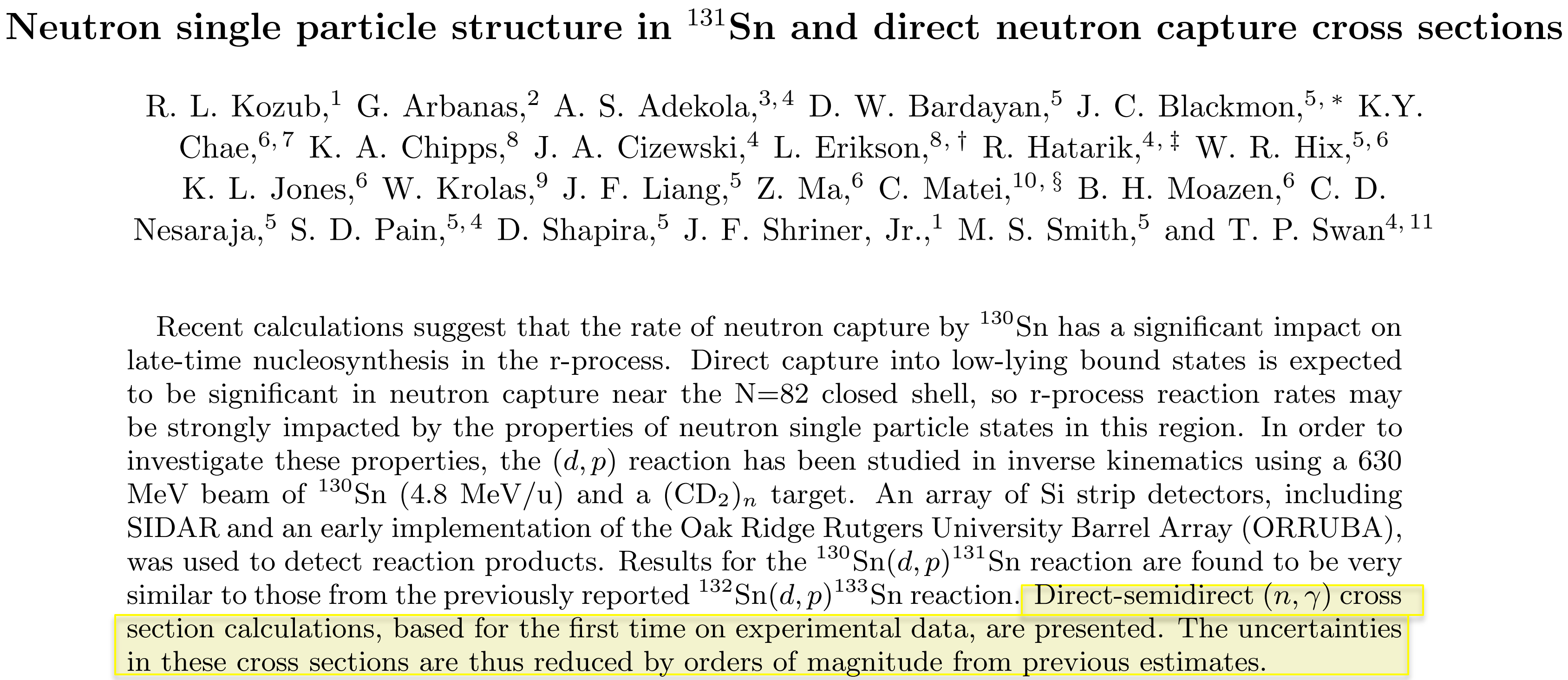
Long-term DSD capture improvements:

- Use recent RPA computations of the electric dipole strength as input to Fresco for computations of DSD capture
  - This would be consistent with structure computations:
  - Analogous to RPA doorway state model of *Nobre et al.*
  - Since GDR can also be thought of as a doorway state.
  - Would self-consistently include GDR and PDR.

DSD via GDR ^{130}Sn(n, γ)



Neutron single particle structure in ^{131}Sn and direct neutron capture cross sections

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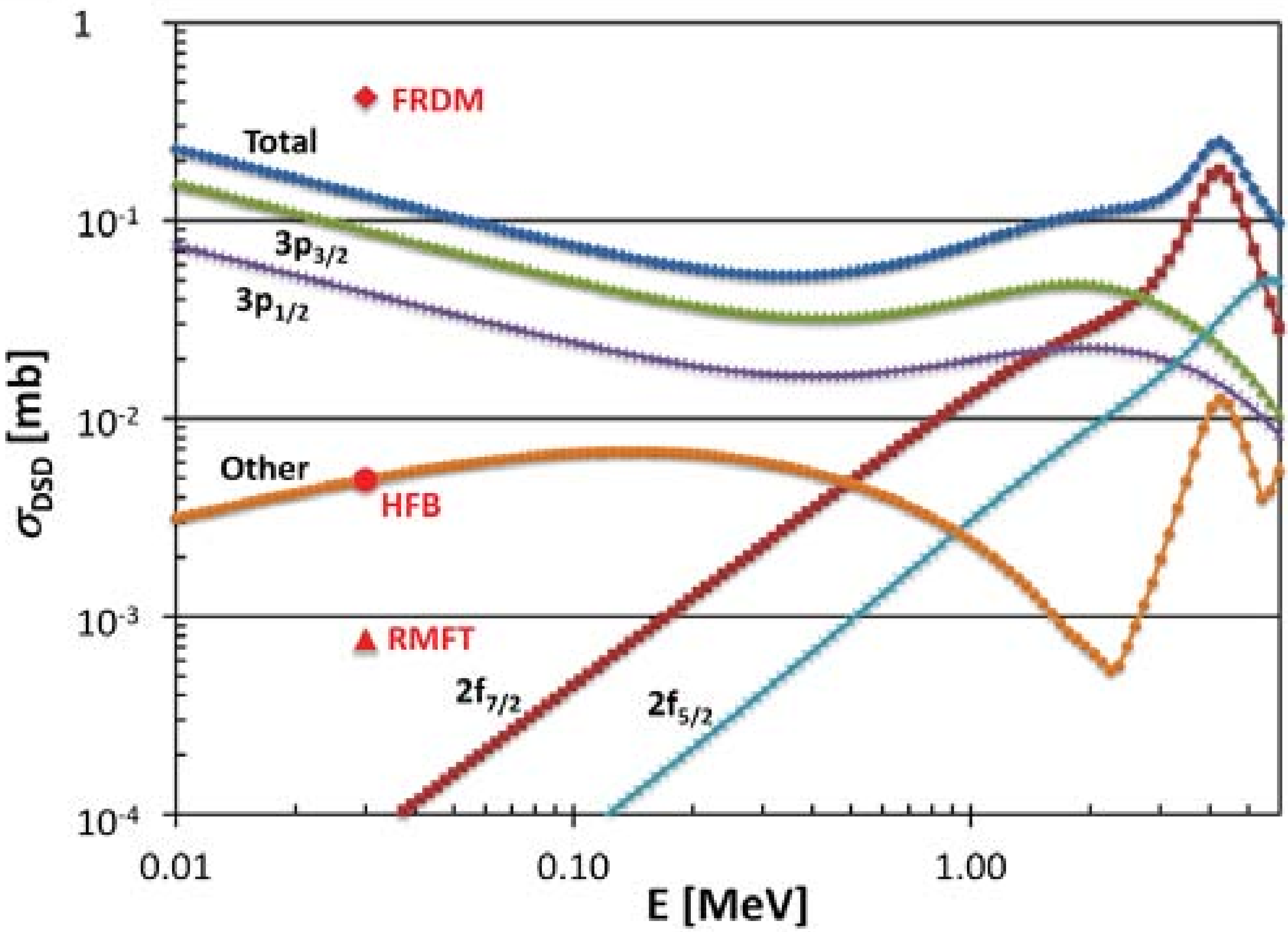
Recent calculations suggest that the rate of neutron capture by ^{130}Sn has a significant impact on late-time nucleosynthesis in the r-process. Direct capture into low-lying bound states is expected to be significant in neutron capture near the N=82 closed shell, so r-process reaction rates may be strongly impacted by the properties of neutron single particle states in this region. In order to investigate these properties, the (d,p) reaction has been studied in inverse kinematics using a 630 MeV beam of ^{130}Sn (4.8 MeV/u) and a $(CD_2)_n$ target. An array of Si strip detectors, including SIDAR and an early implementation of the Oak Ridge Rutgers University Barrel Array (ORRUBA), was used to detect reaction products. Results for the ^{130}Sn$(d,p)^{131}$Sn reaction are found to be very similar to those from the previously reported ^{132}Sn$(d,p)^{133}$Sn reaction. Direct-semidirect (n,γ) cross section calculations, based for the first time on experimental data, are presented. The uncertainties in these cross sections are thus reduced by orders of magnitude from previous estimates.

DSD $^{130}Sn(n, \gamma)$ to various bound s.p. states



Two-hole pairing state in ^{130}Sn g.s.

- A generalization of the Richardson's exactly solvable pairing model to separable level-dependent interaction:
  - Provides additional variational parameters c_i; one per s.p. level

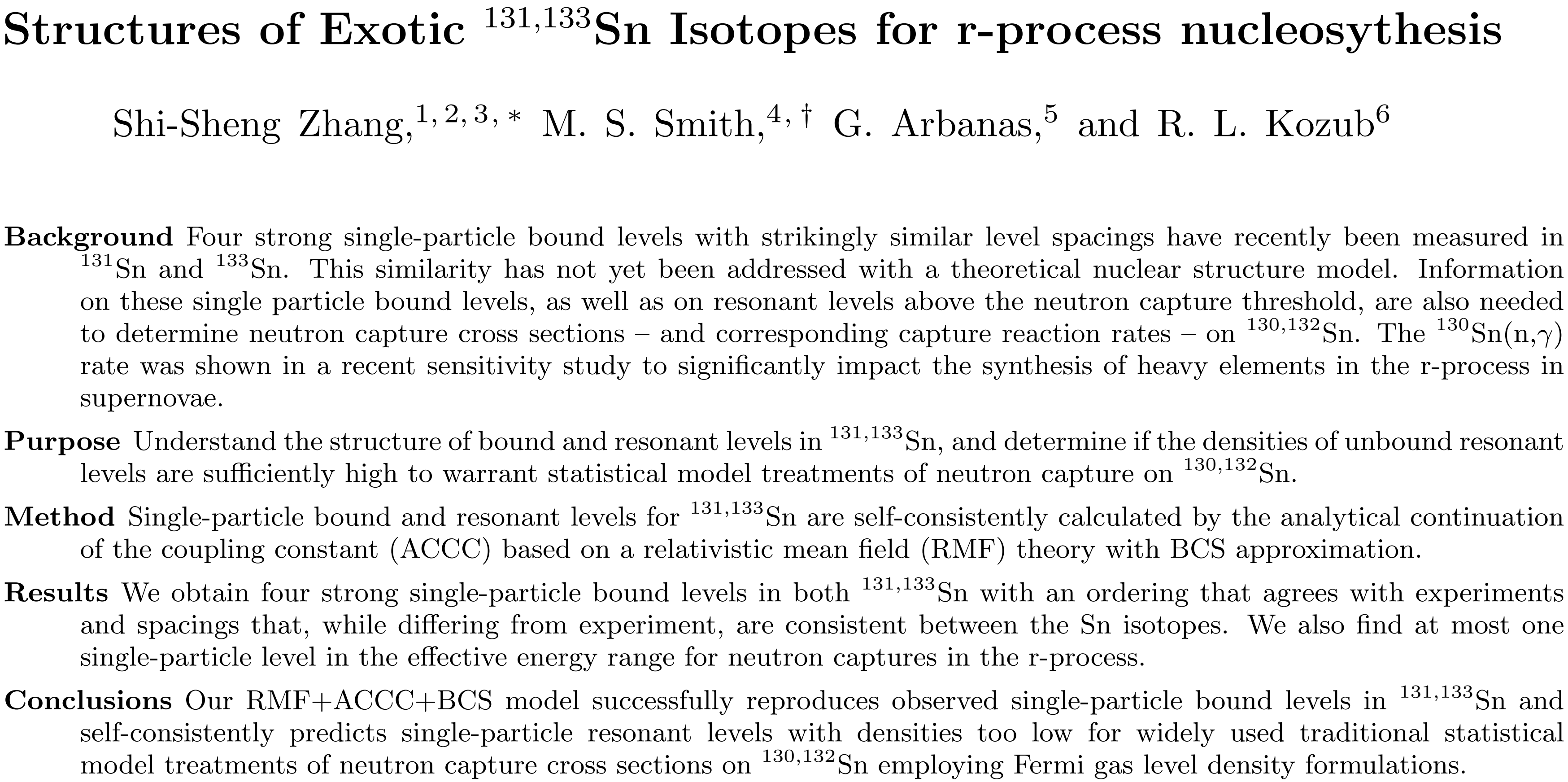
$$H = \sum_i \varepsilon_i \left(a^\dagger_{i_+} a_{i_+} + a^\dagger_{i_-} a_{i_-}\right) - g \sum_i \sum_j c_i c_j a^\dagger_{i_+} a^\dagger_{i_-} a_{j_+} a_{j_-}$$

$$|\Psi_N\rangle = \prod_{\beta=1}^{N} \sum_i \frac{c_i}{2\varepsilon_i - E_\beta} a^\dagger_{i+} a^\dagger_{i-} |0\rangle$$

$$\sum_i \frac{c_i^2}{2\varepsilon_i - E_\beta} = \frac{1}{g} + \sum_{\beta'(\neq\beta)} \frac{2c_{\beta'}^2}{E_{\beta'} - E_\beta}$$

$$E = \sum_i \varepsilon_i \nu_i + \sum_\beta E_\beta$$

RMF levels computations in ^{131}Sn



Structures of Exotic ^{131,133}Sn Isotopes for r-process nucleosythesis

Shi-Sheng Zhang,[1,2,3,*] M. S. Smith,[4,†] G. Arbanas,[5] and R. L. Kozub[6]

Background Four strong single-particle bound levels with strikingly similar level spacings have recently been measured in ^{131}Sn and ^{133}Sn. This similarity has not yet been addressed with a theoretical nuclear structure model. Information on these single particle bound levels, as well as on resonant levels above the neutron capture threshold, are also needed to determine neutron capture cross sections – and corresponding capture reaction rates – on ^{130,132}Sn. The ^{130}Sn(n,γ) rate was shown in a recent sensitivity study to significantly impact the synthesis of heavy elements in the r-process in supernovae.

Purpose Understand the structure of bound and resonant levels in ^{131,133}Sn, and determine if the densities of unbound resonant levels are sufficiently high to warrant statistical model treatments of neutron capture on ^{130,132}Sn.

Method Single-particle bound and resonant levels for ^{131,133}Sn are self-consistently calculated by the analytical continuation of the coupling constant (ACCC) based on a relativistic mean field (RMF) theory with BCS approximation.

Results We obtain four strong single-particle bound levels in both ^{131,133}Sn with an ordering that agrees with experiments and spacings that, while differing from experiment, are consistent between the Sn isotopes. We also find at most one single-particle level in the effective energy range for neutron captures in the r-process.

Conclusions Our RMF+ACCC+BCS model successfully reproduces observed single-particle bound levels in ^{131,133}Sn and self-consistently predicts single-particle resonant levels with densities too low for widely used traditional statistical model treatments of neutron capture cross sections on ^{130,132}Sn employing Fermi gas level density formulations.

Similarity ^{133}Sn(d,p) vs. ^{131}Sn(d,p)

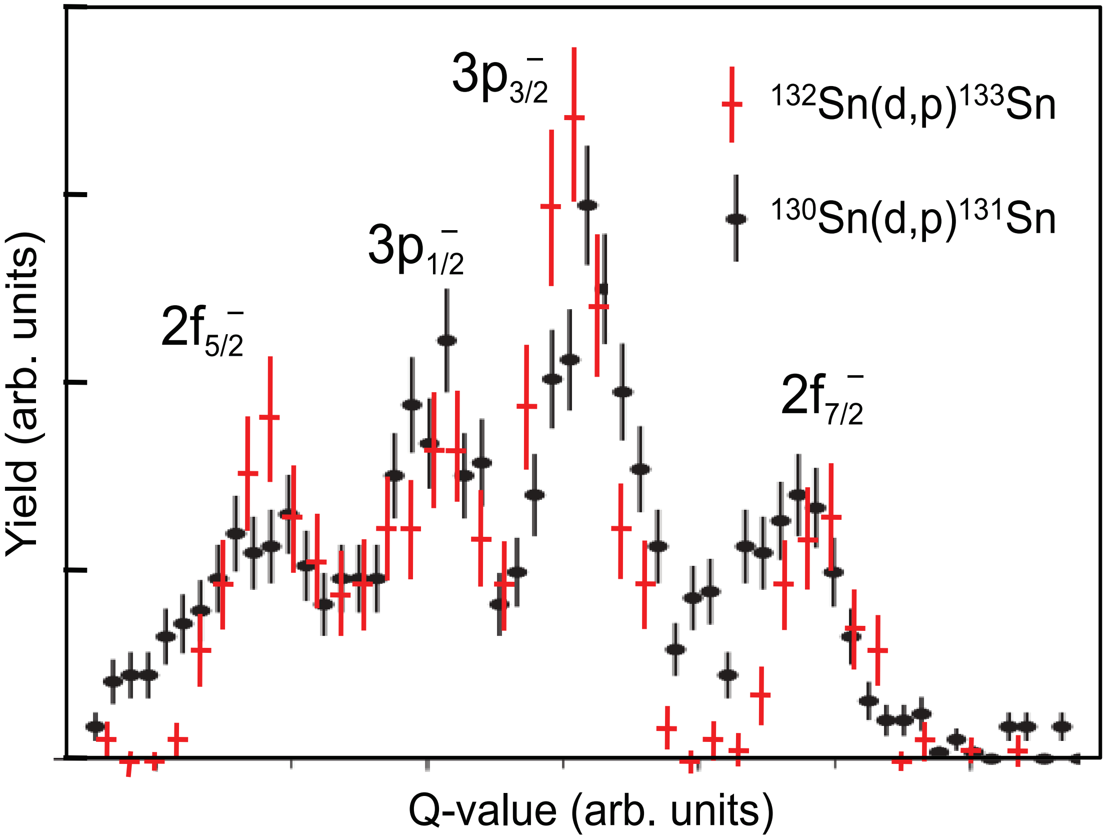
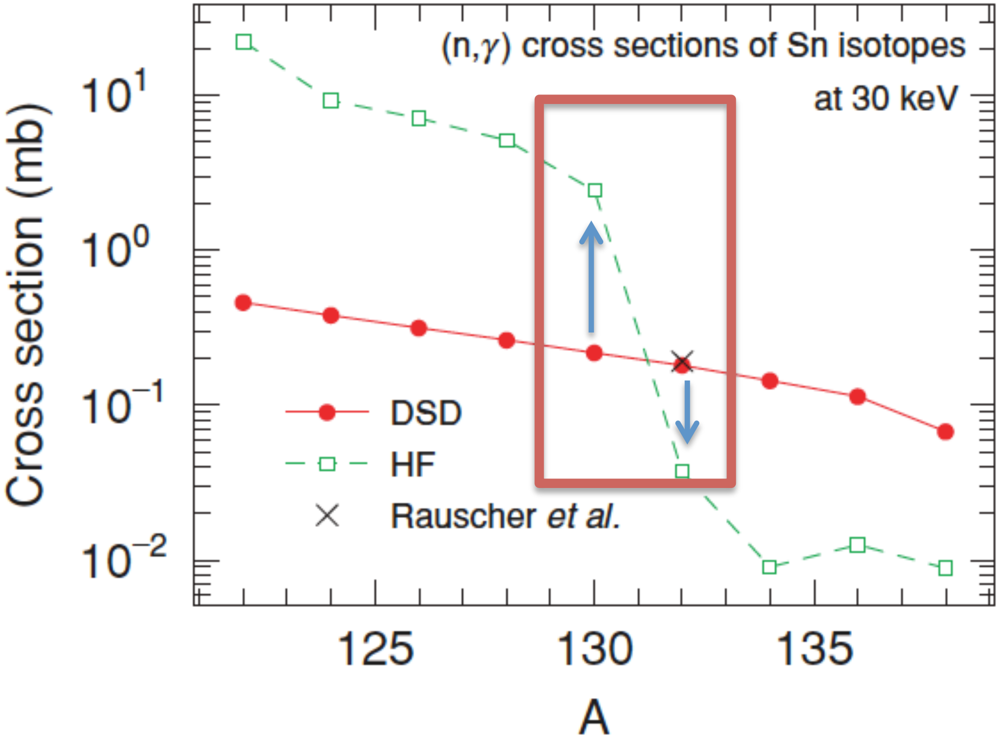


Fig. 1: (Color online) Comparison of strong single-particle levels seen in recent ^{132}Sn$(d,p)^{133}$Sn [1] and ^{130}Sn$(d,p)^{131}$Sn [2] measurements.

- **Possibility of fragmentation of s.p. states via particle-collective (2^+) state interaction may increase level density in ^{131}Sn (as it does in ^{207}Pb)**
- **^{130}Sn(d,pγ) data will reveal this.**

^{130}Sn(n,g) important for nucleosynthesis

- **Relative contribution of DSD vs. compound capture varies**
  - **It depends on level densities**
  - **Level density in Sn-130 may be smaller then previously thought**
    - **This may lead to smaller compound capture →DSD capture may be important.**



S. Chiba et al. Phys. Rev. C 77, 015809 (2008)