Problems in Calculating Low-Energy Neutron Radiative Capture for Astrophysics

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Talk to TORUS Collaboration at LLNL

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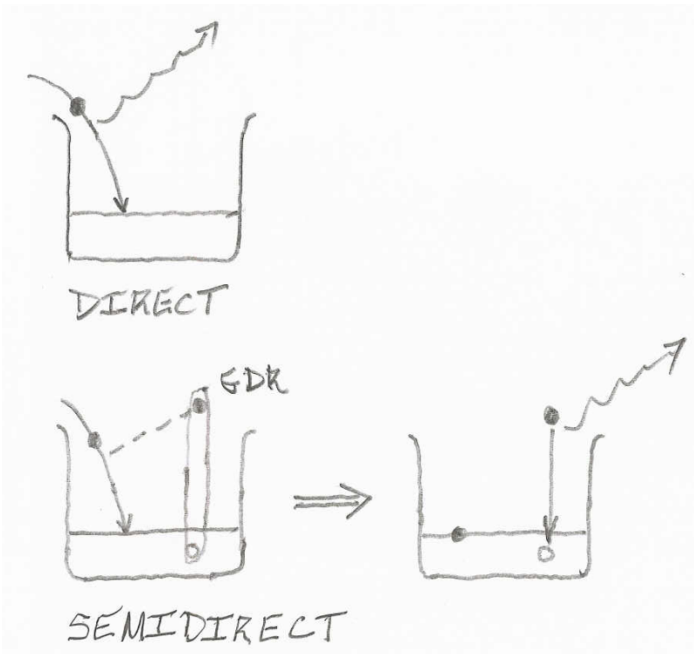
Outline

- **Quick intro to direct-semidirect (DSD) formalism**
- **Examples of DSD at high energies (> a few MeV) where it is fairly well understood**
- **Successes and outstanding problems in understanding (n,γ) at low energies (e.g. 30-keV Maxwellian average cross sections)**

2 interfering terms in direct-semidirect capture



Projectile radiates and is captured in well

1) Projectile excites giant dipole resonance and is captured;
2) Giant dipole collapses and emits the gamma ray

Effective radial electromagnetic operator:

$$Q_L = q_L r^L + \left(\frac{1}{E_\gamma - E_{res} + i\Gamma/2} - \frac{1}{E_\gamma + E_{res}} \right) h_L'(r)$$

direct semidirect

The physics is in the radial integrals of the electromagnetic operators

For each final state, calculate

$$I_{fi}^{L} = \int_{0}^{\infty} dr\, u_f(r) Q_L(r) \psi_i(r)$$

Electromagnetic operator

Bound final state

Continuum initial state

Solve single-particle Schrodinger equation to get initial, final states

Cross section is a bilinear combination of these integrals

$$d\sigma_{n,\gamma} / d\Omega = S_f \sum_{ii'LL'k} C_{ii'LL'fk}\, I_{fi'}^{L'*}\, I_{fi}^{L}\, P_k(\cos\theta)$$

The spectroscopic factor S_f is a measure of the amount of the simple configuration u_f in the actual final state. It may be calculated or gotten from stripping experiments such as (d,p).

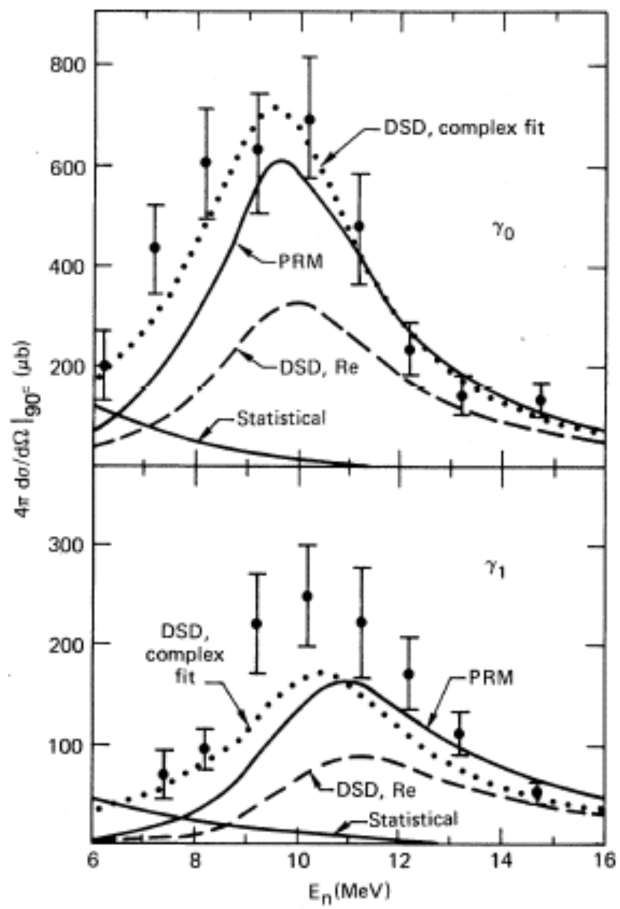
Direct-semidirect capture: observations and problems

DSD is a simple potential model for capture – sometimes too simple

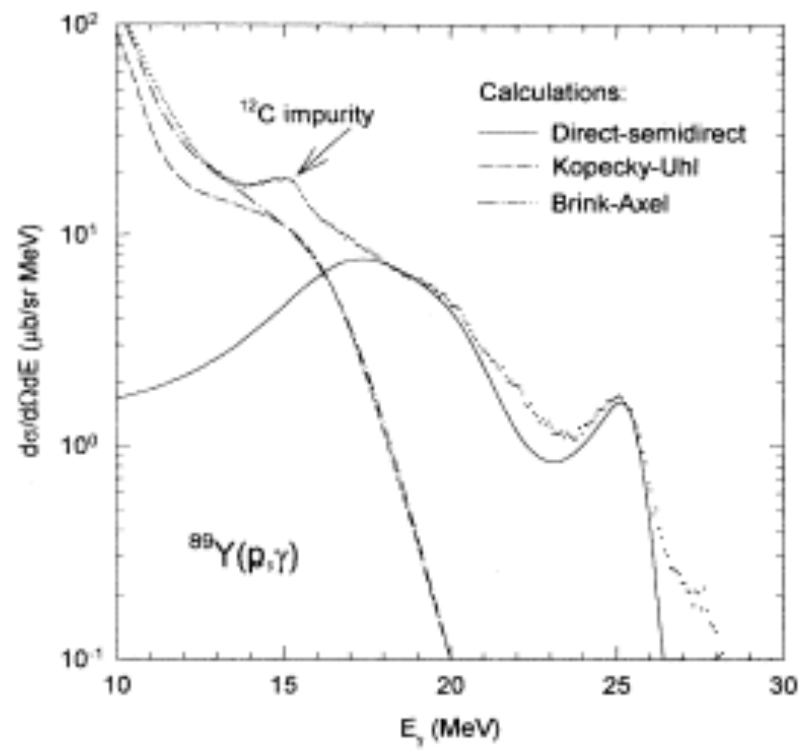
Direct-semidirect capture at low energies must be treated differently than at high energies

- **We are interested in capture *between* resonances (potential capture): what potential should be used to generate incident wave function?**
- **Importance of single-particle resonances**
- **Importance of doorway-state phenomena**

DSD well describes data at energies above region where compound model dominates

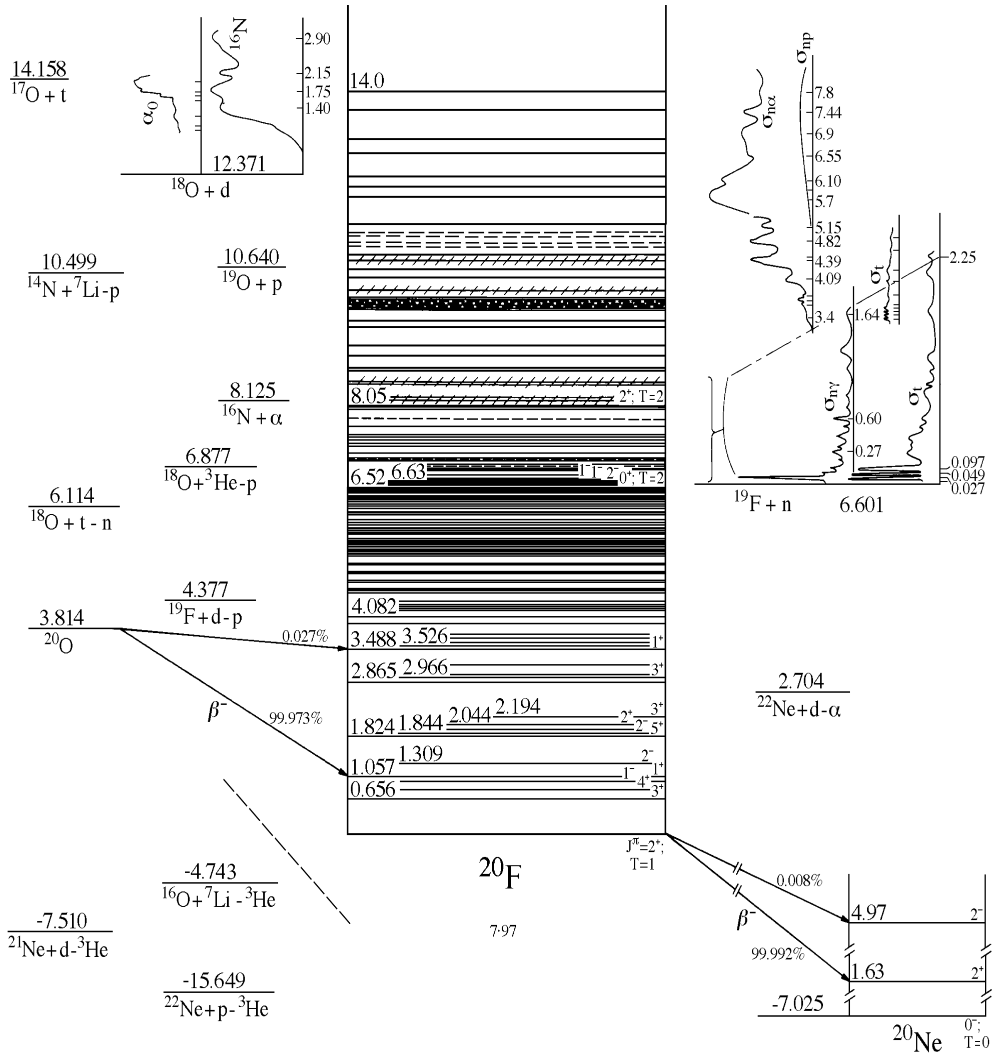


6 to 15 MeV neutrons on ^{208}Pb



19.6-MeV protons on ^{89}Y

Low-energy example: neutron capture on ^{19}F



Capture can occur to many final states in ^{20}F

We look at (d,p) and (^3He,d) experiments on ^{19}F, and calculate direct-semidirect capture only to those states for which significant spectroscopic factors were seen

We add the cross sections for all of the final states that were calculated to get the complete (n,γ) cross section

DSD: High energy vs. low energy projectiles

High energies (above region of separated resonances)

- **Initial state calculated with COMPLEX (optical model) potential**
- **This implies an ENERGY AVERAGE over resonant structure**
- **Compound capture usually more important than DSD for projectiles less than several MeV – use Hauser-Feshbach instead of DSD**
  - *There are some important exceptions to this near closed shells where level spacing is low; some of these are interesting for R-process*

Low energies (where capture between resonances is sought)

- **Energy averaging is not appropriate; therefore use a REAL potential**
  - *There are variants that use a complex potential to evaluate effects of tails of distant resonances (Lane-Mughabghab)*
- **Additional complications, not entirely contained in simple direct-semidirect model: single-particle resonances; doorway states**

Intermediate case – capture over a few resonances: TROUBLE

Stability issues in DSD neutron capture

- **DSD most reliable when radial integrals do not have large cancellations**
- **When there are significant cancellations, results become dependent on details of initial and final state potentials**
  - *How to choose these is not well defined in a simple model using phenomenological potentials*
    - Use same potential for initial and final state?
    - Tune initial potential to fit neutron scattering length?
- **E1 is dominant; fortunate because M1 is very unstable in simple potential model calculations**
  - *Electromagnetic operator is just σ; no radius-dependent parts*
  - *Near-orthogonality of initial and final states leads to cross sections that are small and very unstable*
  - *Needs more detailed nuclear-structure treatment*

In planning experiments, calculations can be used to head off some of the potential problems

Questions that can be addressed with existing codes:

- **Is neutron capture direct (DSD) or statistical (Hauser-Feshbach)?**
  - *Estimate level densities in the compound nucleus*
- **When direct capture is important, are the calculations stable?**
  - *Use DSD calculations to study this*

A special problem for deformed nuclei:

- **There is presently no coupled-channels code for DSD capture**
  - *Not a fundamental problem; it just hasn't been done*
- **Some treatments of deformation effects on spectroscopy of final states have been made, but incident channel is spherical; this is unsatisfactory**

When is semidirect term important (or not)?

Semidirect term is dominant at energies near the giant resonance

For low energy projectiles, the semidirect term always reduces the cross section (i.e., interference is destructive)

If capture takes place well outside of the nucleus, semidirect capture is negligible

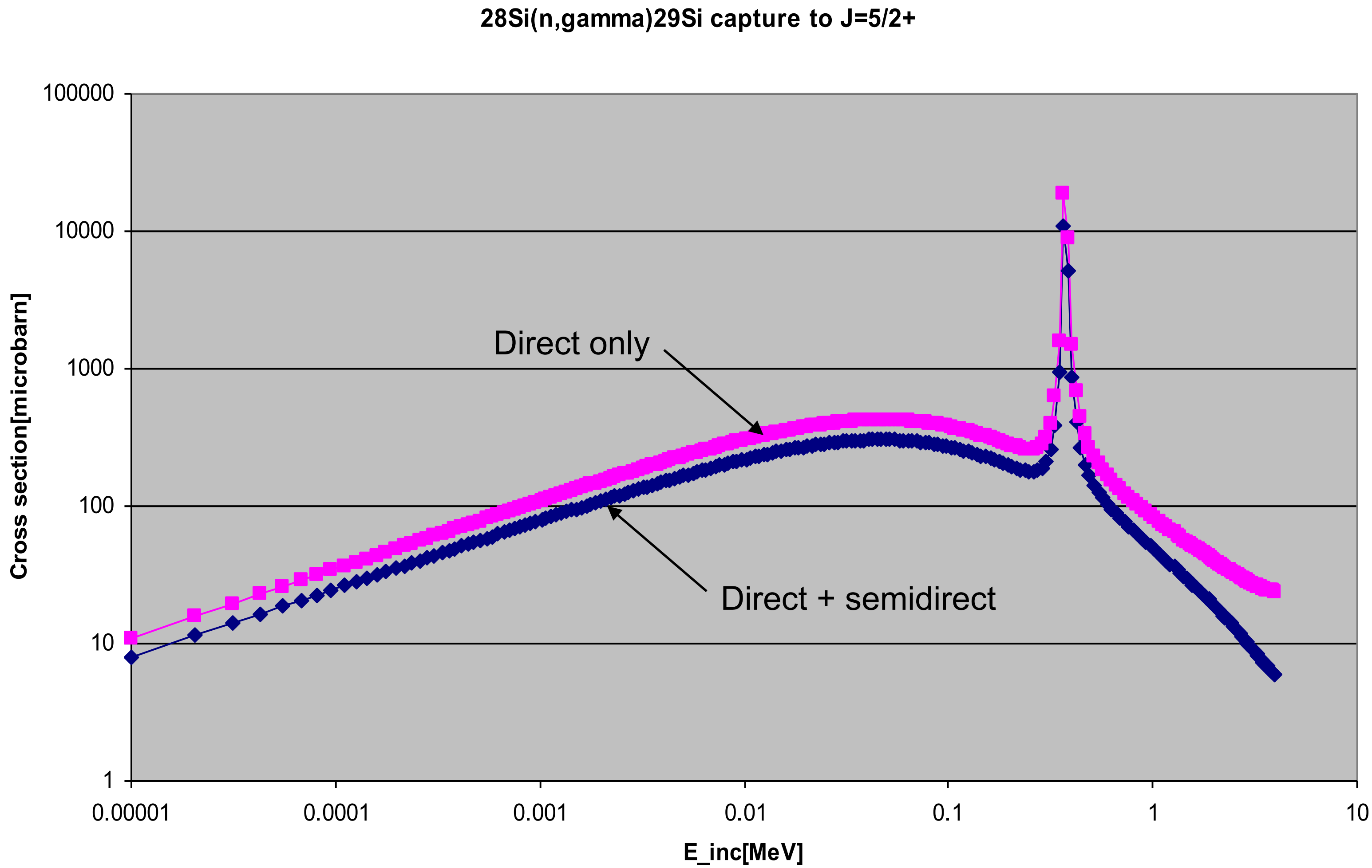
- **Always true for charged projectiles at sufficiently low energy**
- **Sometimes true for neutrons; depends on target, energy, and angular momentum channel**

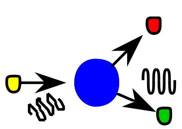
In low-E region, we find semidirect term can modify cross section by ~15-20%

This is significant, but there are more serious issues

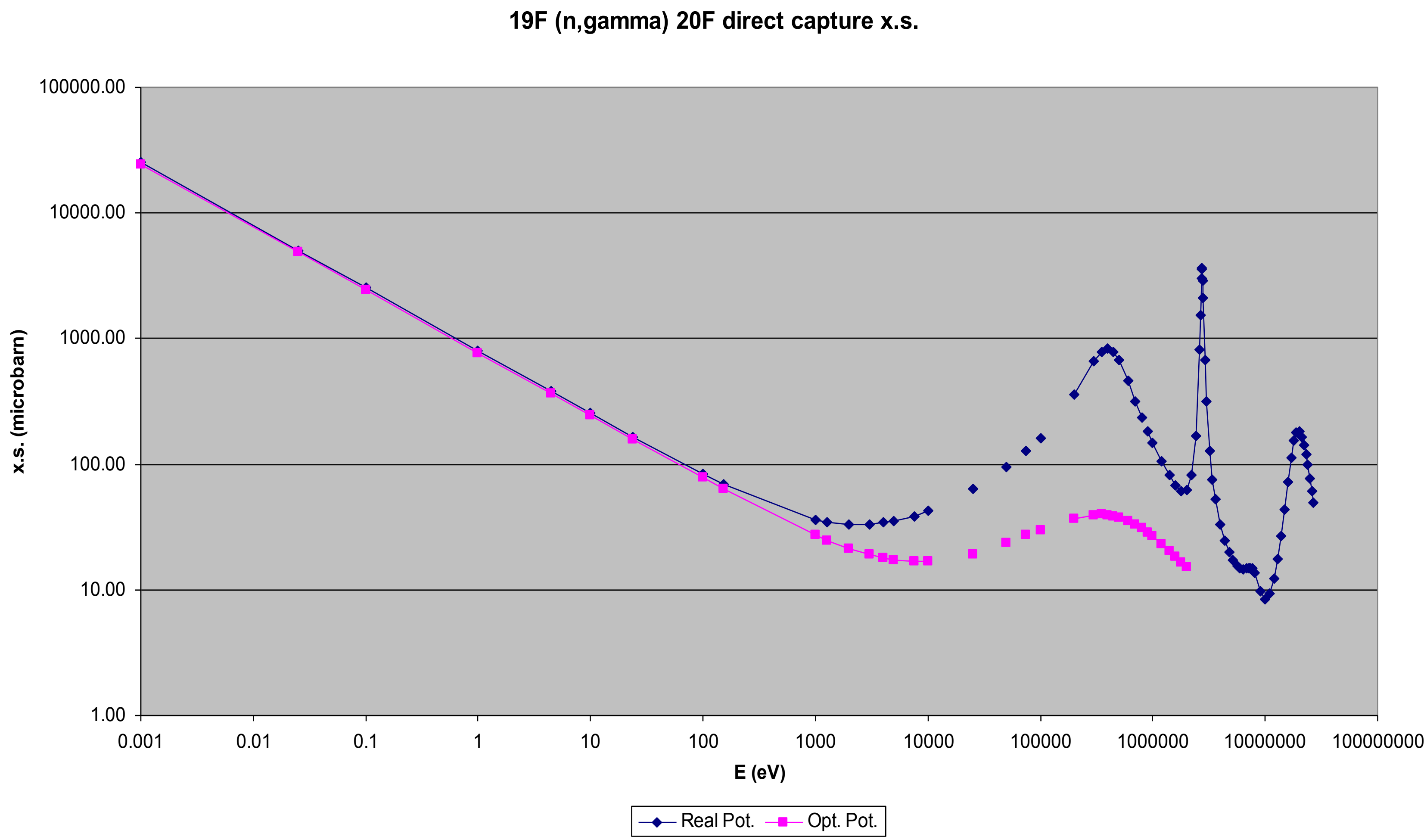
Example of direct-semidirect interference – semidirect lowers cross section by ~35%

Capture to 2nd excited state in ^{28}Si(n,γ)

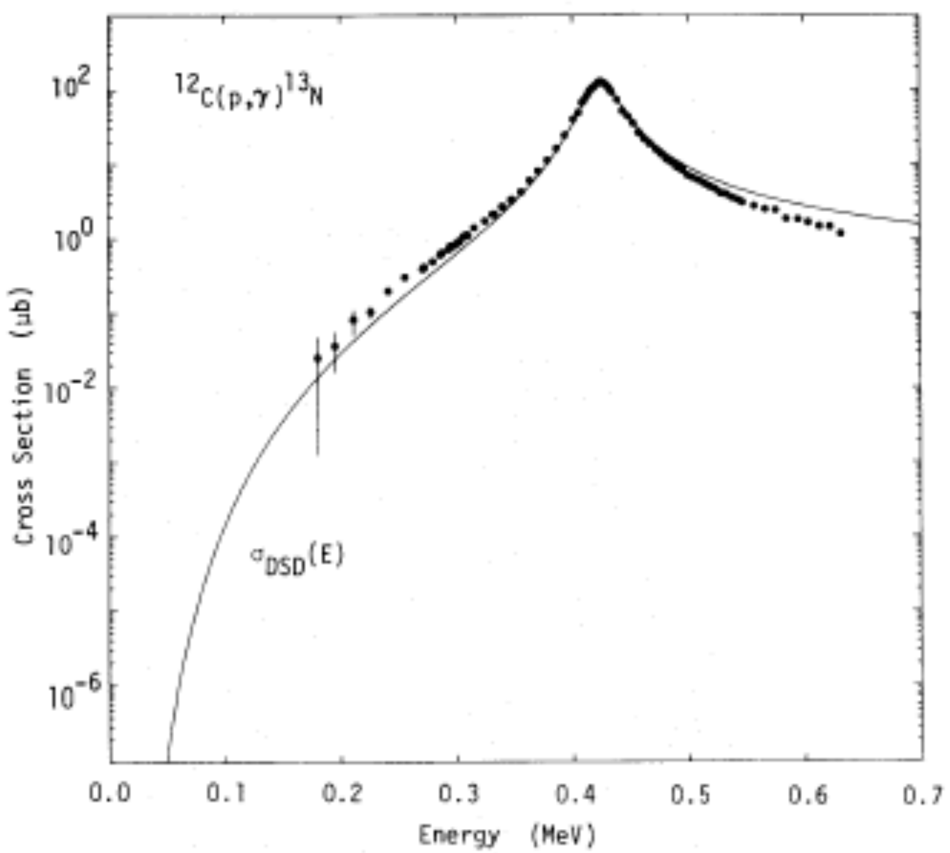




Direct capture exhibits single-particle resonances in incident channel when calculated with a real potential



In some cases (in light nuclei only!) these resonances appear as a single resonance in nature



Mathews and Dietrich used a DSD calculation to calculate resonant $^{13}N(p,\gamma)^{14}O$ for hot CNO cycle (ApJ 287, 969 (1984))

Single-particle resonances cause problems in low-E capture calculations in medium and heavy nuclei

These resonances do not show up in nature, because they are highly fragmented (and spread in energy) among the background states

This leads to correlations between the neutron and gamma widths of resonances (this is the valence capture problem)

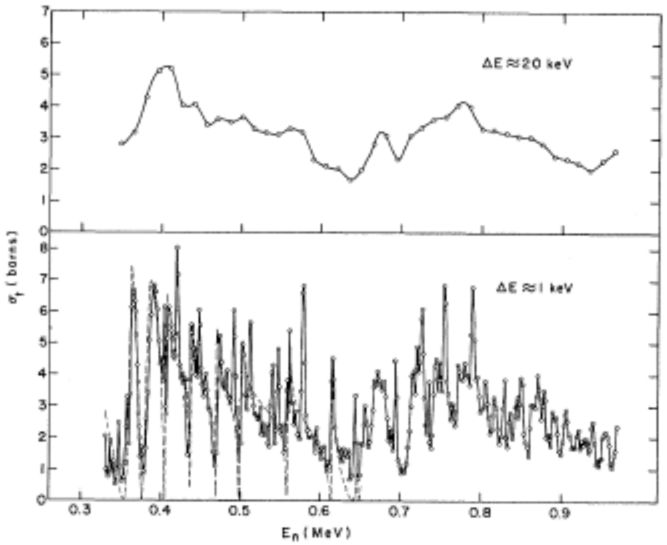
When DSD calculations with a real potential show strong resonances or near-threshold s-wave states, we have a problem

- *Prominent example: the 3s near-threshold state in the A~60 region*

Some methods for dealing with this, not yet fully implemented:

- **Use projection operator techniques to remove single-particle resonances/ states from the continuum; apply a damping width and reinsert them**
- **Doorway state model (AKK can comment later)**

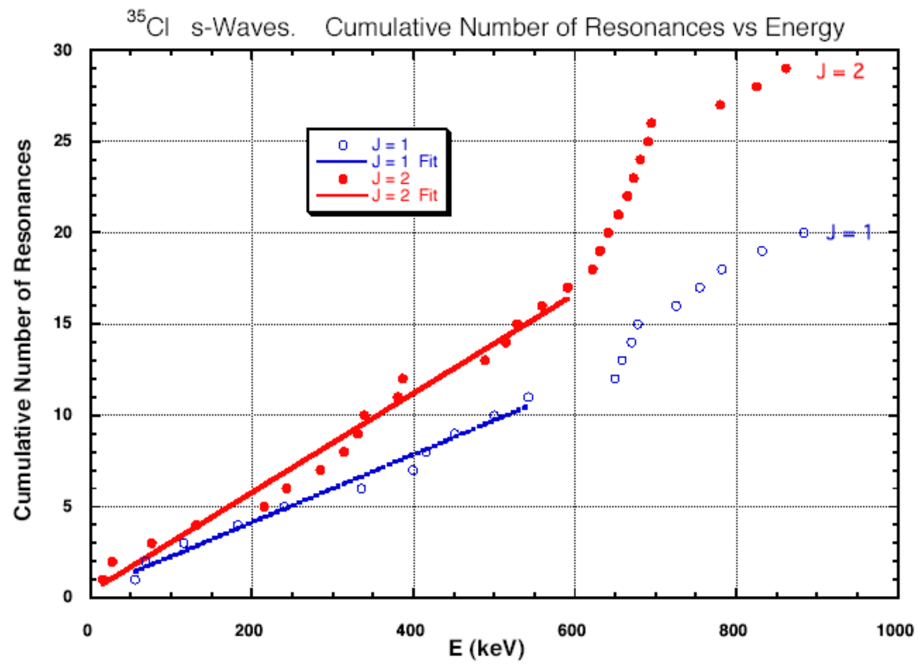
Extra complication: intermediate structure not contained in simple potential models



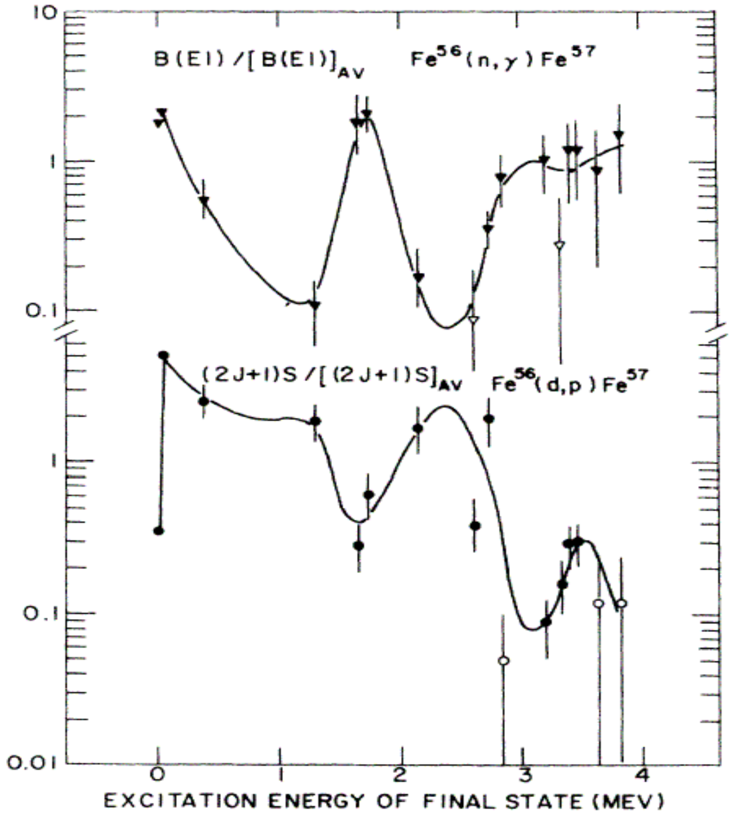
Neutron total cross sections on ^{56}Fe (Monahan/Elwyn)

Interpreted as doorway states

Recent analysis of s-wave resonances for n+35Cl (ORELA; R. O. Sayer)



Doorway states cause mischief to simple capture theory



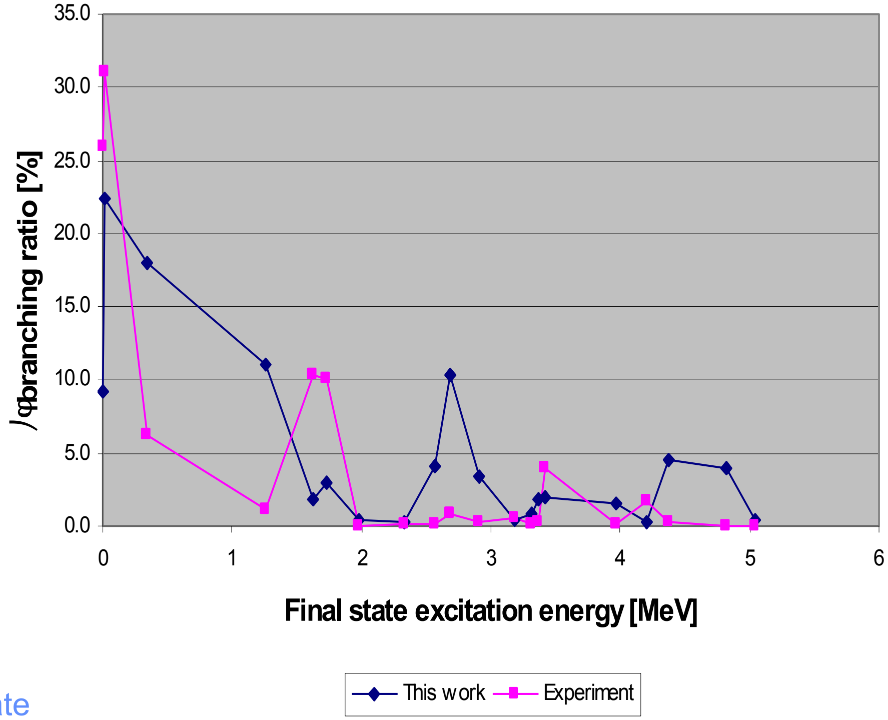
Correlation between (n,γ) to specific final states and (d,p) spectroscopic factors is disastrous

Example: ^{56}Fe(n,γ) at thermal energy

Recall 56Fe+n showed evidence for intermediate structure

Direct capture csec should be proportional to d,p spectroscopic factor

Direct-capture calculation similarly shows poor correlation



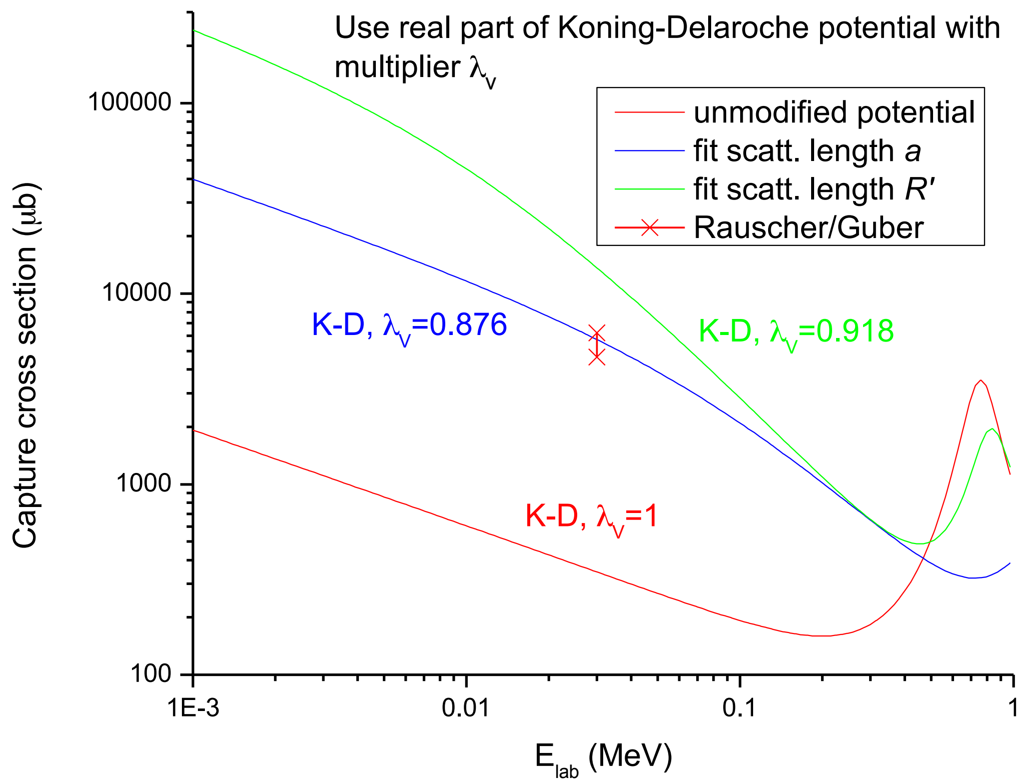
Current case of interest is $^{62}Ni(n,\gamma)$ – simple direct capture calculation is problematic

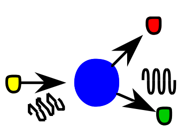
Our calculation with unmodified Koning-Delaroche scattering potential is lower than Rauscher's by factor of ~10

Scaling strength of potential to fit *a* or *R'* scattering lengths yields results similar to Rauscher's, but scaling seems unphysical

Lane-Mughabghab procedure (not shown) leads to even smaller results

You can get any answer you want!





Neutron scattering lengths *a* and *R'*, and relation to scattering potentials

a **is the coherent scattering length, gotten at thermal energies**

For real potential,

$$a = (-1/k) \tan \delta$$

R' **is the total cross section *between* resonances,**

$$\sigma_{tot} = 4\pi R'^2$$

For complex potential,

$$R' = (-1/k)\, \mathrm{Re}(\tan \delta)$$

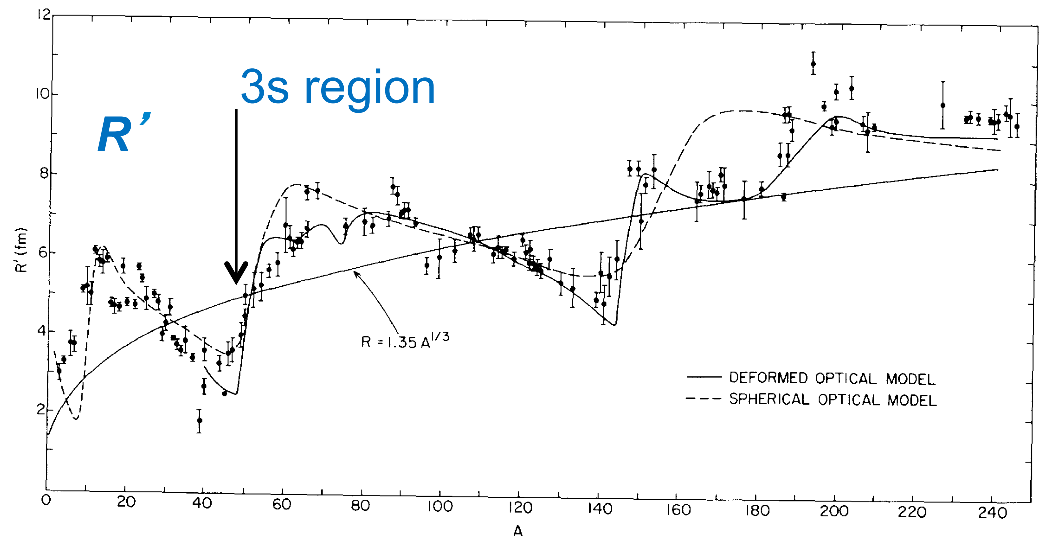


Figure 2. Variation of the scattering radius R' with mass number A. The solid curve is based on deformed optical model calculation[47] with the following parameters: $V_o = 43.5$ MeV, $V_{so} = 8.0$ MeV, $W_D = 5.4$ MeV, and $r_o = 1.35$ fm. The dashed curve is a spherical optical model calculation of the present work with the same optical model parameters. The deformation of the nucleus in the mass region 160-190 has a large effect on R'.

Good review of theory issues in low-energy capture problem:
J. Cugnon and C. Mahaux, Ann. Phys. **94**, 128 (1975)

Some rough experience-based conclusions

- In most cases, DSD works well and reproduces measured cross sections at the ~20% level
- When DSD doesn't work well, we usually understand why at high energies, not always at low energies
- Treatment of single-particle resonances and near-threshold s states in low-energy capture needs to be cleaned up
- Doorway states can cause problems for capture, and we need better understanding of when this happens
- Available techniques are useful to help plan experiments, at least in spherical nuclei
- A coupled-channels treatment of capture is needed for reliable calculations in deformed nuclei