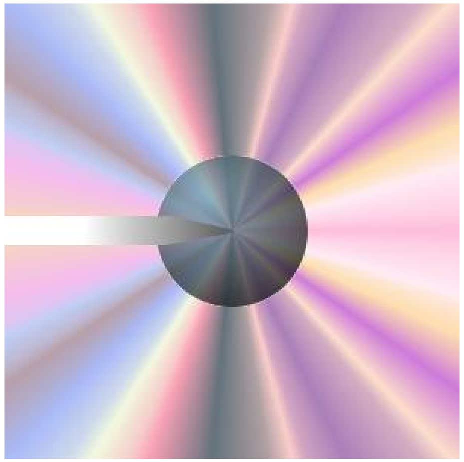
New Era of Nuclear Physics in the Cosmos, the r-process Nucleo-Synthesis
RIKEN, Japan, Sep. 25,26, 2008

Statistical-Model and Direct-Semidirect-Model Calculations of Neutron Radiative Capture Process



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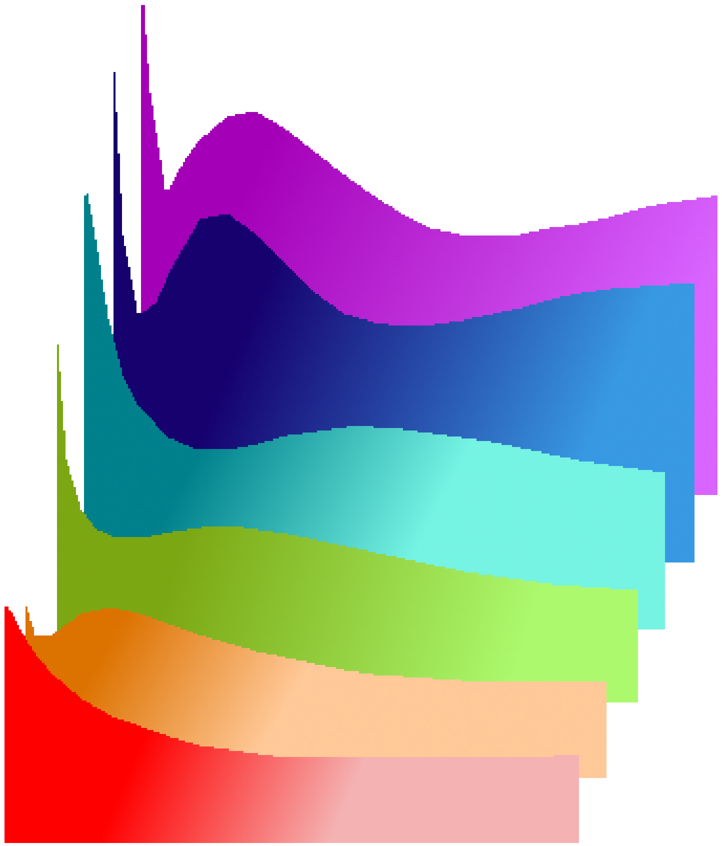
Nuclear Reactions in the Fast Energy Range

- The Hauser-Feshbach statistical theory has been widely used for nuclear reaction data applications,
  - nuclear reaction rates for astrophysics (nucleo-synthesis)
  - nuclear data libraries for energy applications (mainly for neutron)

- however, questions still persist regarding:
  - applicability in the domain of off-stability
  - global inputs

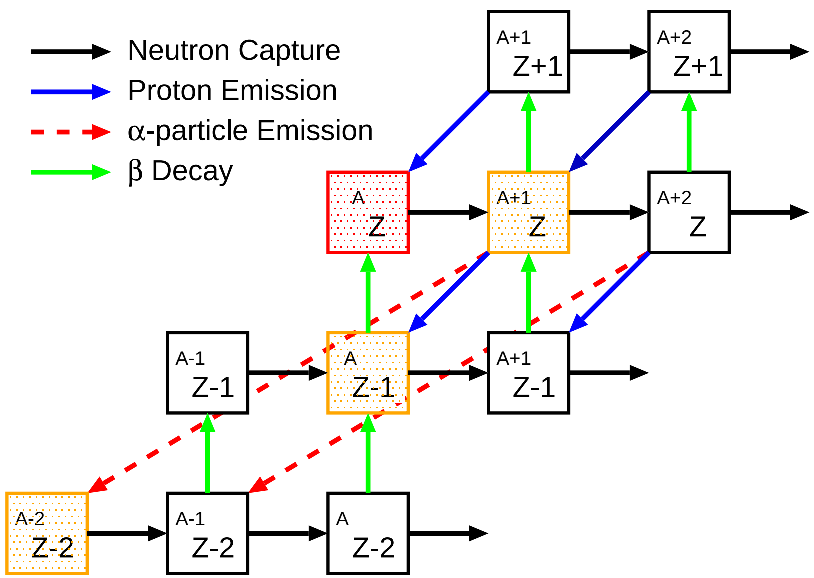
    level densities, optical potentials,

    γ-ray strength function
  - nuclear deformation effect
  - width fluctuation correction
    $\langle \frac{\Gamma_a \Gamma_b}{\Gamma} \rangle \neq \frac{\langle \Gamma_a \rangle \langle \Gamma_b \rangle}{\langle \Gamma \rangle}$
  - inclusive / exclusive observables
    - partial γ-rays, coincidence, etc.
    - Monte Carlo approach to the HF needed
  - interaction on the excited state (isomer)



Nuclear Reaction Rate in Astrophysics

Nuclear Reaction Chain



- Nuclear reactions in astrophysical environments
  — s and r-processes
  - targets are often neutron-rich and unstable
  - neutron capture process is mostly important
  - β-delayed neutron emission and fission
- Model prediction is crucial for
  - reaction cross section
    — Hauser-Feshbach theory
  - nuclear structure, including mass
    — macro/microscopic model, Hartree-Fock

Understanding of the neutron capture process is important to study nucleo-synthesis, which includes models for γ-ray strength function, GDR (Giant Dipole Resonance), nuclear level densities, and spectroscopic factors.

Nucleon Radiative Capture

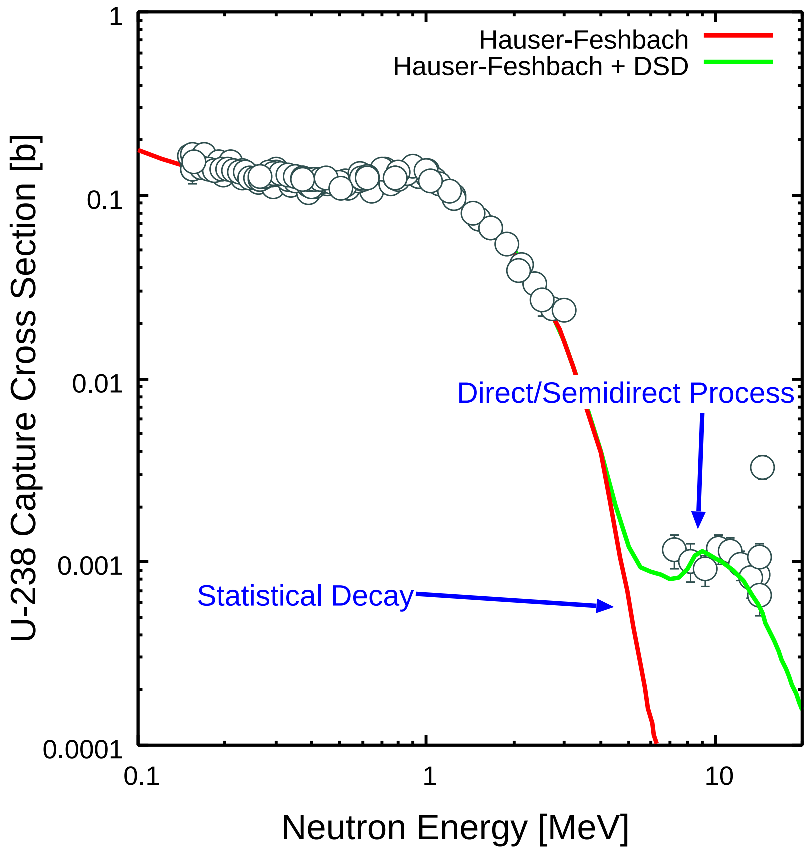
CN and DSD Processes

Compound Reaction

- An incident neutron and a target form a compound nucleus, and it decays.
- Hauser-Feshbach statistical theory, with width fluctuation.
- Cross section decreases rapidly when neutron inelastic channels open.

Direct/Semidirect Capture

- Direct transition to one of the unoccupied single-particle state.
- Giant Dipole Resonance (GDR)



DSD becomes important when (1) incident particle energy is high, or (2) compound capture cross section is small (few resonance, neutron-rich, doubly-closed shell nuclei.)

Photo Emission / Absorption

Inverse process of γ-ray emission

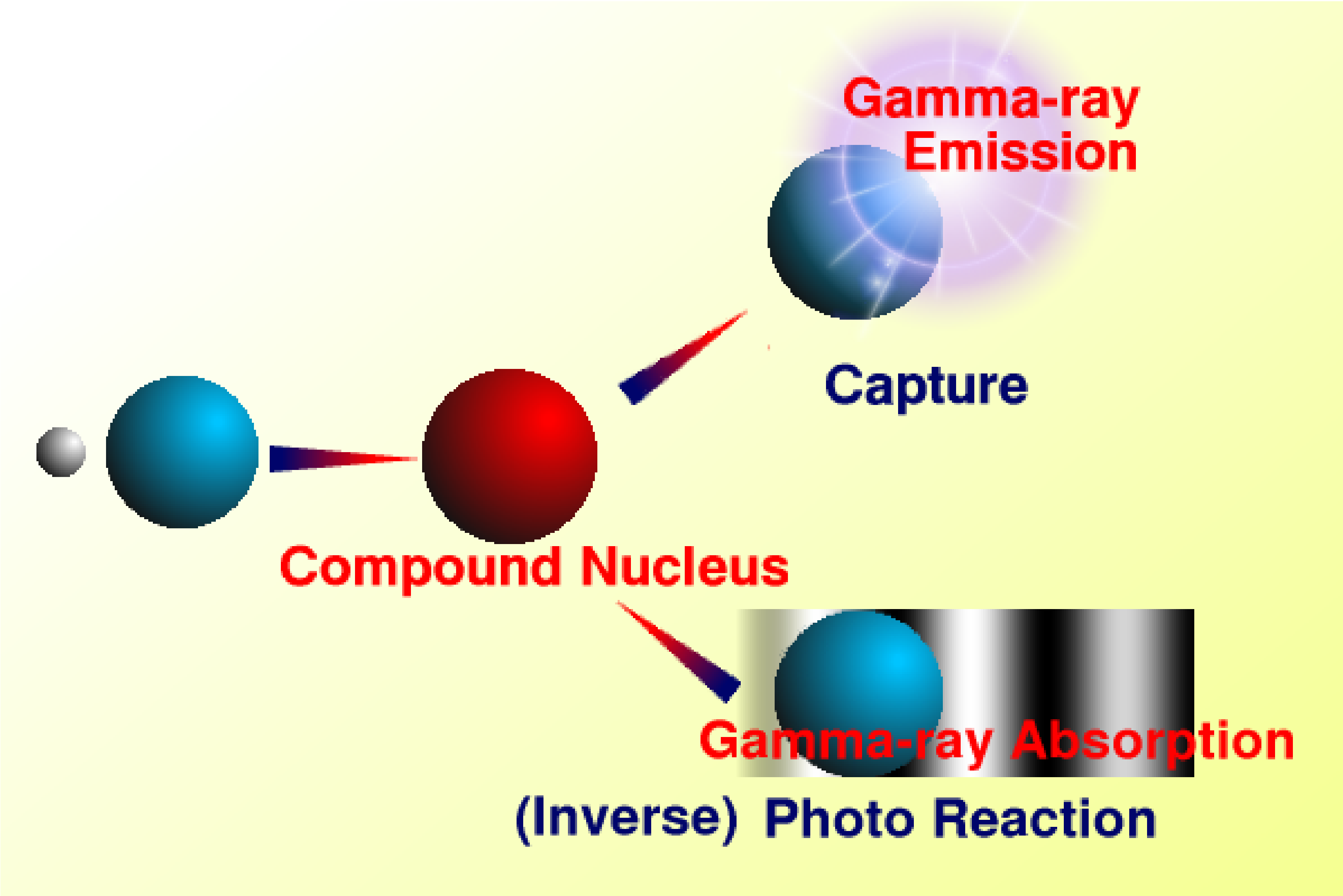
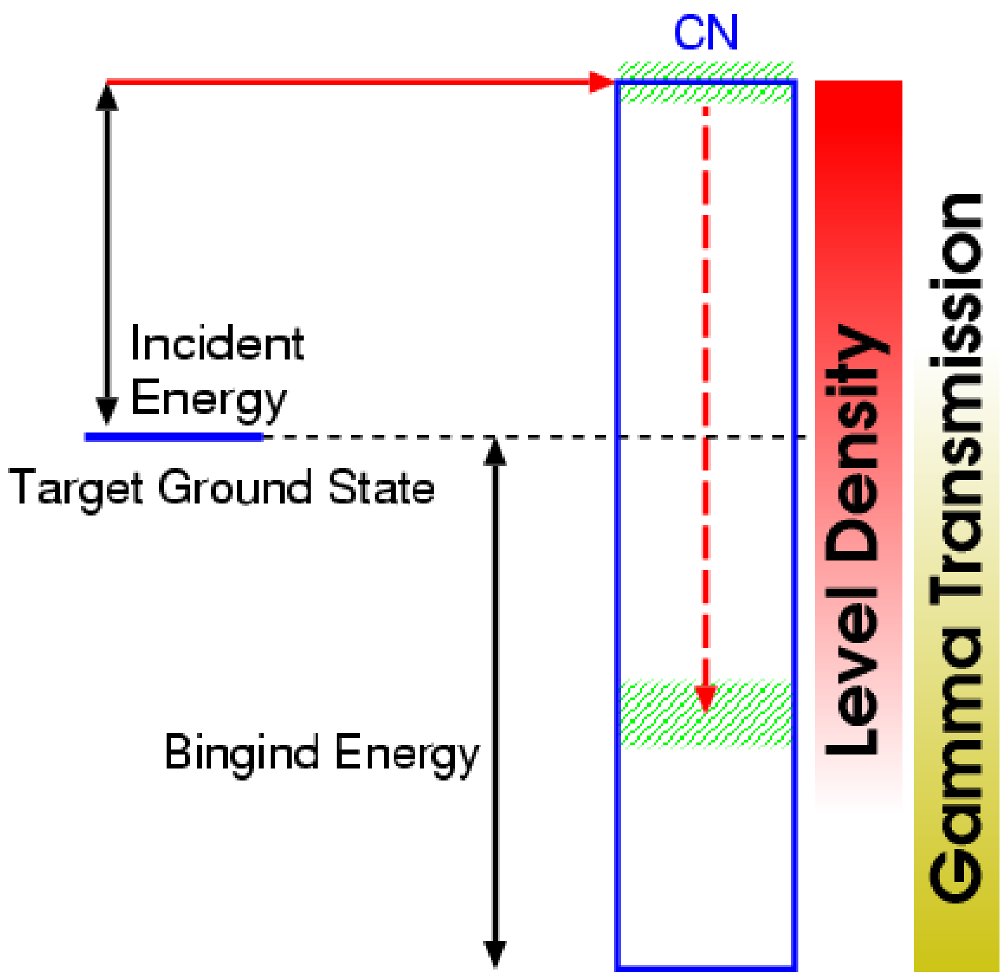


Photo Reaction

Neutron capture calculations for s and p-process



- Total reaction cross section is determined by the optical model.
- The decay width — the sum of transmission probabilities for all decay processes.
  - The γ-ray radiation width is calculated from the γ-ray absorption probability (the inverse process) and the final state density.
  - Brink's hypothesis is used.
  - Important to understand γ-ray transmission $T_{\mathrm{E1}}(E)$, and the level density $\rho(E)$, off-stability.

γ-Ray Strength Function and Transmission

- Standard Lorentzian

$$f_{\mathrm{E1}}(E_\gamma) = C\sigma_0\Gamma_0 \frac{E_\gamma \Gamma_0}{(E_\gamma^2 - E_0^2)^2 + E_\gamma^2\Gamma_0^2}$$

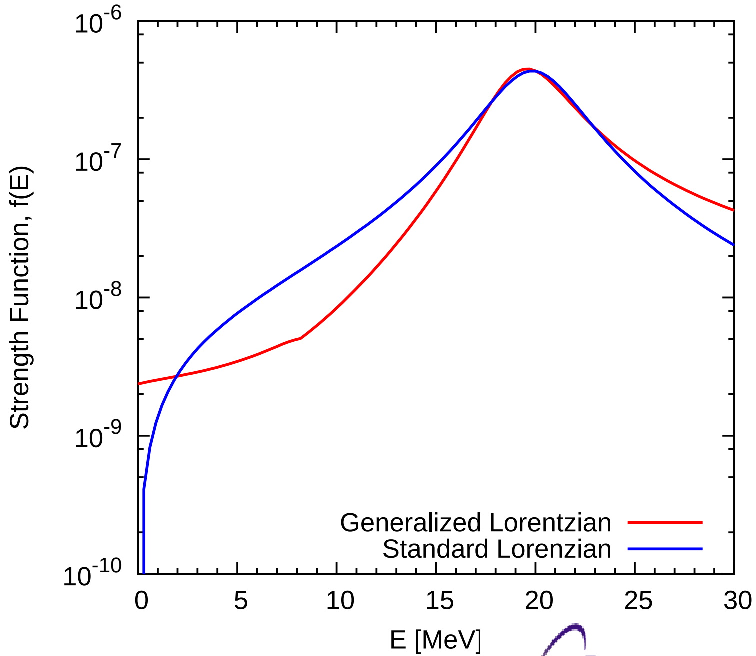
- Generalized Lorentzian, finite value at low energies, energy dependent width

$$f_{\mathrm{E1}}(E_\gamma) = C\sigma_0\Gamma_0 \left\{ \frac{E_\gamma \Gamma(E_\gamma, T)}{(E_\gamma^2 - E_0^2)^2 + E_\gamma^2\Gamma^2(E_\gamma, T)} + 0.7\frac{\Gamma(E_\gamma = 0, T)}{E_0^3} \right\}$$

where $C = 8.68 \times 10^{-8}$ mb^{-1}MeV^{-2}, or can be obtained by normalization to an experimental value if available.

The γ-ray transmission coefficient is given by

$$T_{\mathrm{E1}}(E_\gamma) = 2\pi E_\gamma^3 f_{\mathrm{E1}}(E_\gamma)$$



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Normalization of γ-Ray Strength Function

An absolute capture cross section is still hard to predict, however, it can be estimated from average resonance properties.

$$\frac{\langle \Gamma_\gamma \rangle}{D_0} \propto \int_0^{B_n} T_{\mathrm{E1}}(E_\gamma)\rho(E_x)dE_x$$

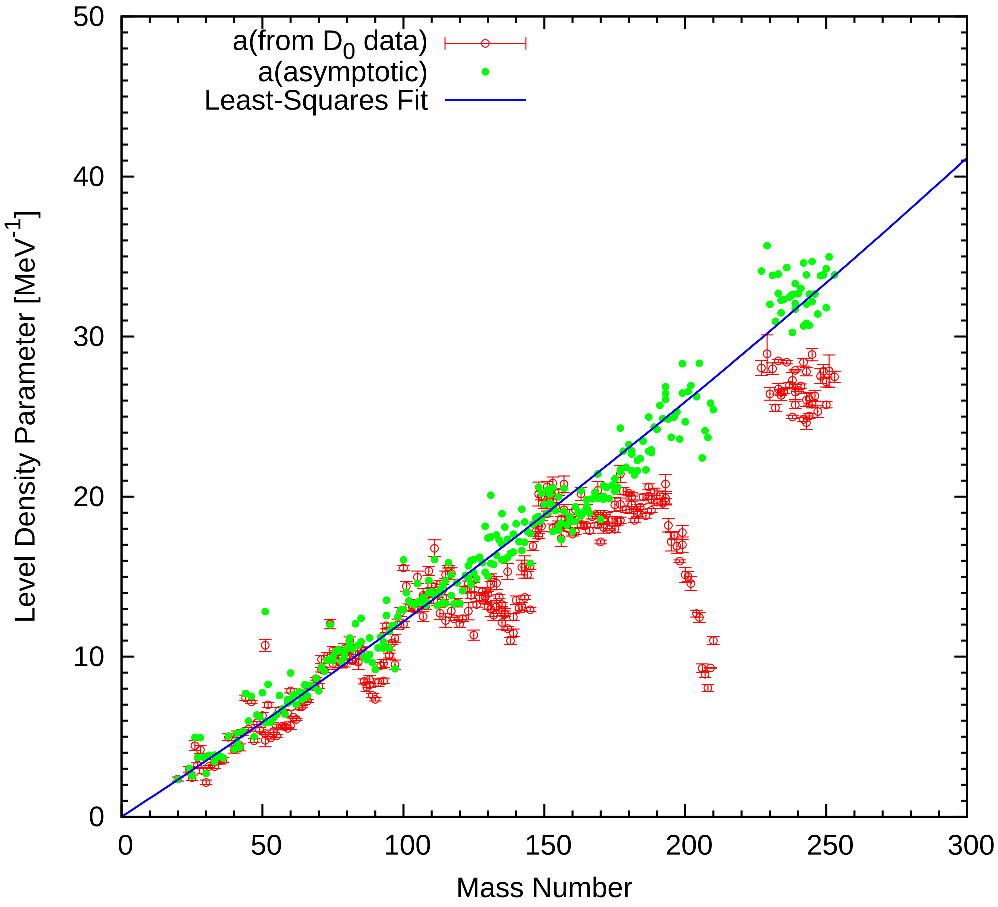
where

- D_0 is the average s-wave resonance spacing near the neutron binding energy:
- $\langle \Gamma_\gamma \rangle$ is the average γ decay width

Compound Nucleus	D_0 keV	$\langle \Gamma_\gamma \rangle$ meV
^{57}Fe	25.4	920
^{91}Zr	6.0	130
^{239}U	0.0208	23.6

or we just re-normalize the calculated capture cross section to experimental data avaiable by adjusting $\langle \Gamma_\gamma \rangle / D_0$.

Level Density Parameter Systematics



Washing-out of Shell Effects

- Shell correction (δW) and pairing energies (Δ) taken from KTUY05 mass formula

$$a = a^* \left\{ 1 + \frac{\delta W}{U} \left(1 - e^{-\gamma U} \right) \right\}$$

$$a^* = 0.114A + 7.65 \times 10^{-5} A^2$$

- At low excitation energies, the constant temperature model is used with

$$T = 48.1 A^{-0.88} \sqrt{1 - 0.1 \delta W}$$

  - obtained from discrete level data of more than 1000 nuclei.

TK, S. Chiba, H. Koura, J. Nucl. Sci. Technol., **43**, 1 (2006)

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Hauser-Feshbach on Deformed Nuclei

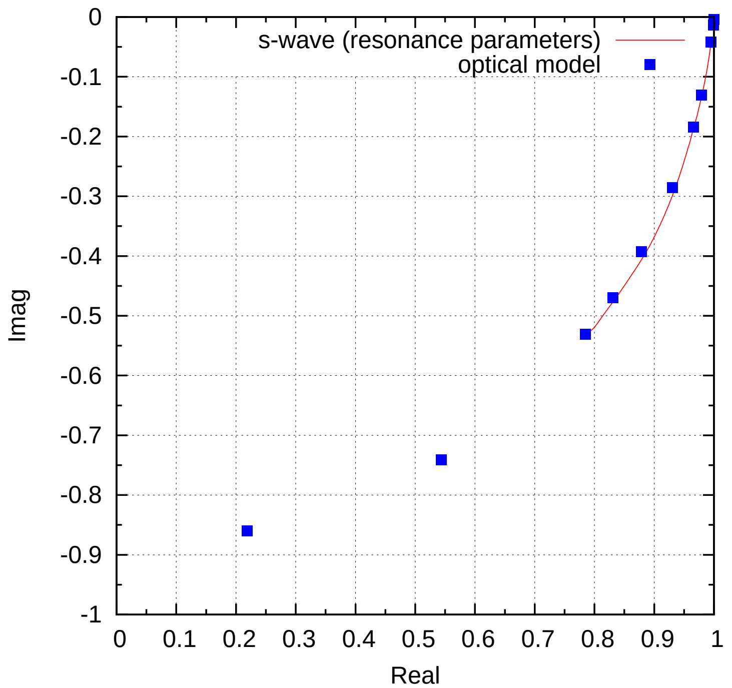
Incorporate Coupled-Channels (CC) method into the HF formula

- Scattering matrix is no longer diagonal.
- Inverse channel problem
  - What is the appropriate transmission coefficient for the excited states ?
  - Replaced by the one for the ground state (historical)
  - Solve the CC equation for the excited state (detailed balance)
- Width fluctuation correction when off-diagonal elements exist
  - Moldauer
  - Engelbrecht-Weidenmüller transformation
  - Kawai-Kerman-McVoy (TK, L.Bonneau, A.Kerman, Nice conf. 2007)
    - Our preliminary results showed that KKM gives almost identical results as Moldauer.
  - Nishioka-Weidenmüller-Yoshida, GOE for coupled-channels

Coupled-Channels Potential Parameters

Modification to the Global CC Potential of Soukhovitskiĩ, et al.

- E. Sh. Soukhovitskiĩ, et al., J. Phys. G: Nucl. Part. Phys. **30**, 905 (2004).
- Adjust the imaginary potential to match the energy averaged S-matrix elements from resonance parameters (TK, F.H. Fröhner, NSE, **127**, 130 (1997)).
- When the S-matrix elements (resonance and optical model) are obtained, total and reaction cross sections are automatically reproduced.



W_s = 2.59 MeV for $E_n < 1.13$ MeV

R' = 9.606 fm (9.6$\pm$ 0.1 in Atlas, Mughabghab)

S_0 = 1.13 $\times 10^{-4}$ ((1.29$\pm$ 0.13) $\times 10^{-4}$, ibid)

S_1 = 2.07 $\times 10^{-4}$ ((2.17$\pm$ 0.19) $\times 10^{-4}$, ibid)

Original SoukhovitskiĩPotential (in the paper)

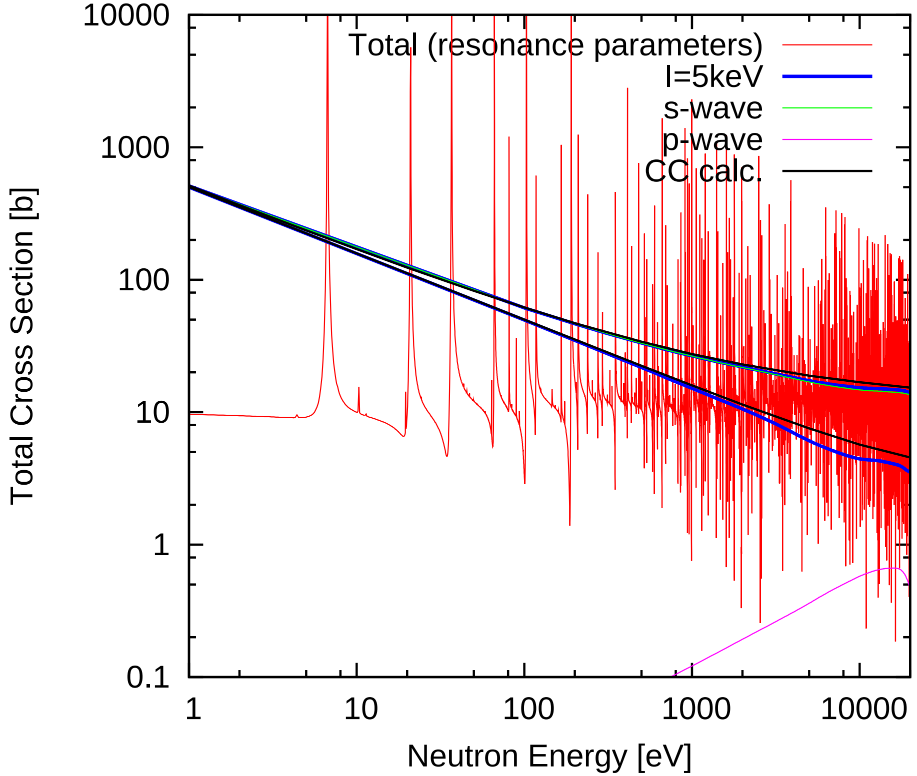
R' = 9.57 fm

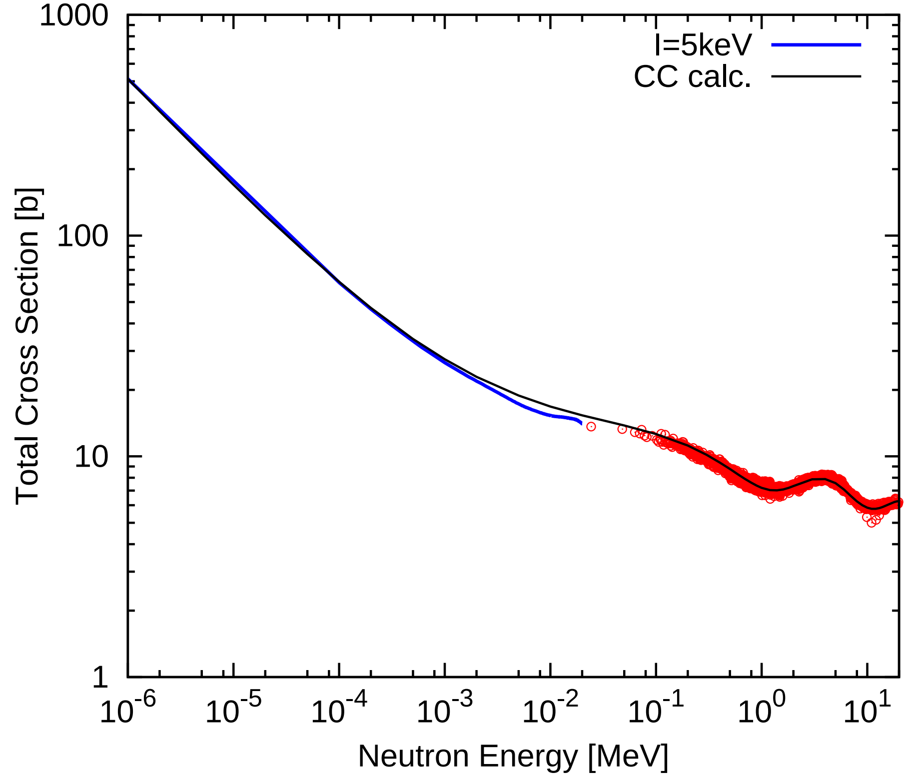
S_0 = 0.95 $\times 10^{-4}$

S_1 = 1.80 $\times 10^{-4}$

U-238 Total Cross Section

With Modified Soukhovitskiĩ Potential

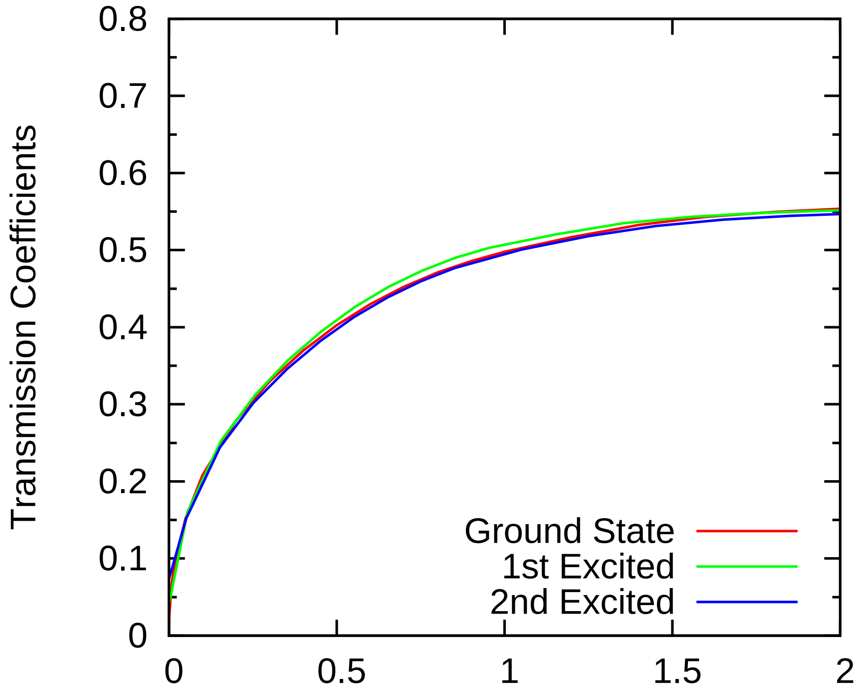




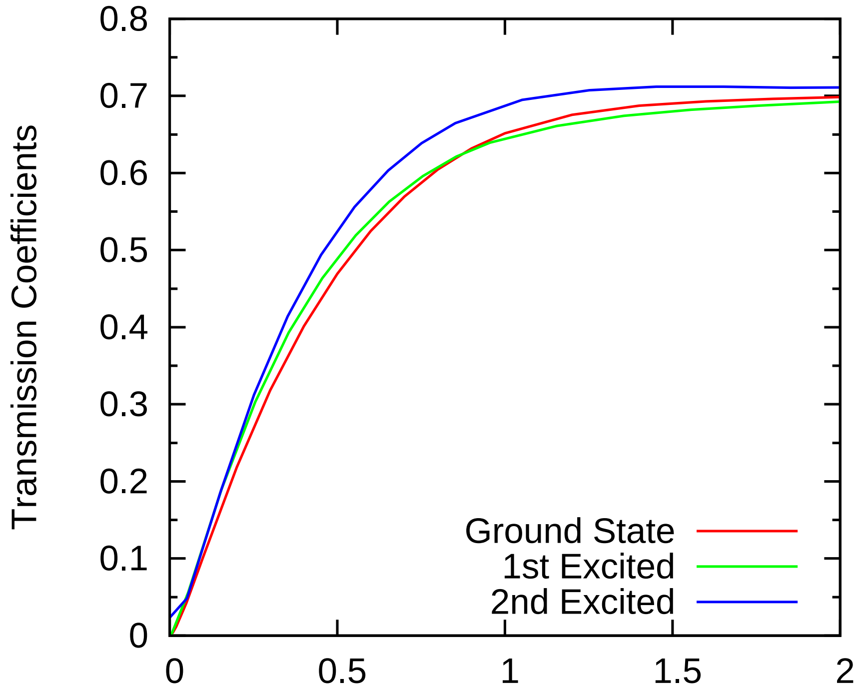
- With the modified Soukhovitskiĩ Potential, the energy averaged total cross section in the resonance range is well-reproduced.
- Above 1.13 MeV, the parameters are the same as the original ones.

Transmission for Inverse Reactions

Transmission Coefficients for the Inverse Channels



s-wave



p-wave

In a usual case, the ground-state transmission is used for all the calculation. However, this might underestimate the (n,n') cross-section to the 2^+ and 4^+ states, because the true transmission to the 2^+ and 4^+ are larger.

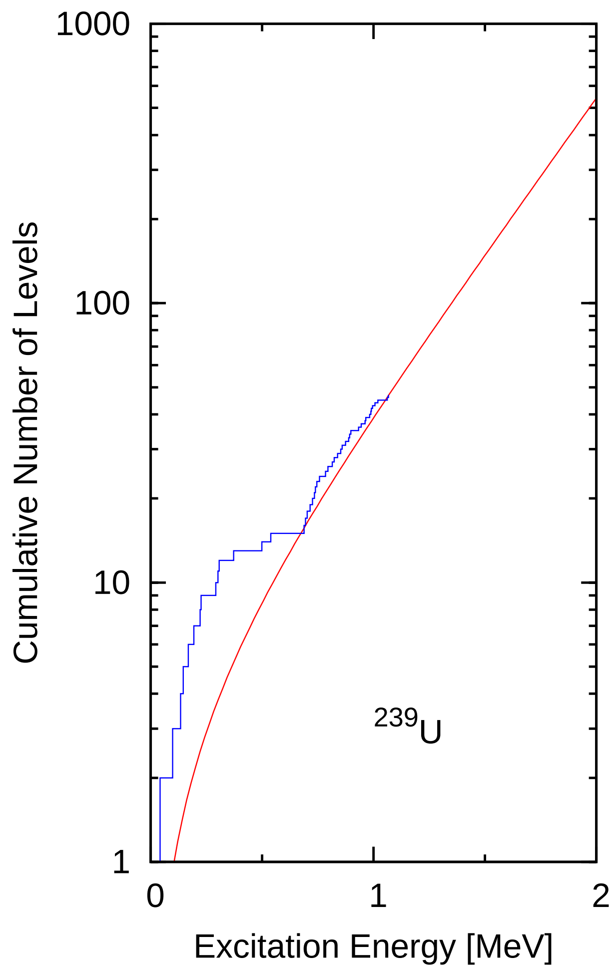
Capture Cross Section Calculations

Model Parameters

- Optical Potential
  - Modified Soukhovitskiĩ
  - CC calculations are made for the G.S. band
  - 0^+-2^+-4^+-6^+-8^+ coupling
  - Spherical potential for the uncoupled states
- Level density
  - Ignatyuk level density formula
  - a^*=34.69 MeV^{-1} for ^{239}U (reproduce D_0=20.3 eV)
  - Shell correction and pairing energies from KTUY mass formula
  - Spin-cut off parameter,

$$\sigma^2 = 3.47 \times 10^{-3} \sqrt{U/a} A^{5/3}$$

- Average γ-ray width
  - $\langle \Gamma_\gamma \rangle$=23.36 meV from resonance analysis
  - or, to be adjusted if needed



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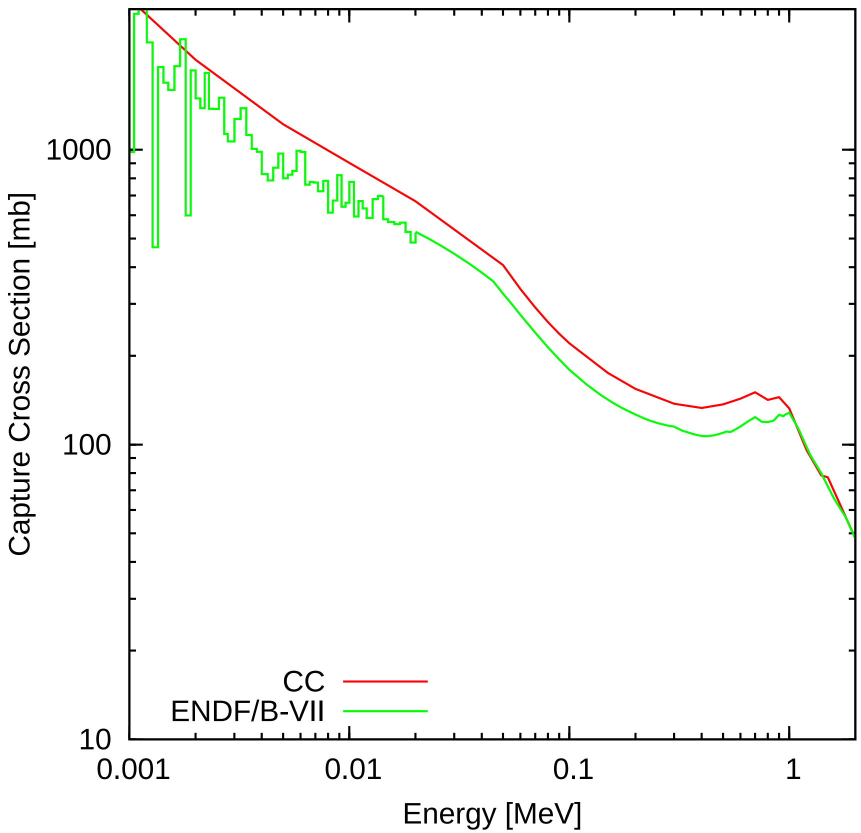
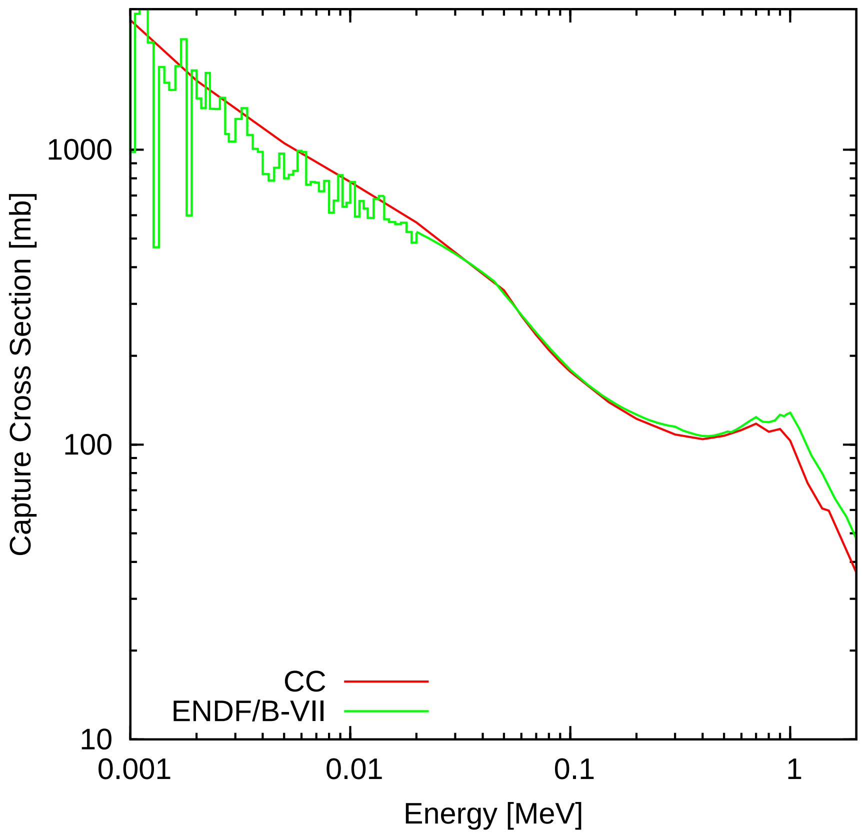
U-238 Results

Comparison with ENDF/B-VII (a part of standards evaluation)



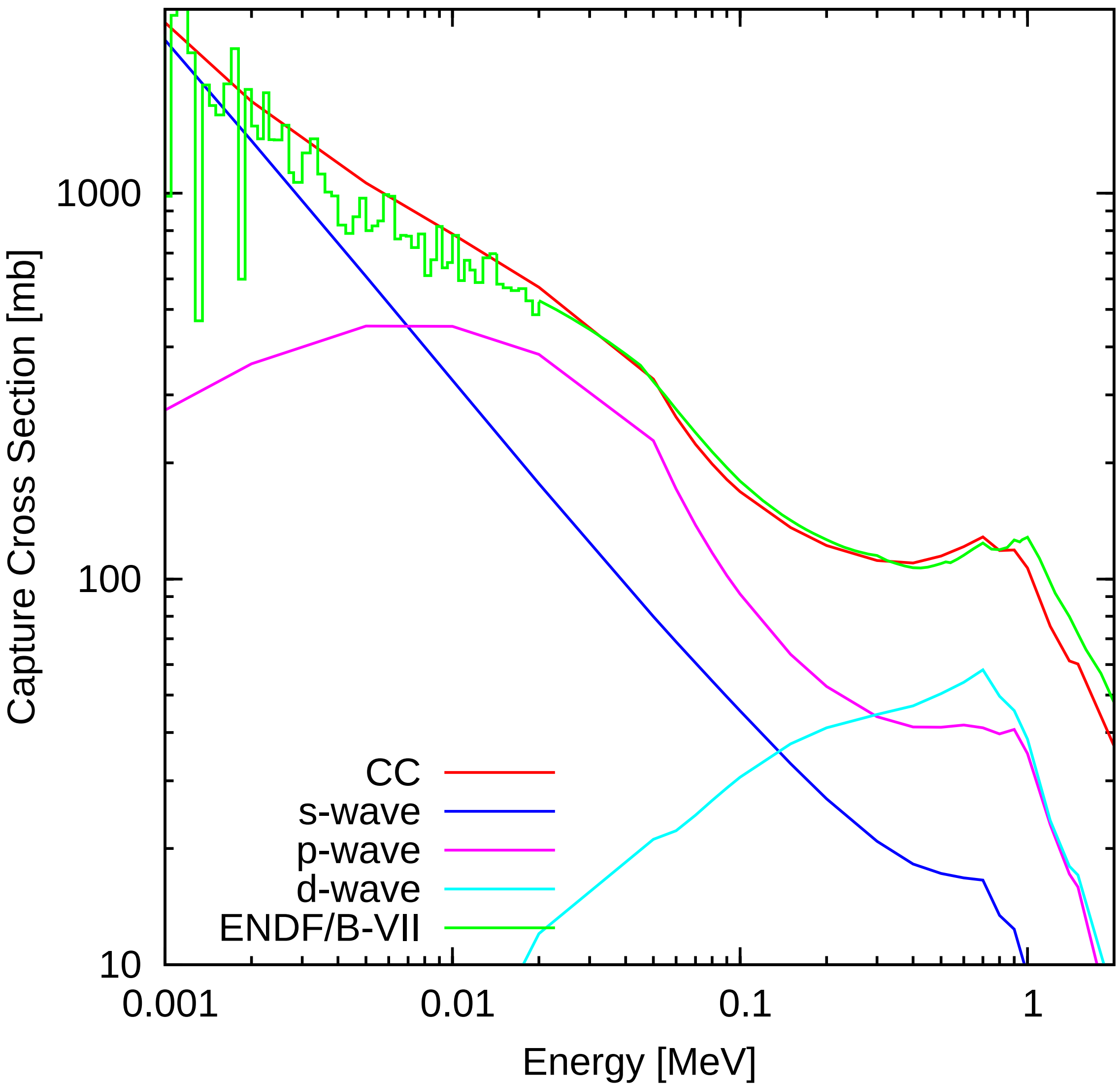
$\langle \Gamma_\gamma \rangle$=23.36 meV



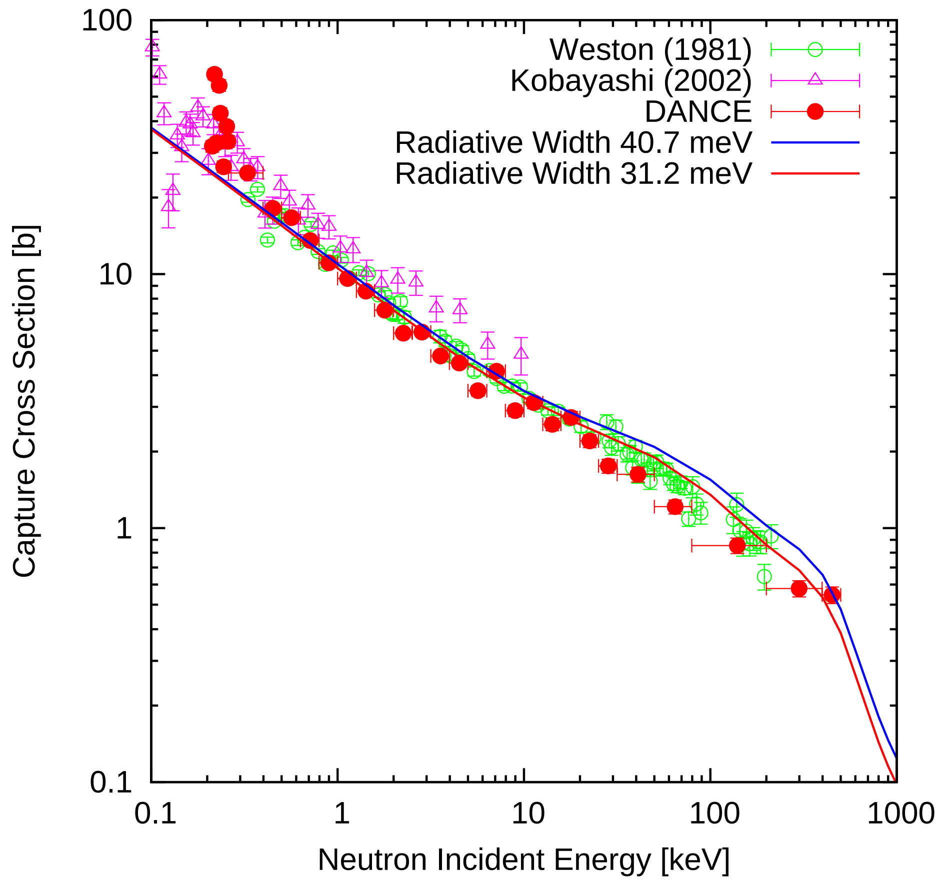
$\langle \Gamma_\gamma \rangle$=17.83 meV

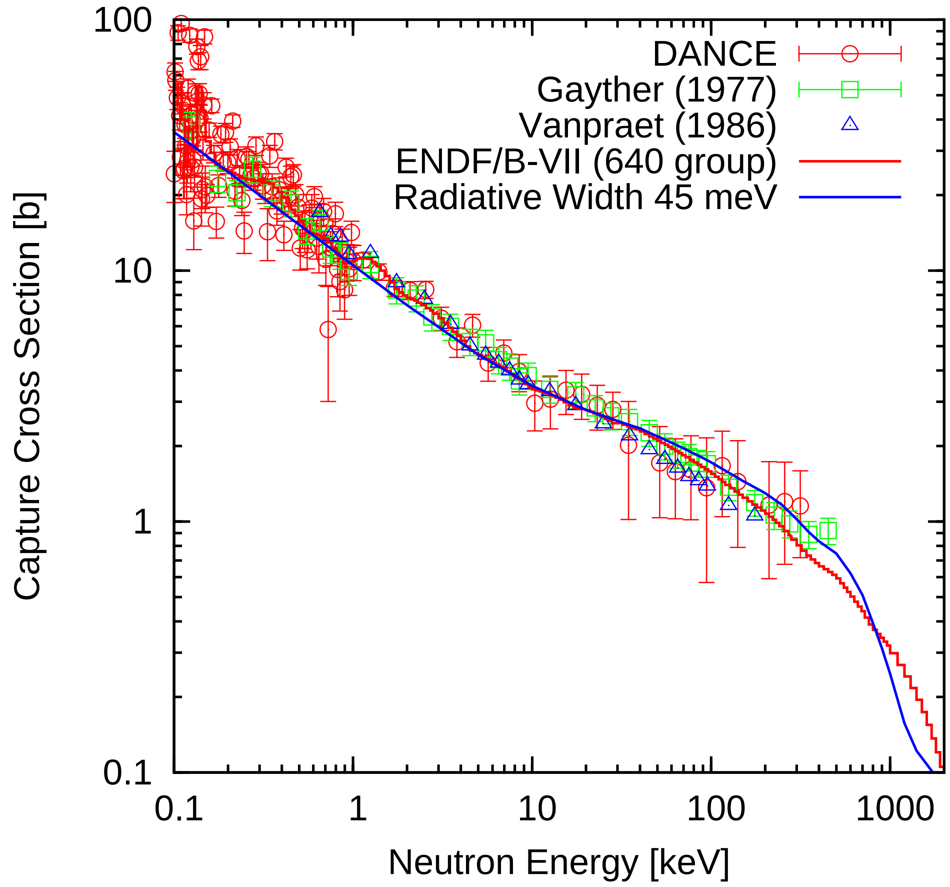
Partial Wave Contribution

Decomposition into Each Partial-Wave Contribution



Comparisons with DANCE Data

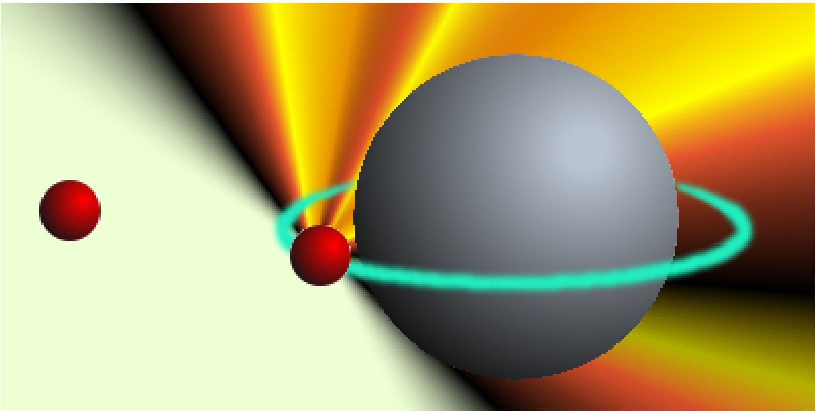




When the calculated capture cross section for ^{241}Am is averaged over the Jezebel spectrum, it gives a 5% higher value than that for ENDF/B-VII.

Direct/Semidirect Nucleon Capture Model

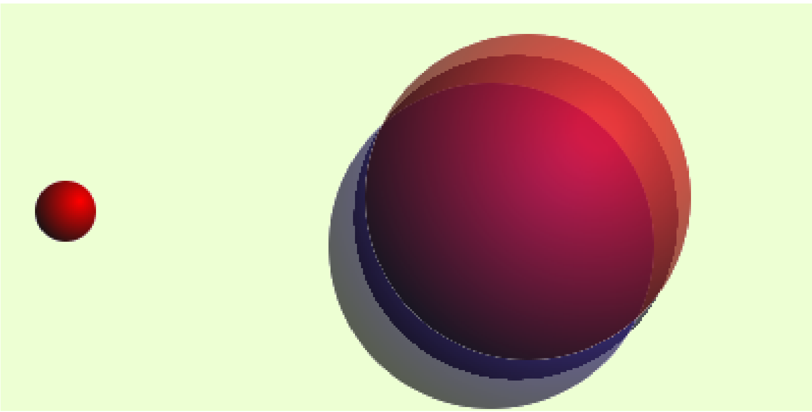
Direct Capture



- Electric dipole radiation transition from optical potential to single-particle state
- Amplitude

$$T_d = C_d \langle R_{nlj} | r | R_{LJ} \rangle$$

Semidirect (Collective) Capture



- Excite GDR, and decay into single-particle state
- Vibration-particle coupling, $V_1 h(r)$
- Amplitude

$$T_s = C_s \langle R_{nlj} | V_1 h(r) | R_{LJ} \rangle$$

$$\times \frac{|M_{GDR}|^2}{E_\gamma - E_{GDR} + i\Gamma_{GDR}/2}$$

DSD with Hartree-Fock BCS Theory

L. Bonneau, T.K., T. Watanabe, S. Chiba, Phys. Rev. C **75**, 054618 (2007)

Model Improvements

spectroscopic factor S_{ljK}

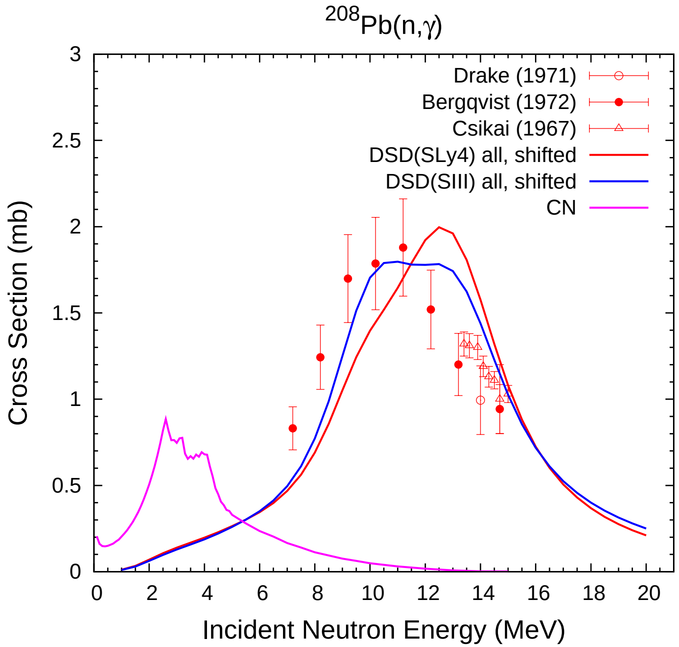
- previous studies
  - experimental data (often not available for astrophysical calculations)
- DSD/HF-BCS
  - single-particle occupation probabilities
  - no experimental data needed

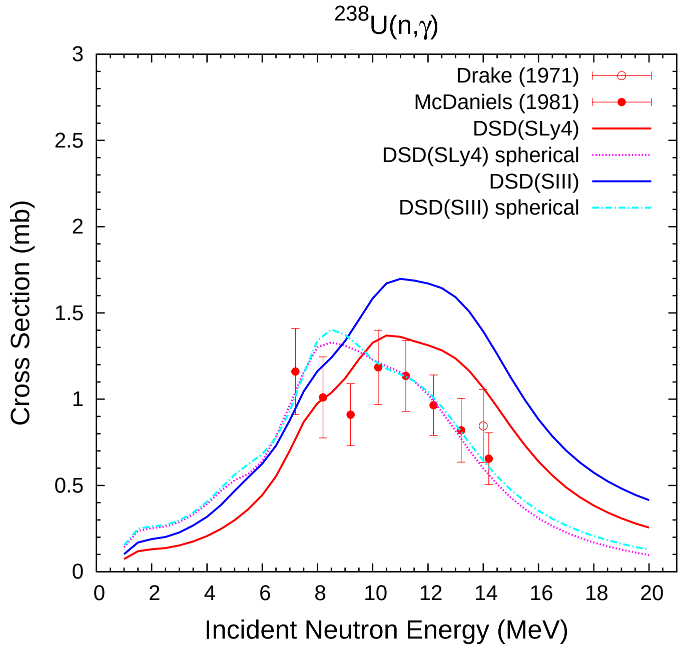
single-particle wave-function, $R_{ljK}(r)$

- previous studies
  - spherical Woods-Saxon, Nilsson model, coupled-channels model to bound states
- DSD/HF-BCS
  - HF-BCS calculation and decomposition into spherical HO basis
  - consistent treatment for all nuclei from spherical to deformed nuclei

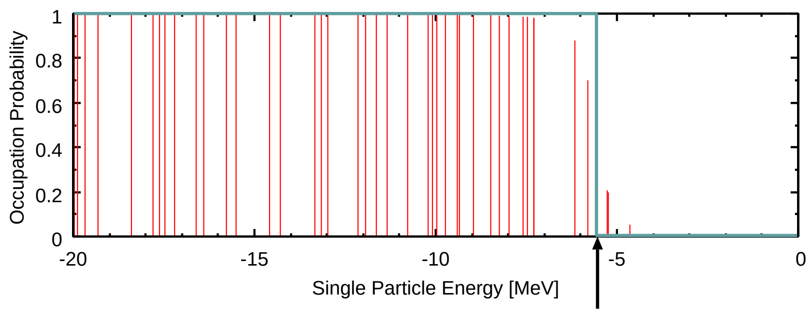
Calculated Results

DSD Cross Sections for Spherical and Deformed Cases

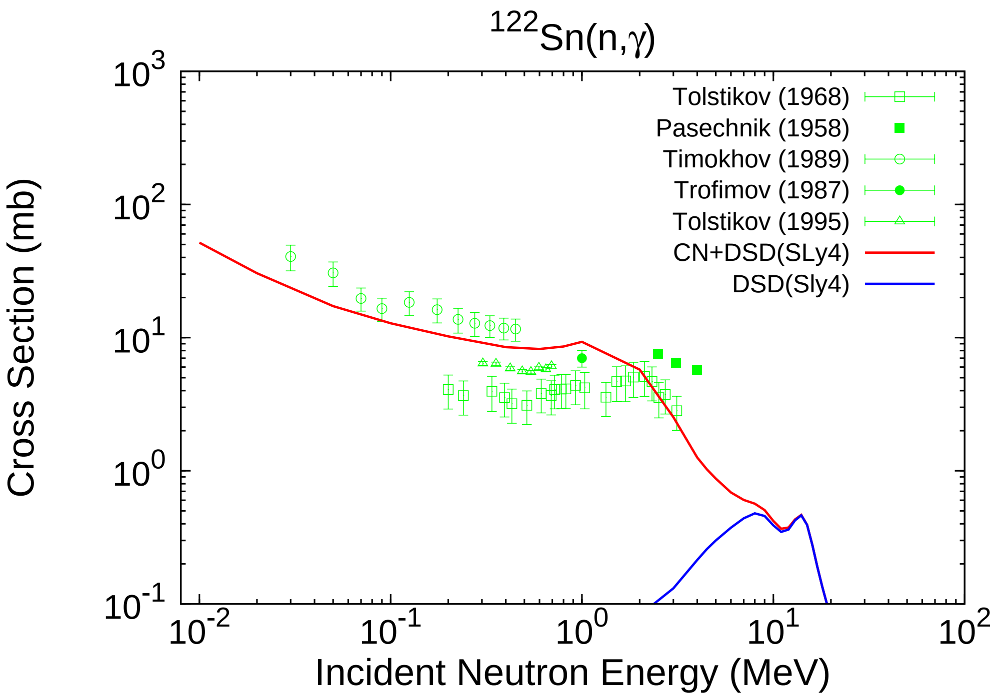


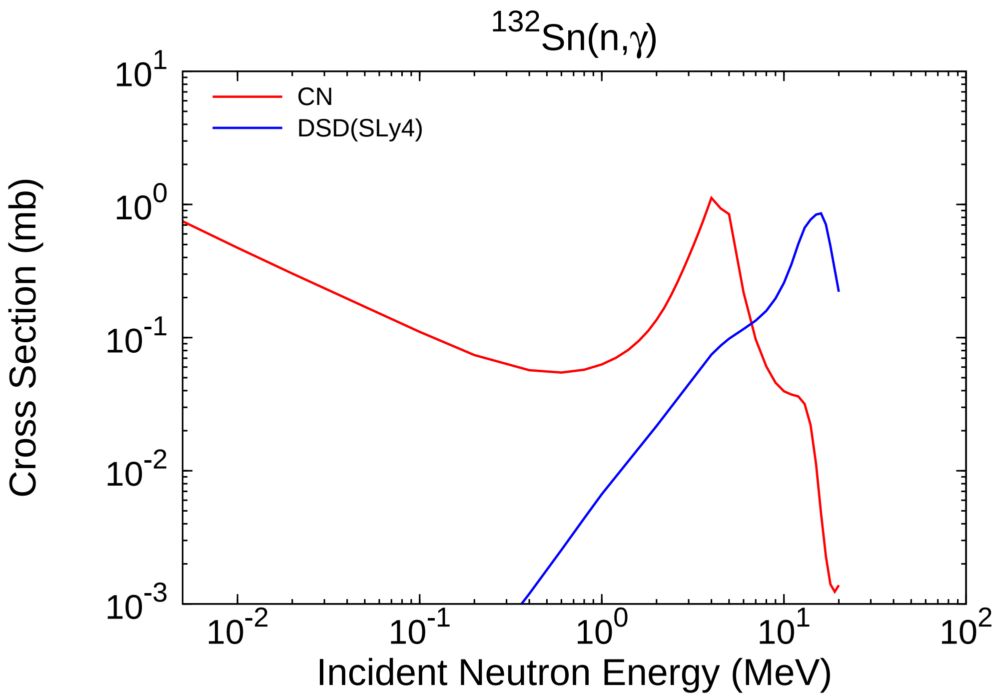


Occupation Probabilities for U-238



Neutron Capture Off-Stability — Sn-122,132





- Since global Hartree-Fock-BCS calculations for all nuclides are feasible, this technique will be a powerful tool to estimate the neutron capture rates in the r-process.
- HF calculation problems for the odd nuclei still exist.
- Proton capture calculations underway.

Applications of the Hauser-Feshbach Model to Different Areas

Combining with nuclear structure calculations

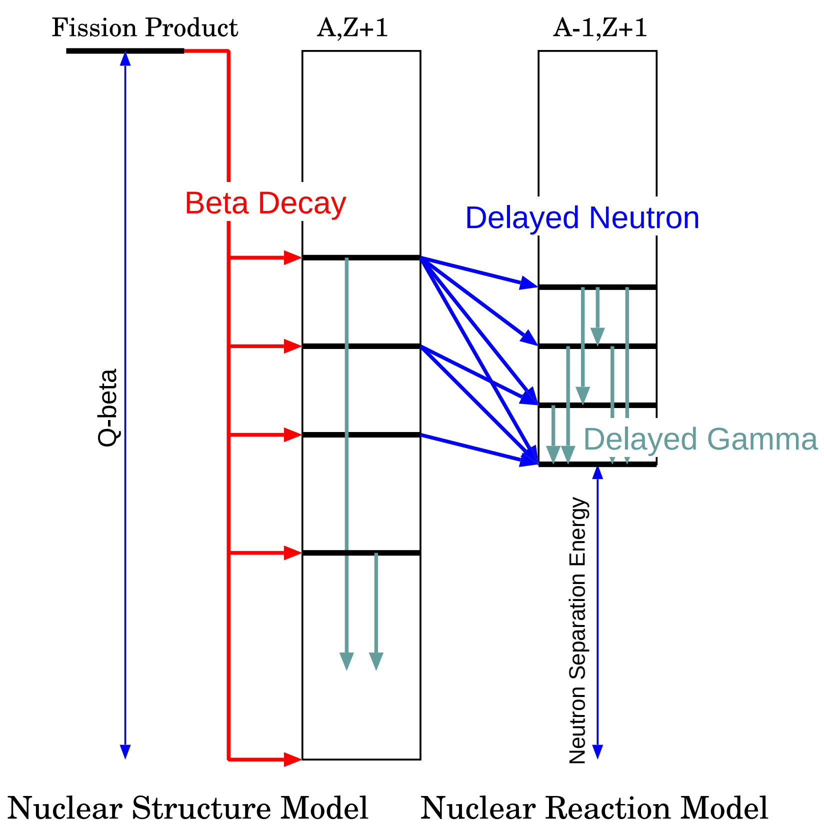
- β-decay and electron capture produce highly excited states of nuclei, and the excitation energies can be larger than the neutron separation energy.
- Nuclear structure models, such as QRPA, predict final states of β-decay and EC.
- Compound decay from a daughter nucleus at given E_x, J^π.

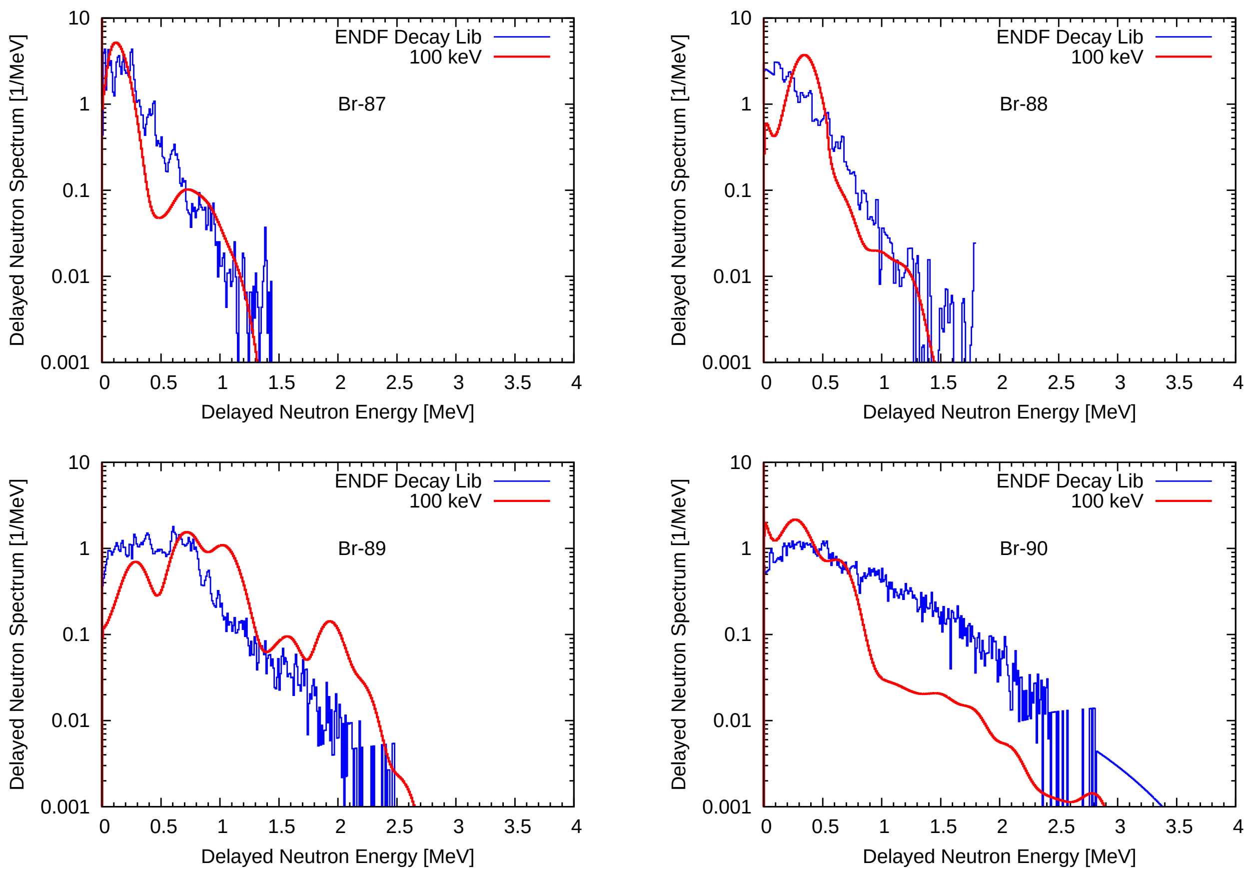
Monte Carlo approach to the Hauser-Feshbach

- HF gives an integrated cross-section for all possible intermediate transitions.
- However, recent experiments are sometimes conducted by measuring partial γ-rays, coincidence with a particular γ-ray transition, selected events such as a fixed γ-ray multiplicity.
- Correlation information is needed.

Application of HF to Delayed Neutron Emission

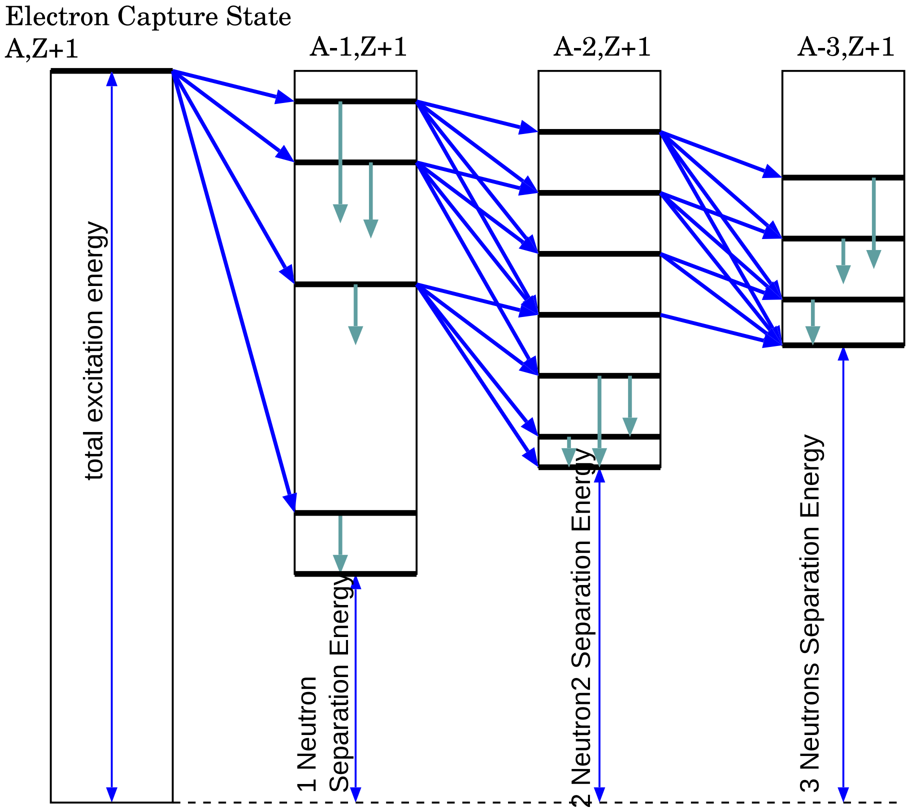
QRPA and Hauser-Feshbach model for Beta-Delayed Neutron





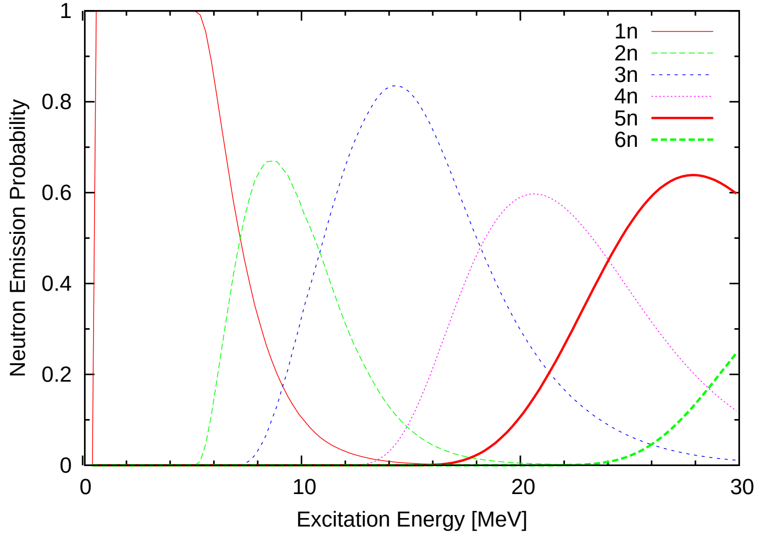
We assume that the excited state after β-decay is a compound state, having a fixed J value, $|I-1| \leq J \leq I+1$, where I is the spin of precursor.

Sequential Neutron Emissions

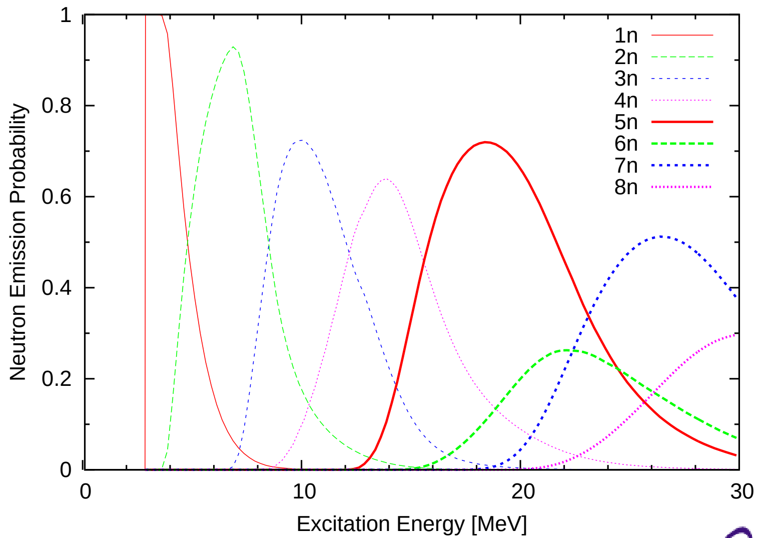


Electron capture produces a highly excited state, which subsequently decays by emitting several neutrons (very fast process).

Si-43



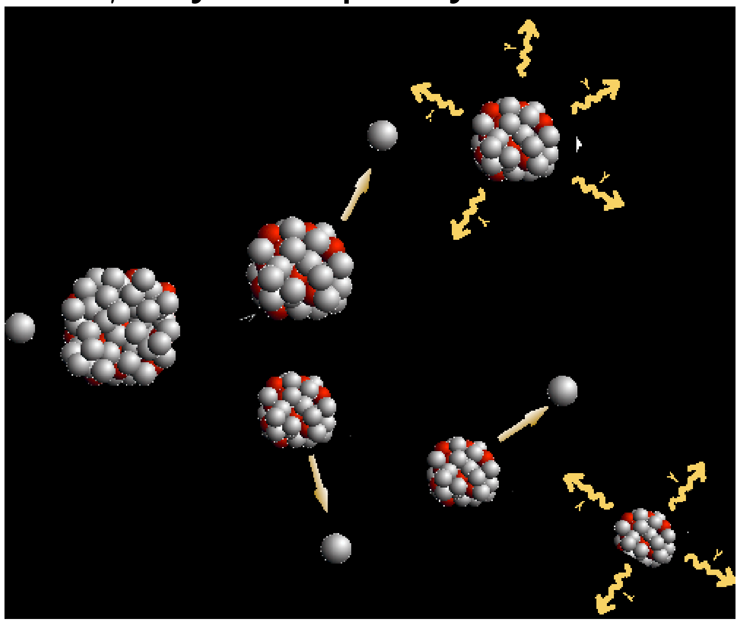
Sr-118

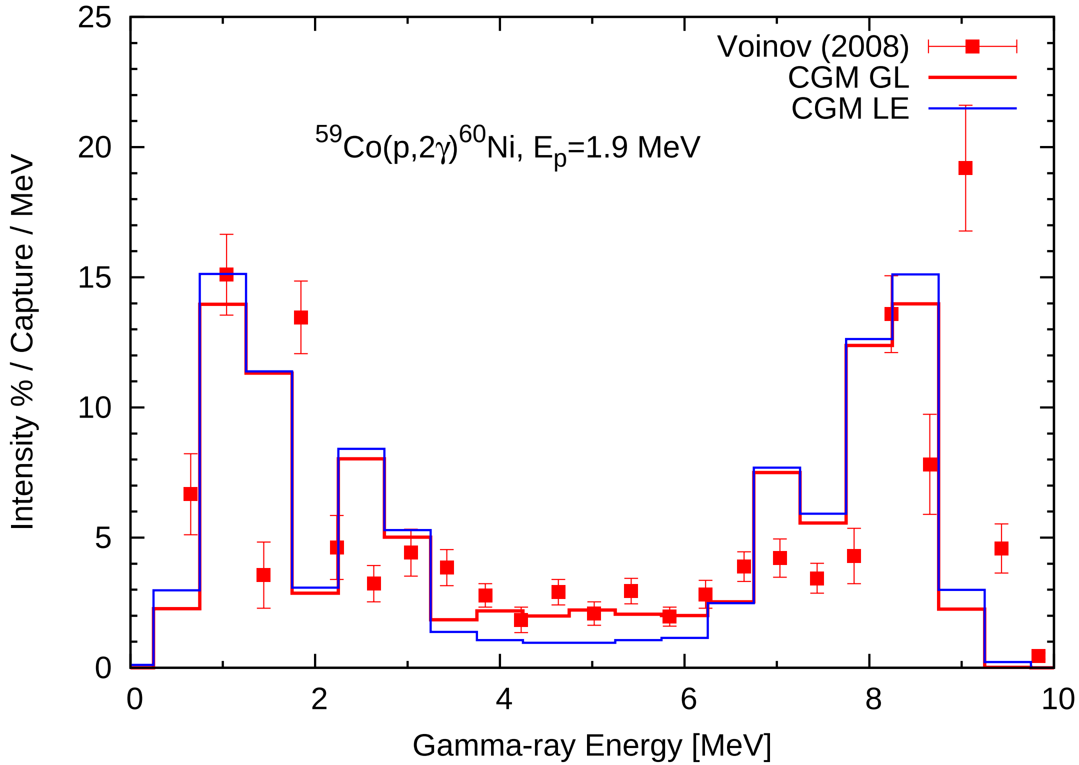


Monte Carlo Simulation for Particle Emission

Application of Monte Carlo to Hauser-Feshbach Model at LANL

- β-delayed γ
- prompt fission neutron spectrum
  - n-γ correlation
  - γ-ray competition
- γ-ray cascading
  - γ-ray multiplicity dist.





A preliminary result of the γ-ray spectra from proton capture for the multiplicity 3 case (2 γ-rays and the $2^+ \rightarrow 0^+$ transition). Data taken from the proc. of Yosemite conference, 2008

Concluding Remarks

Nuclear Reaction Modeling: Recent Development for Astrophysics

Compound Nuclear Reaction

- Improved Hauser-Feshbach model for capture reaction, including nuclear deformation effect, which supports experimental data at LANSCE with DANCE.

Direct/Semidirect Nucleon Capture

- The Hartree-Fock BCS theory for the DSD process has a potential to predict neutron capture cross-sections near the neutron drip-line.

Extension of the Hauser-Feshbach Model Applications

- Beta-delayed and EC neutron emission
- Prompt fission neutron spectra
- Monte Carlo approach : correlations of particle emissions