Importances of exit channel fluctuations in reaction branching ratios

G.F. Bertsch
University of Washington

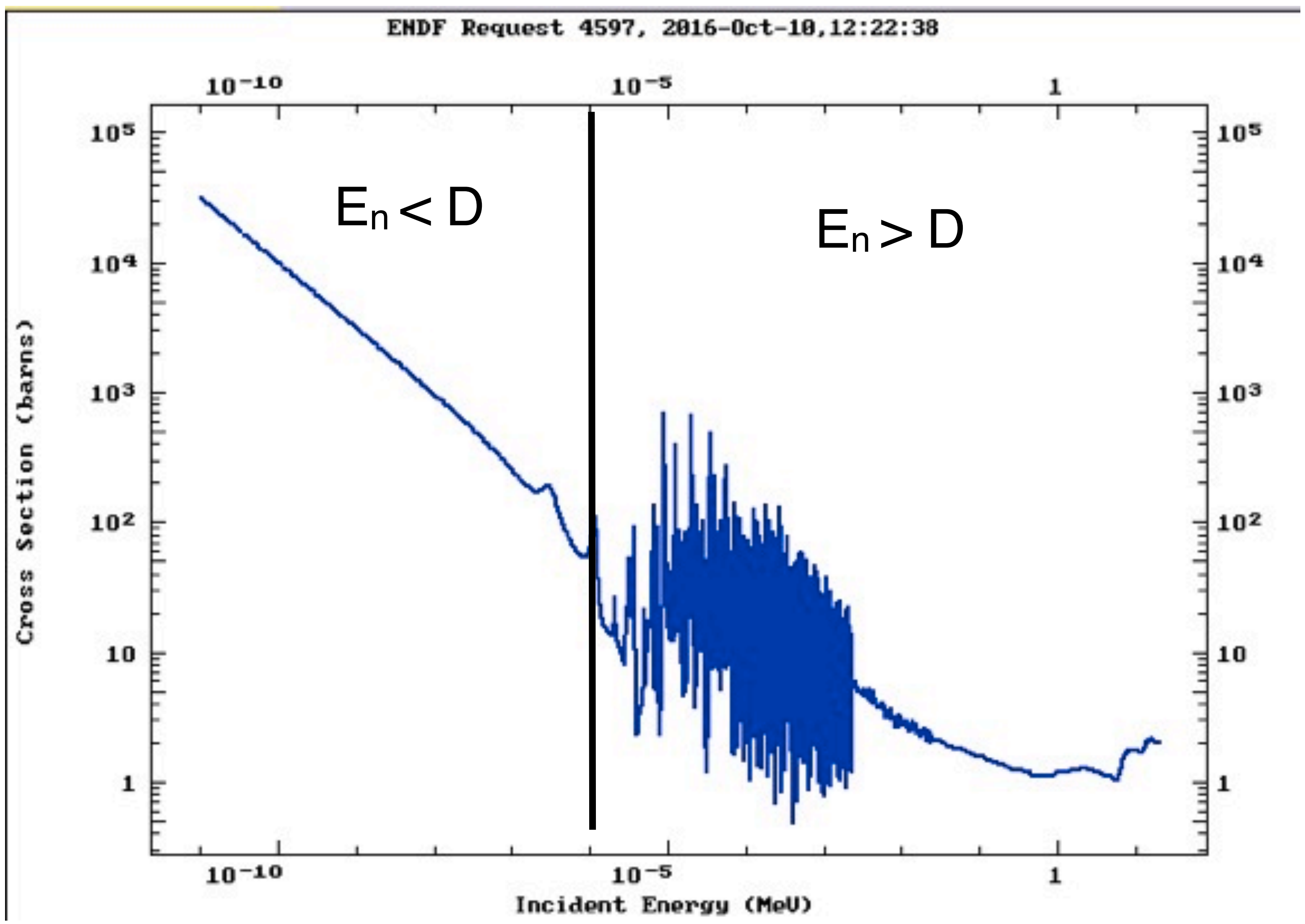
NMP17, MSU
March 7, 2017

Outline of my talk

1. Motivation: theory of induced fission
2. A new approach: CI
3. Mazama: a flexible code to implement CI methods
4. First results

Motivation

I would like an understanding of fission dynamics, based on a nucleonic Hamiltonian.



$^{235}U(n,f)$ Text

The transmission coefficient, a key concept.

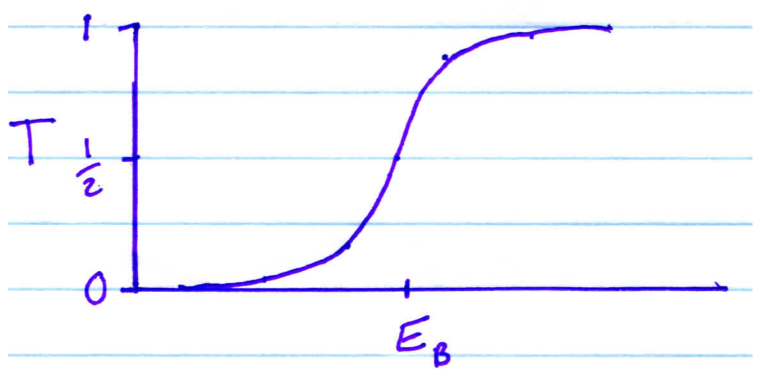
Wigner, Eyring, Weisskopf (1930-1937)

Bohr-Wheeler (1939)

$$\Gamma_F(E) = \frac{1}{2\pi\rho}\sum_c T_c(E)$$

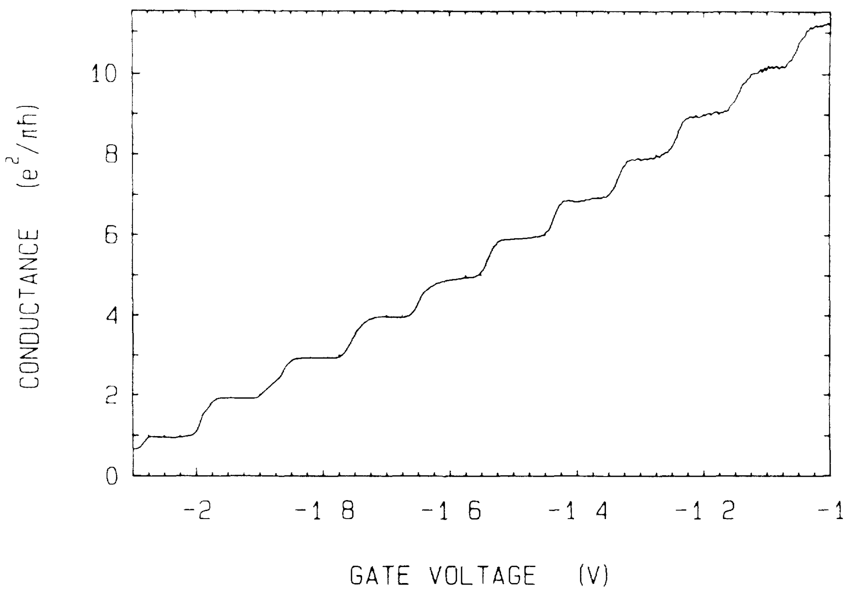
Hill-Wheeler (1953)

$$T(E) = \frac{1}{1+\exp(2\pi(E_B - E)/\hbar\omega)}$$



Well-known in mesoscopic physics as the Landauer formula for quantized conductance.
(See Bertsch, J. Phys. Condens. Matter 3 373 (1991).

$$G = 1/R = \frac{e^2}{2\pi\hbar}\sum_c T_c$$

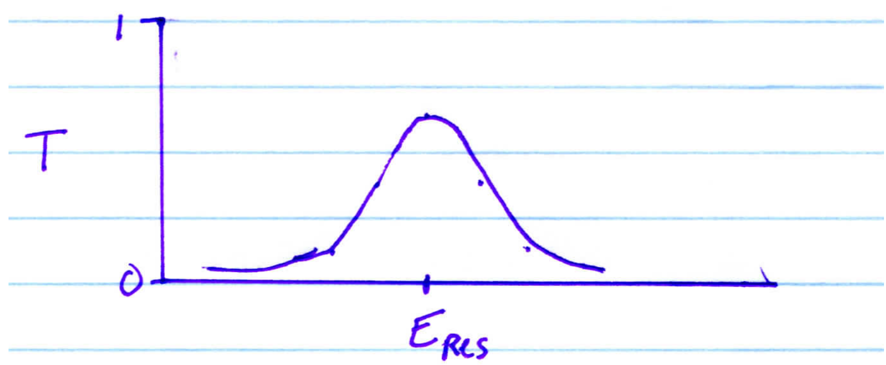


B.J. van Wees, et al. Phys. Rev. Lett. 60 848 (1988).

Transport through quantum dots (resonances)

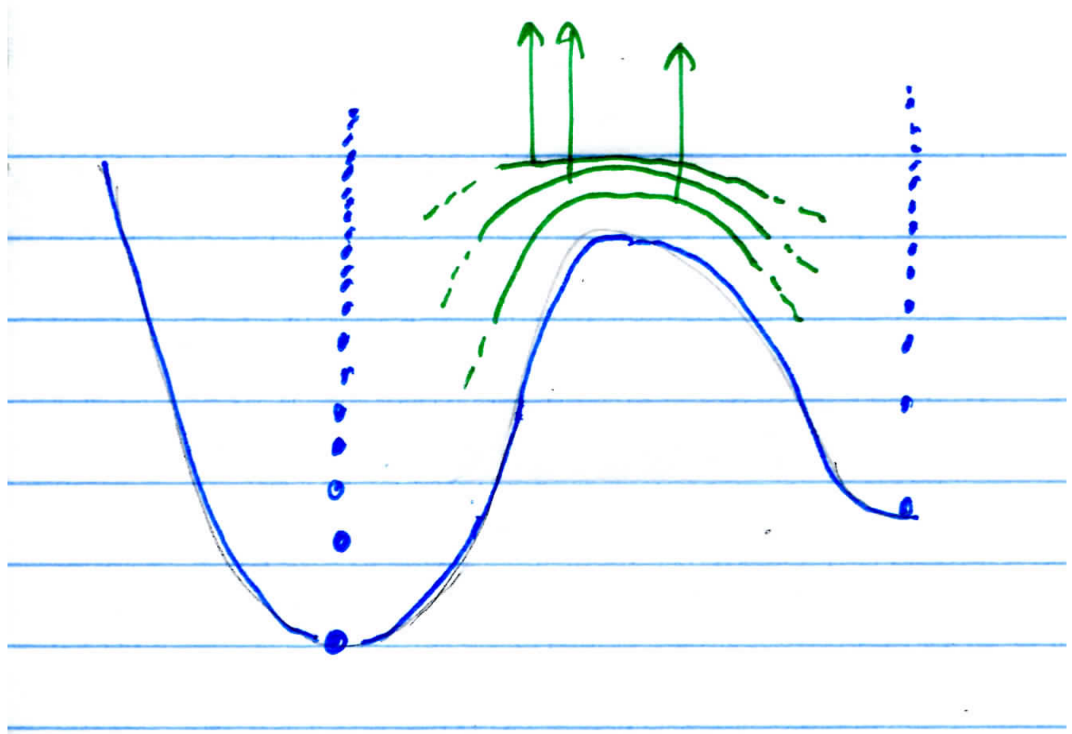
See Alhassid, RMP **72** 895 (2000)

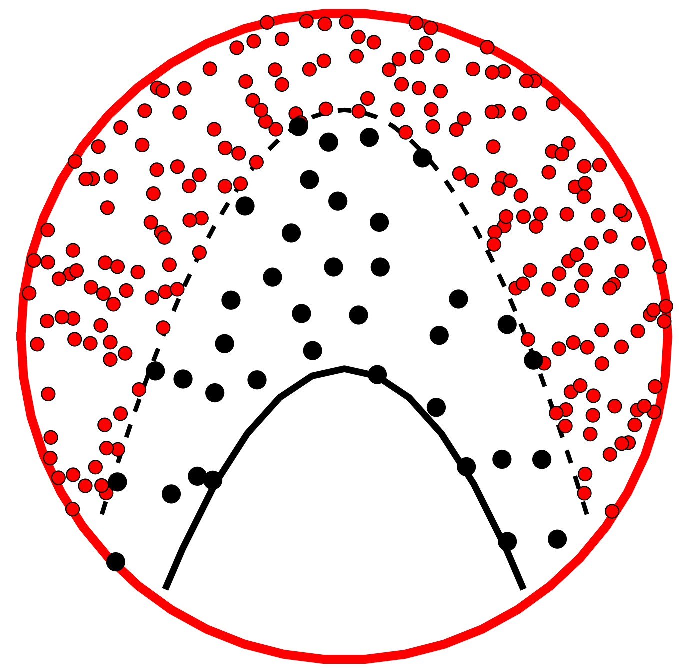
$$T_{res}(E) = \frac{\Gamma_R \Gamma_L}{(E - E_{res})^2 + (\Gamma_R + \Gamma_L)^2/4}$$



Maximum T=1, when left and right widths are equal.

States or Channels?





Remarks:
1)There is (as yet) no way to connect the states to the channels with the nucleonic interaction.

2)Transport through intermediate states is well established in mesoscopic physics.

3) Meager evidence for collectivity in the shape degree of freedom near the ground state.

4) Are there any observable consequences?

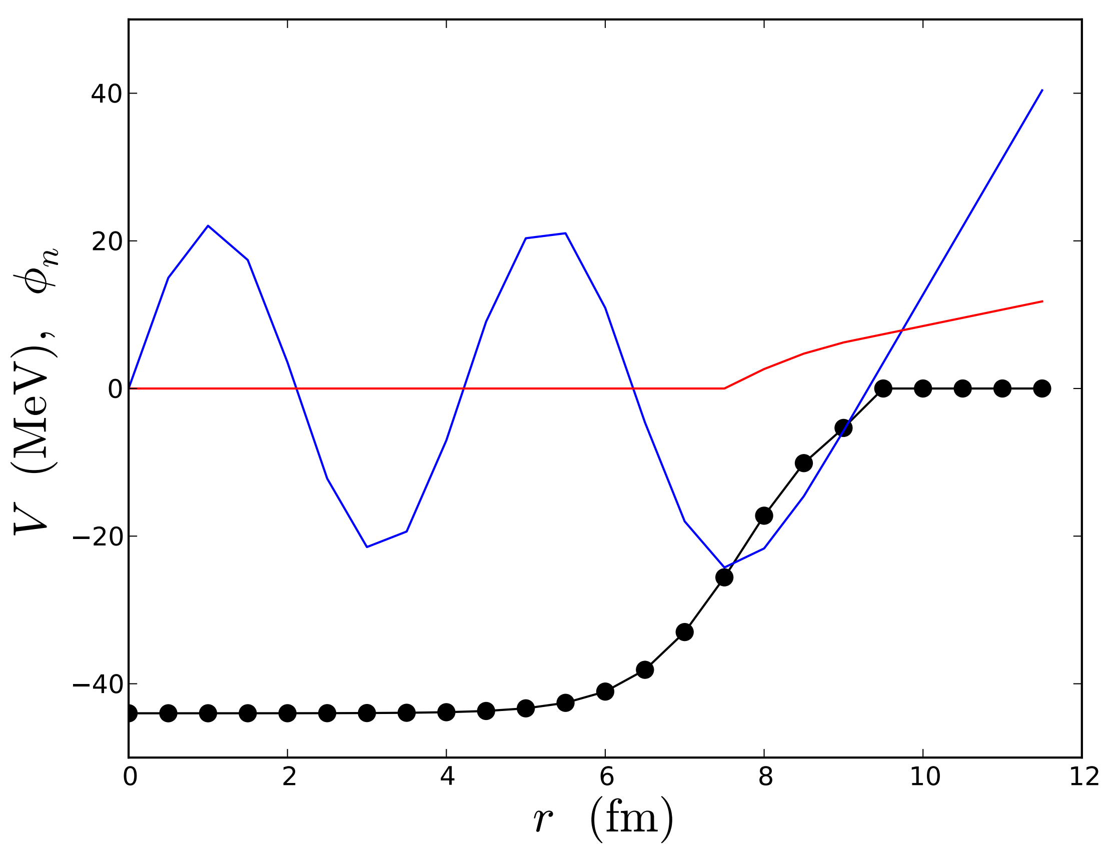
The Mazama code: implementing a discrete basis for neutron-induced reactions.

The Hamiltonian is set up in stages, each one connects only with its neighbors.

-Entrance channel
-Internal stage I
-internal stage 2
-...

Entrance channel: continuum neutron wave function represented on an r-space mesh.

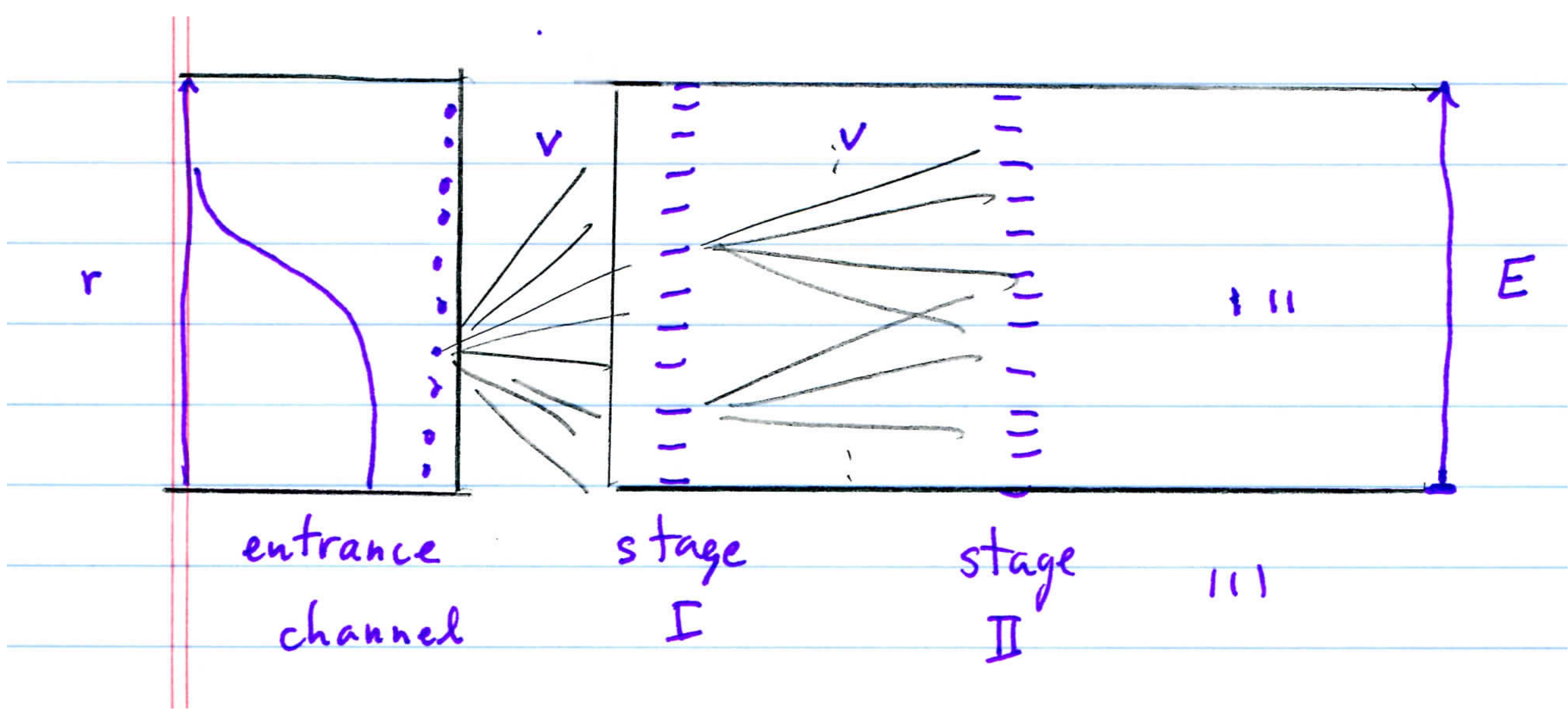
Woods-Saxon potential: $$V(r_i) = \frac{V_0}{1 + \exp((r_i - R)/a)}$$ No imaginary W!



black: V
blue: phi_n.real
red: phi_n.imag

Other stages are described by a spectrum of levels with space either uniform or following the GOE ensemble. An imaginary contribution Gamma/2 may be added to the energies to represent decay modes other than coupling to neighboring stages.

Interactions between levels in neighboring stages are taken from a Porter-Thomas distribution (i.e. Gaussian-distributed).



The Hauser-Feshbach formula

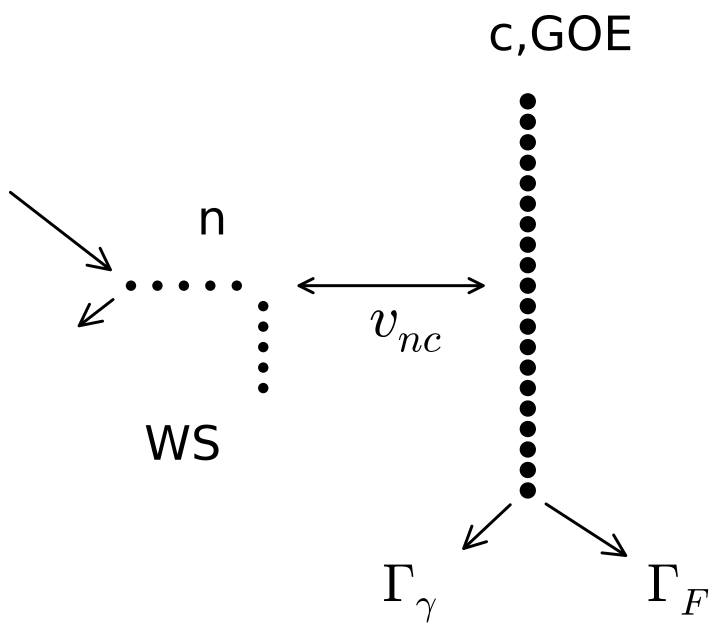
$$\sigma_{\alpha,\beta} = \frac{(2l+1)\pi}{k^2}\frac{\Gamma_\alpha \Gamma_\beta}{\Gamma^2}$$ (prefactor modified by symmetries)

Definition of compound nucleus

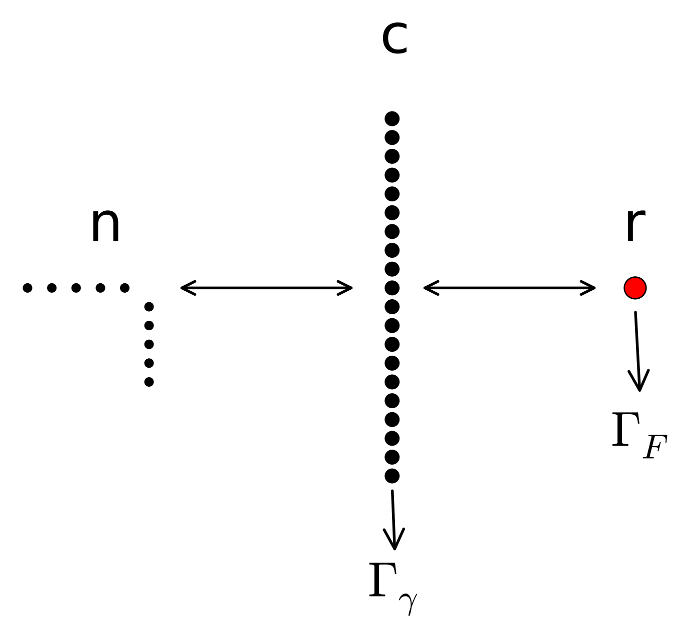
1) level spacing follows GOE spectrum
2) matrix elements $\langle \alpha | v | x \rangle$ follow Porter-Thomas distribution

$$P(\langle \alpha | v | x \rangle) = \exp(-v^2/2v_0^2)$$

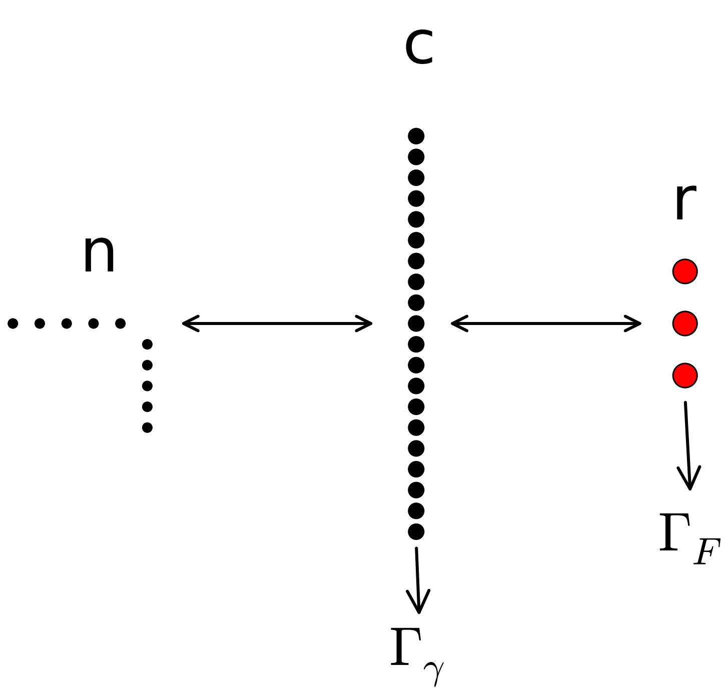
Examples of models that can be analyzed with Mazama.



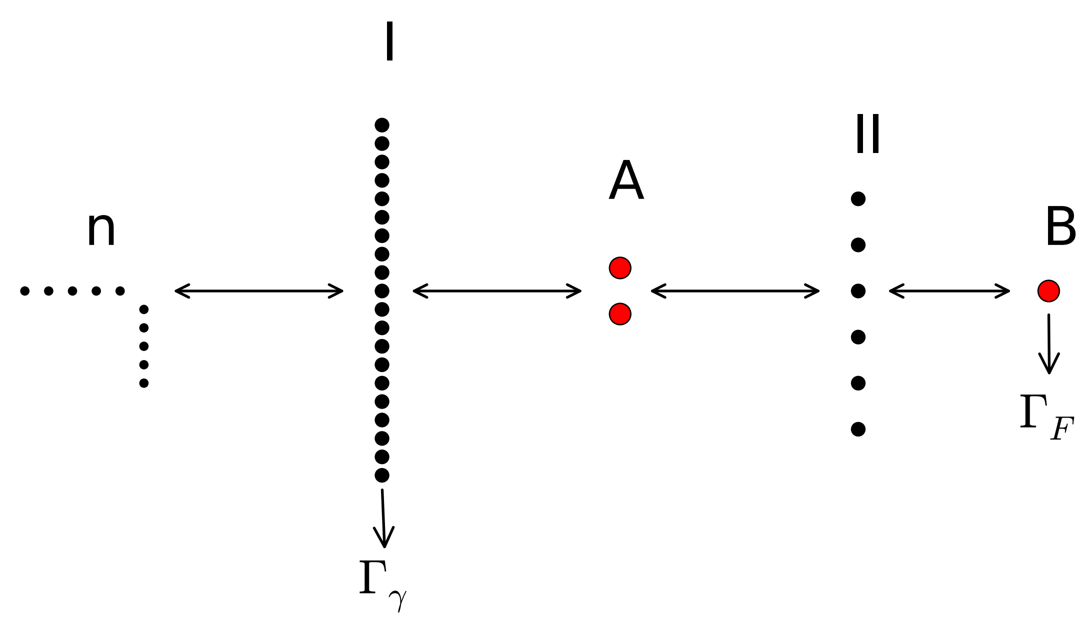
Hauser-Feshbach



Simple barrier model



More transition states

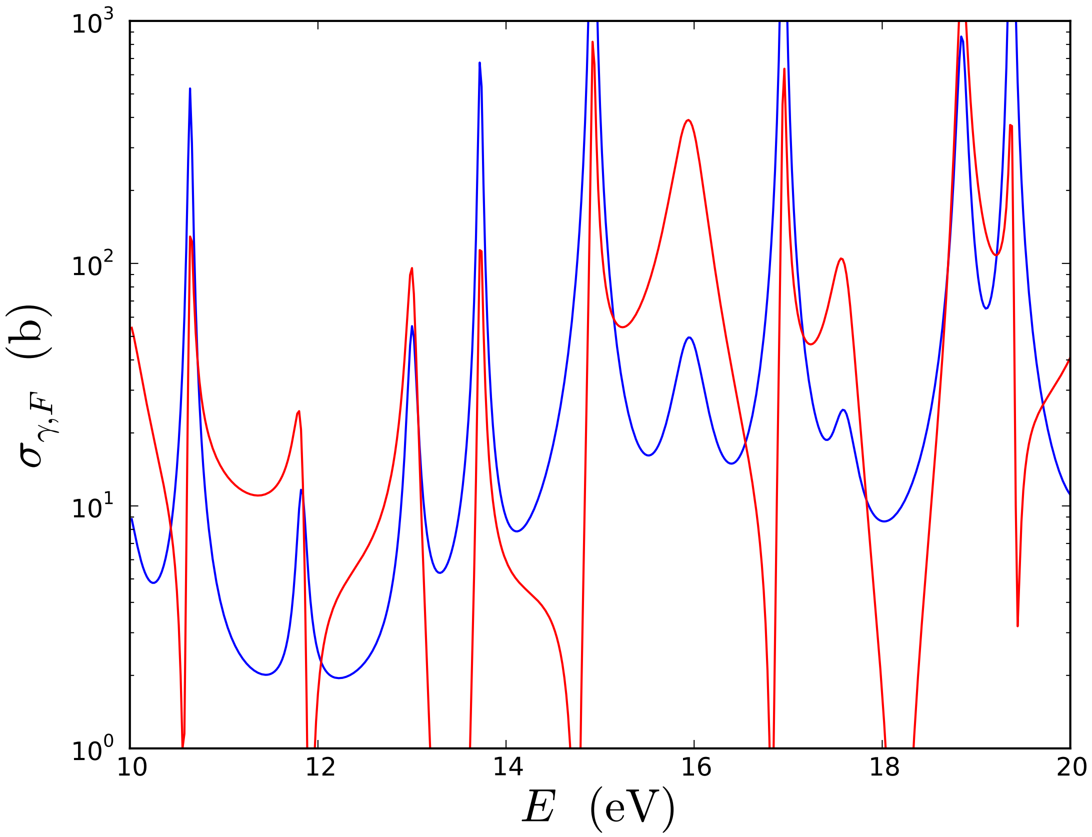


Double-barrier dynamics

How far can we get with the simpler barrier model?

Average low-energy properties of ^{235}U(n,..) :

$$\langle\frac{\Gamma_n}{D}\rangle = 10^{-4}\left(\frac{E_n}{1\text{eV}}\right)^{1/2} \qquad \Gamma_\gamma \approx 35 \text{ meV} \qquad \Gamma_F \approx 100 \text{ meV} \qquad \alpha^{-1} \approx 2.8$$



Blue: capture; red: fission

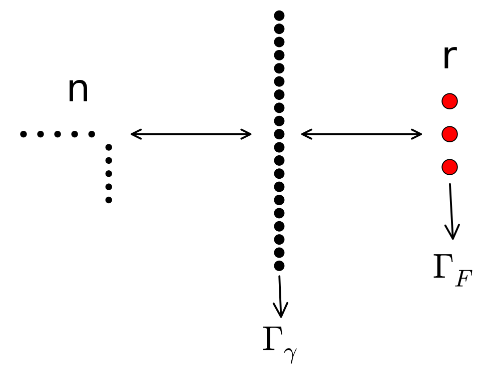
Single transition state

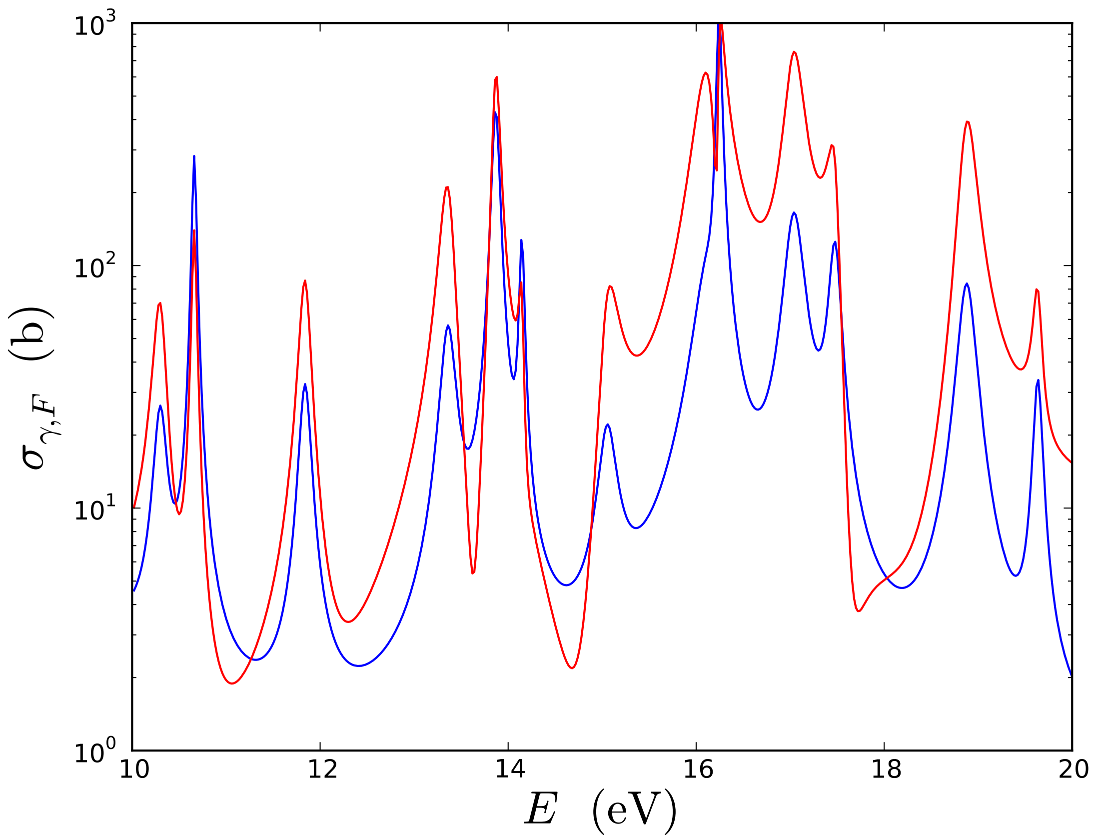
```
0.5  24 15            # delta_r, Nn,  i_vnc
-44.0 0.65 1.25 235. # V_ws a_r r0 A
2  1                 # Nstage seed
200 -50.e-6 1.0e-6 35.0e-9 2.5e-3 w
            #Nc,E0c,dEc,gamma_c,v_nc
1  50.0e-6  0.0 2.0e-5 1.0 u
            # 100.e_9 *200 = 2.e_5
10.0e-6 2.0e-8 1000 sig # E0, delE, NE, S/sigma
```

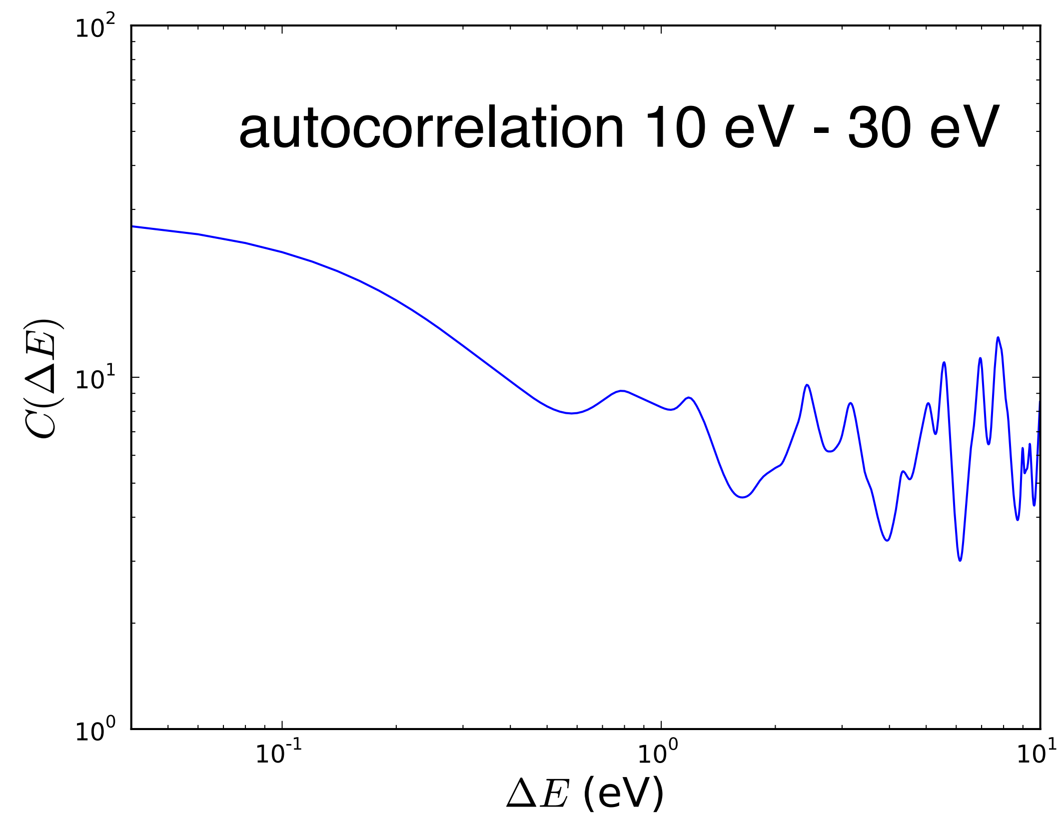
$$\alpha_{sts}^{-1} \approx 0.9$$

Hauser-Feshbach violation!

Adding transition states







Blue: capture; red: fission

$$\alpha_{3ts}^{-1} \approx 3$$

Two sources of Hauser-Feshbach violation

Text

Bertsch and Kawano, arXiv:1701.00276 (2017)

1) well-known in the evaluator community--"width fluctuation correction"

Moldauer, Phys. Rev. C 14 764 (1976).

$$\left\langle \frac{\Gamma_\alpha}{\Gamma_\alpha + \Gamma_0} \right\rangle_\alpha \Big/ \left\langle \frac{\Gamma_0}{\Gamma_\alpha + \Gamma_0} \right\rangle_\alpha < \left\langle \frac{\Gamma_\alpha}{\Gamma_0} \right\rangle_\alpha$$

2) In principle known, but forgotten: T<1. Need to solve explicitly for the S-matrix:

$$K = \pi \tilde{\gamma}^T \frac{1}{E - H} \tilde{\gamma} \qquad\qquad S = \frac{1 - iK}{1 + iK}$$

Future

Fluctuations:

1. When is Porter-Thomas violated?

   Claim in PRL 115 052501 (2015): properties of the entrance channel can produce violations of otherwise statistical distributions.

2. Validity of Ericson's treatment of compound-nucleus fluctuations

Autocorrelation function $$C(\epsilon) = \left\langle \frac{\sigma(E)\sigma(E+\epsilon)}{\bar{\sigma}^2} \right\rangle$$

Width of CN states $$C(\epsilon) = 1 + \frac{1}{N_c}\frac{1}{1+(\epsilon/\bar{\Gamma})^2}$$

E_B>> Gamma $$C(0) - 1 = \frac{1}{N}\frac{1}{1+(E_B/\pi\bar{\Gamma})}$$

P. Fessenden, et al., Phys. Rev. Lett. 15 796 (1965).