Fluctuations: unexplained experiments and possible theories

A new approach to barrier-top fission dynamics

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FUSTIPEN workshop

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Outline of talk

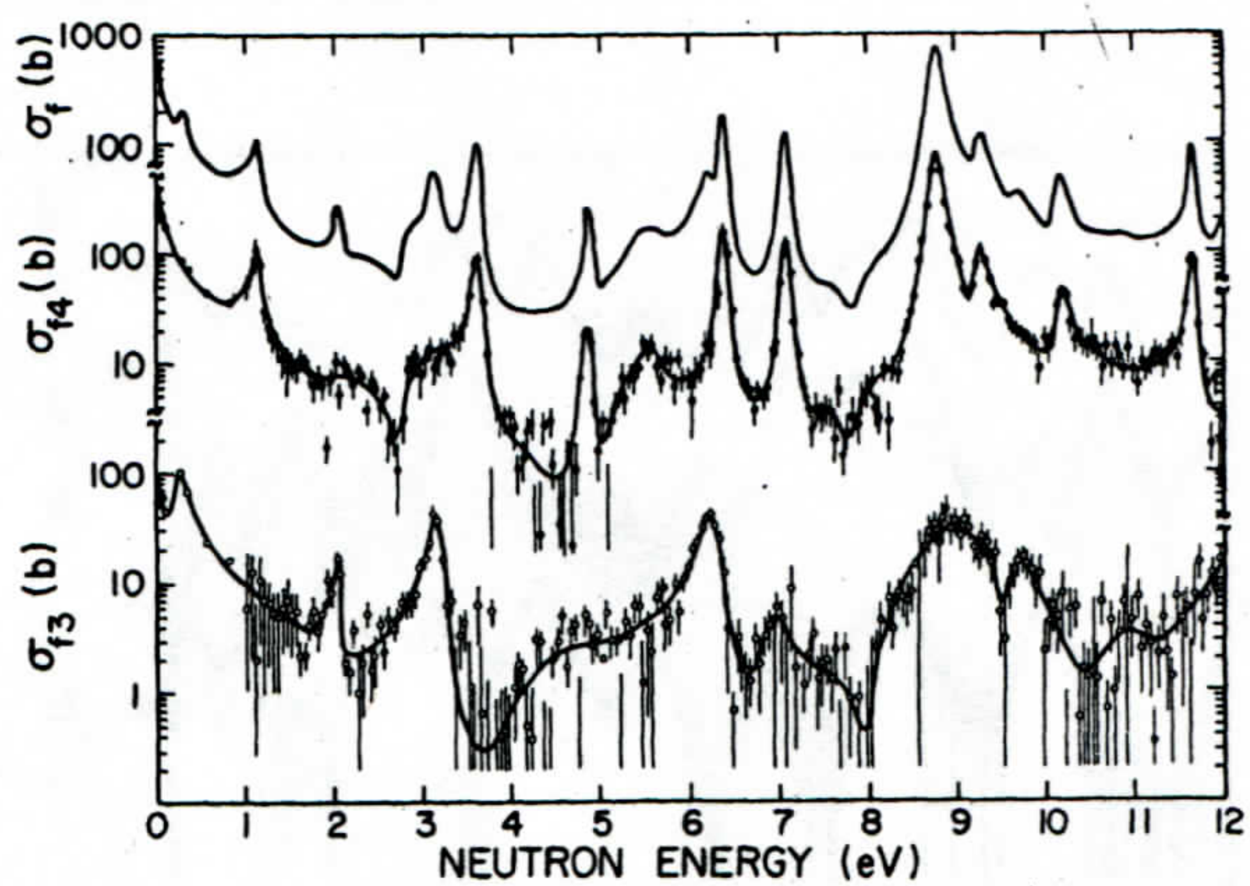
1. Recalling some very old experiments
2. Channels or states?
3. A basis by constraining K-pi

Do we understand the fluctuations in (n,f) cross sections?

$^{235}U + n$ --> fission, resolved into J= 3 vs. J=4

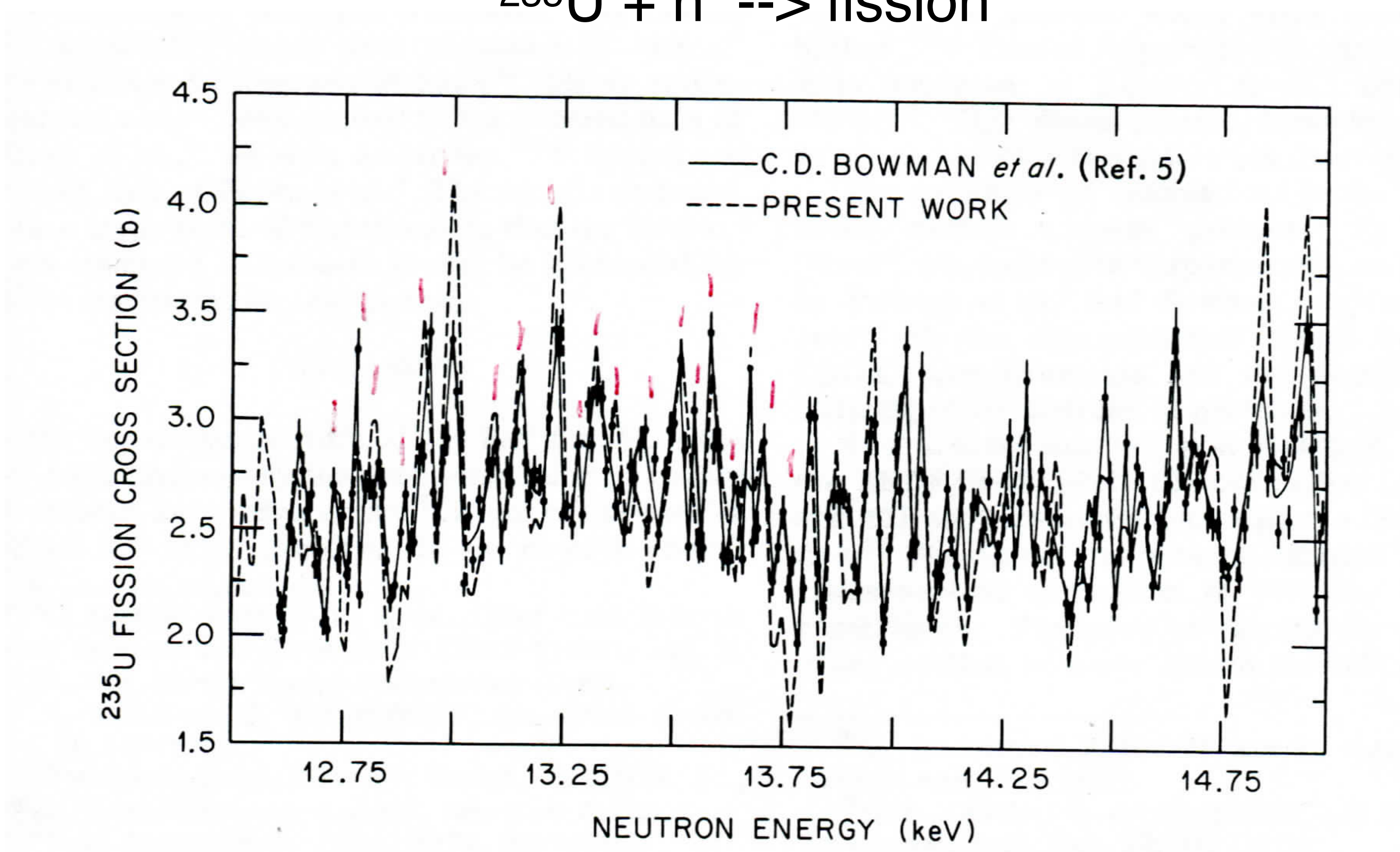
M.S. Moore, et al., Phys. Rev. C 18 1328 (1978).

On the smallest energy scale, compound nucleus statistics with D=0.45 eV



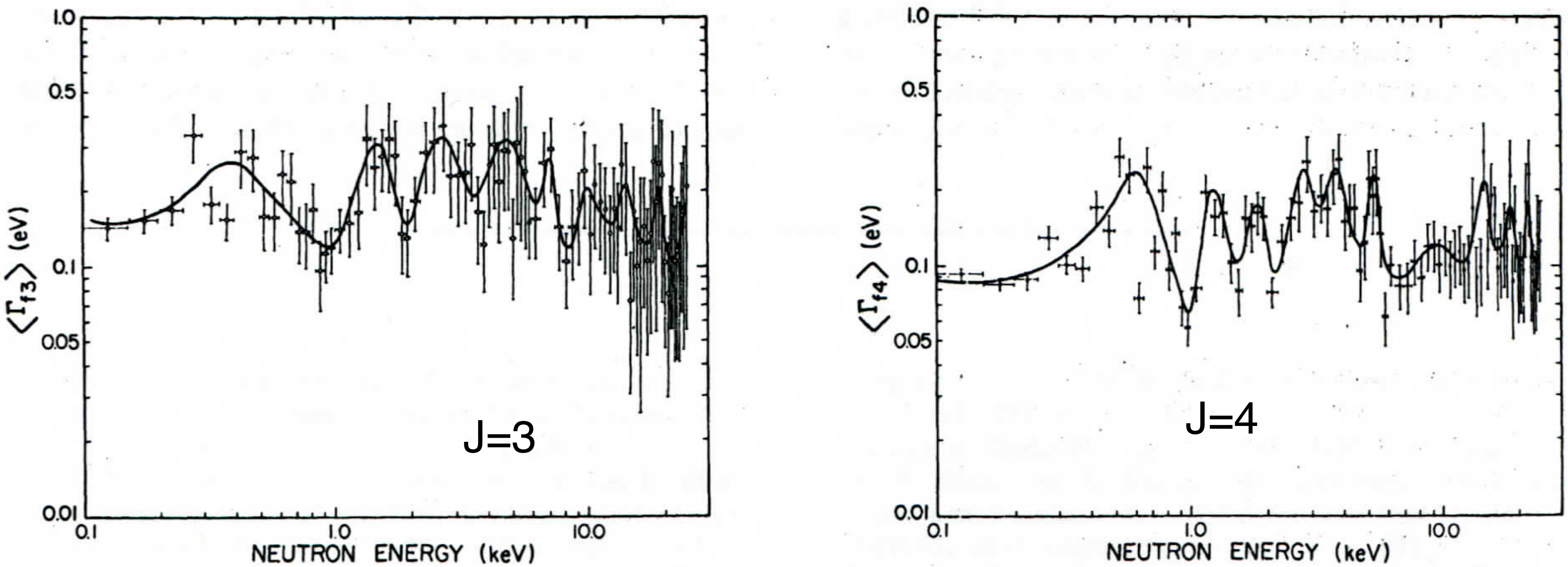
On the 100 eV scale, level density of class II states

$^{235}U + n$ --> fission



R.B. Perez, et al., Nuclear Science and Engineering **55** 203 (1974)

But what about fluctuations on a 1 keV scale?



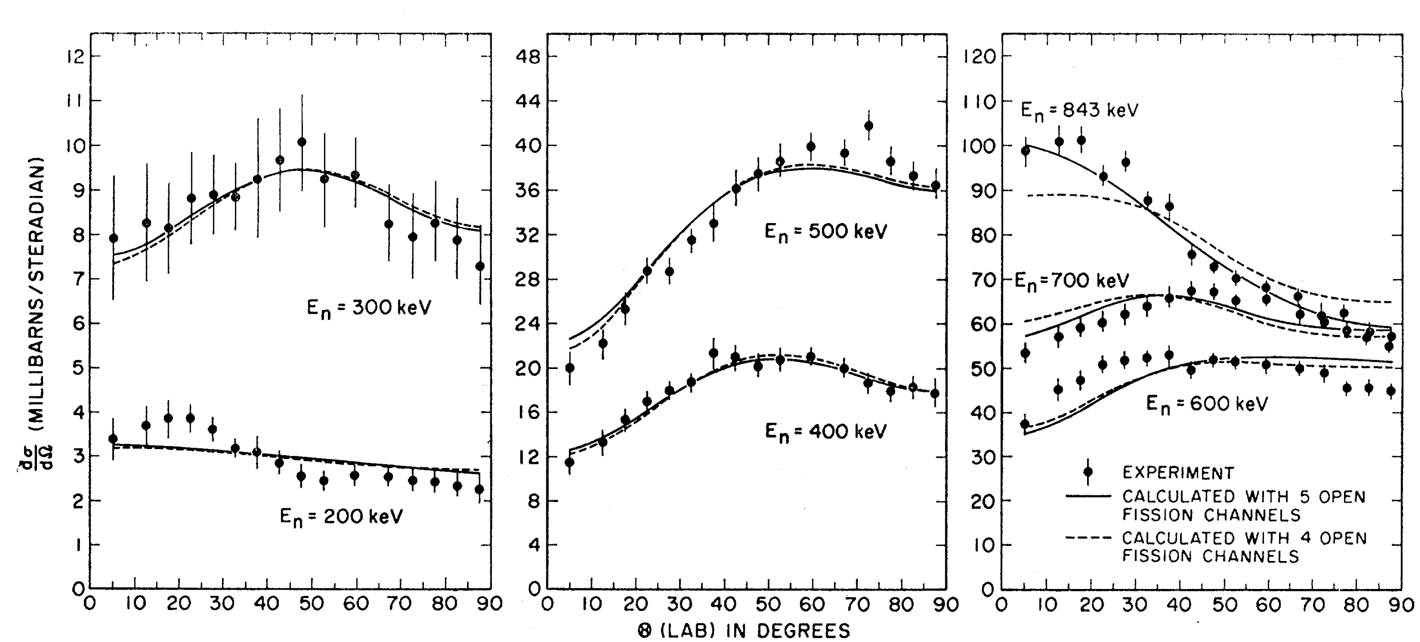
Fluctuations in angular distributions.

1) (gamma,f) well understood at threshold with opening K-pi identified channels. (Little K-mixing at E = 5.5 MeV)

2). (X,f) well understood at higher energy by thermal distribution of K-pi channels.

3). Not so clear at energies just above the barriers.

A. Behkami, et al., Phys. Rev. 171 1267 (1969).



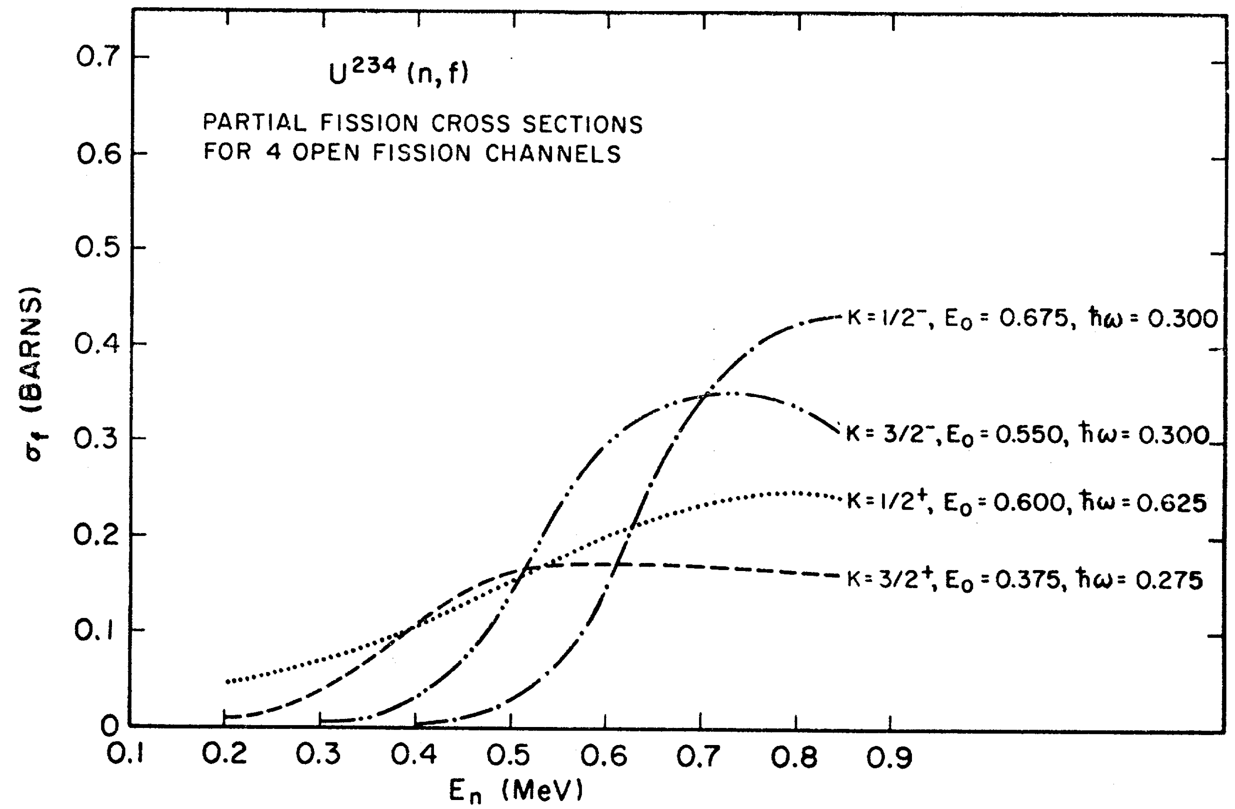


FIG. 8. Summary of the parameters describing the accessible states of the transition nucleus and the partial fission cross section associated with each state as a function of the incident neutron energy. The energies are given in MeV. A possible fourth state in the transition nucleus is also shown.

hypotheses involving weakly excited states which will fit the data. We simply cannot say anything about them.

Beginning with the case of the data from two neutron energies, $E_n = 200$ and 300 keV, and two accessible states of the transition nucleus, we found, after extensive searching, that we could reject all hypotheses not assigning values of $\frac{1}{2}+$ and $\frac{3}{2}+$ for the K, π of these two states. A few sample fits to the angular distributions are shown in Fig. 5. We found that the data at 400 and 500 keV could be adequately described by adding a third accessible state in the transition nucleus and assigning values of $(K,\pi) = \frac{3}{2}-$. The fits to the 400- and 500-keV angular distributions and the total fission cross section[12] are shown in Figs. 6 and 7. Detailed calculations revealed that the values of E_0 and $\hbar\omega$ given in Table III should be regarded as uncertain to at least ± 50–100 keV. The partial fission cross sections are shown in Fig. 8.

Further attempts to fit the data from $E_n = 200$ keV to $E_n = 843$ keV by adding a fourth and fifth accessible state in the transition nucleus were unsuccessful. The best attempts at fitting this data are shown in Figs. 9 and 10, although it should be understood that these are not satisfactory fits to the data when judged by a χ^2 criterion. About all that can be said is that there must be at least one more accessible state of the transition nucleus with $K = \frac{1}{2}$ coming into play before $E_n = 843$ keV.

Channels or Resonances?

Bohr-Wheeler framework $$W = \frac{1}{2\pi\hbar\rho_I}\sum_c T_c$$

Typical channel $$T_c(E) \approx \frac{1}{1+\exp(2\pi(B_c - E)/\omega_c)}$$

Typical resonance $$T_r = \frac{\Gamma_R\Gamma_L}{E_b^2 + (\Gamma_R+\Gamma_L)^2/4}$$

Questions:

1. How to calculate transmission coefficients at the channel interface?
2. What is the bandwidth of the channels?
3. How to calculate mixing between channels?

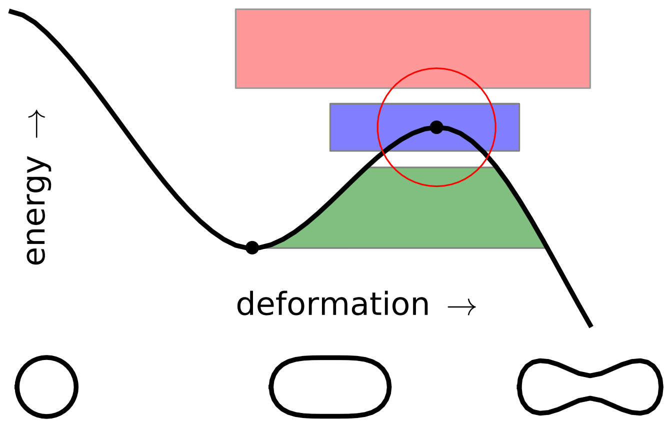
Answers from the literature:

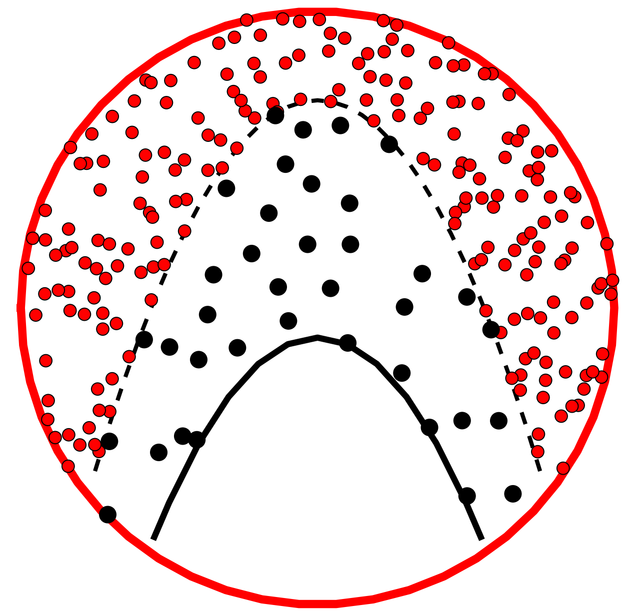
1. None
2. None
3. R. Bernard, H. Goutte, D. Gogny and W. Younes, Phys. Rev. C 84 044308 (2011)

Problems with the channel picture:

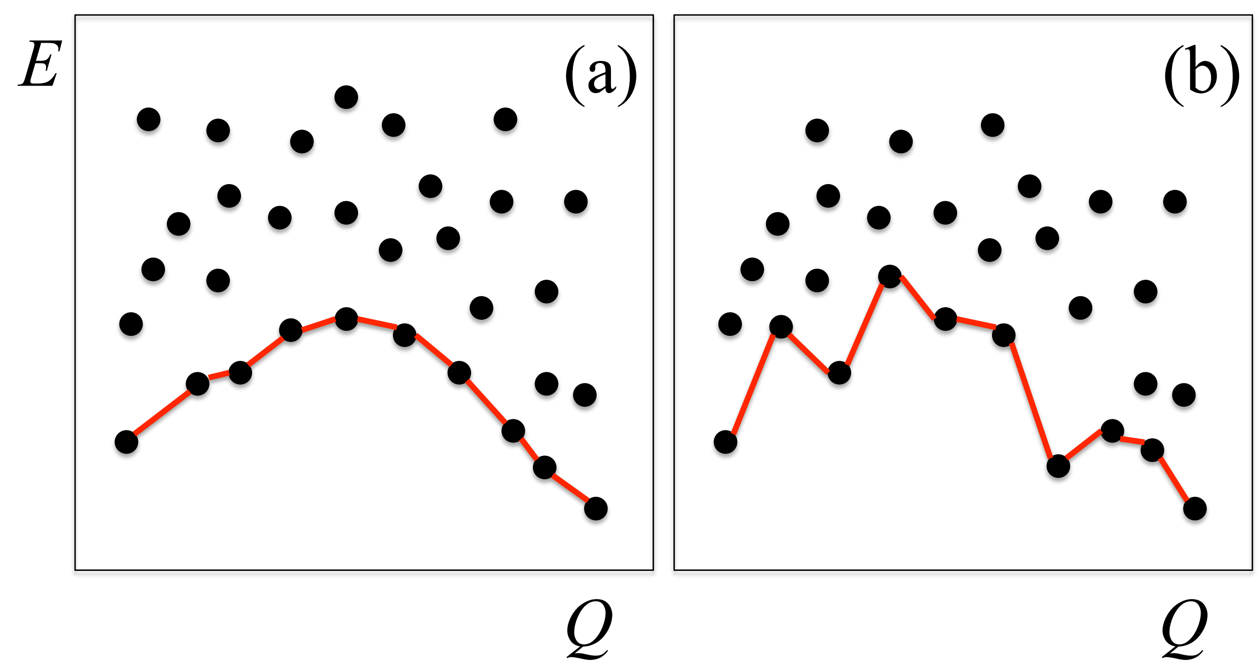
1. Nonorthogonality
2. Separation of collective and intrinsic energy scales (unlike the Born-Oppenheimer separation in chemistry).

My picture



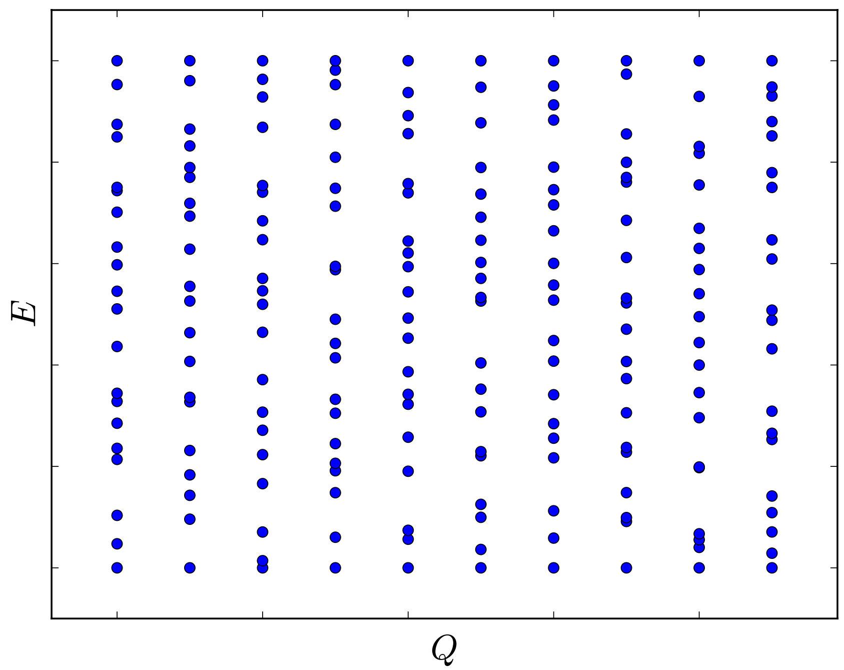


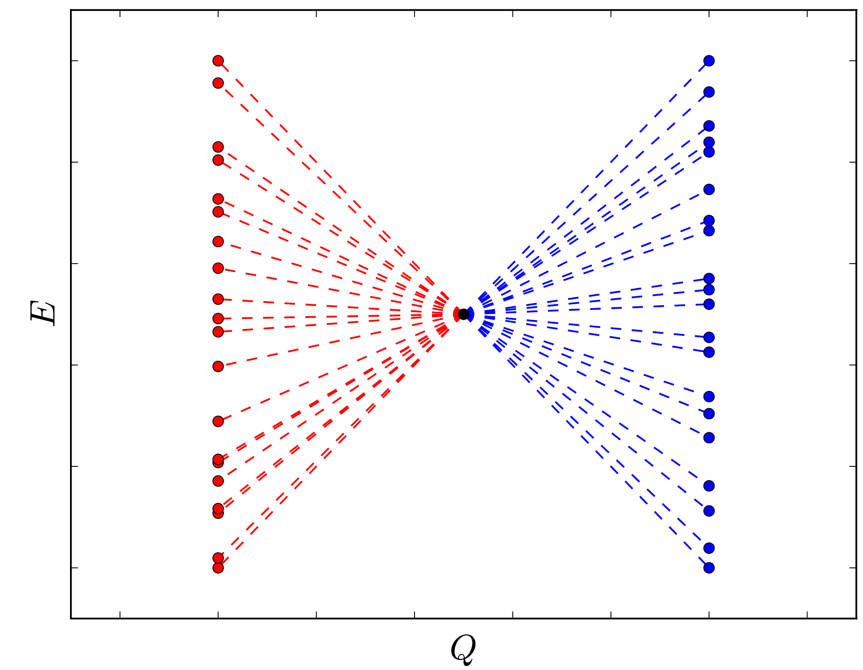
Start with a discrete representation of the many-body wave functions

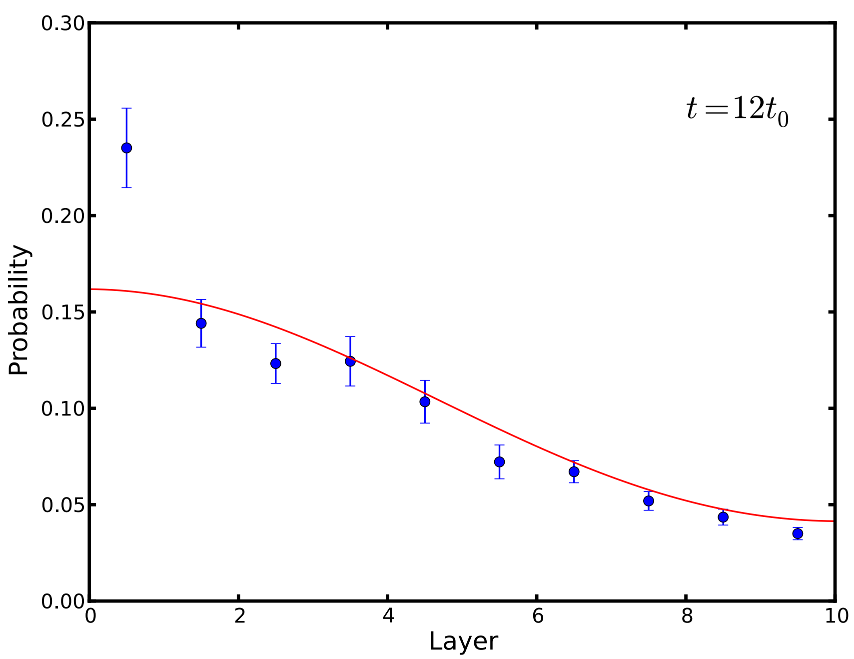


Diffusive limit $$\frac{\partial P}{\partial t} = D\frac{\partial^2 P}{\partial q^2}$$

Resonance-mediated conductance limit







$$T_r = \frac{\Gamma_R \Gamma_L}{E_b^2 + (\Gamma_R + \Gamma_L)^2/4}$$

See:
Bertsch, arXiv:1407.1899.pdf (2014)
Alhassid, RMP 72 895 (2000)

$$D = 2\pi\rho(E)\overline{(q_\alpha - q_\beta)^2 \langle\alpha|v|\beta\rangle^2}$$

Advantages of a discrete basis representation

--Close connection to microscopic Hamiltonians

--Well-known CI computational methods are applicable

--Conceptual bridge to condensed matter theory (quantum transport)

--Different dynamical limits are accessible
- --channel limit
- --diffusive limit
- --resonance-mediated conductance limit

Possible implementation: the axial basis

Instead of using a generator coordinate to distinguish states, use the filling of orbitals by the K quantum number.

Example ^{16}O in shell model: $s_{1/2}$, $p_{3/2}$,$p_{1/2}$

K	1/2	3/2	5/2	7/2	9/2	11/2	13/2
p^+	2						
p^-	4	2					
n^+	2						
n^-	4	2					

A toy model for fission

	1/2	3/2	5/2
p^+	6	2	2
p^-	4	2	
n^+	6	2	2
n^-	4	2	

^{32}S

→

	1/2	3/2	5/2
p^+	4	2	
p^-	2		
n^+	4	2	
n^-	2		

^{16}O

+

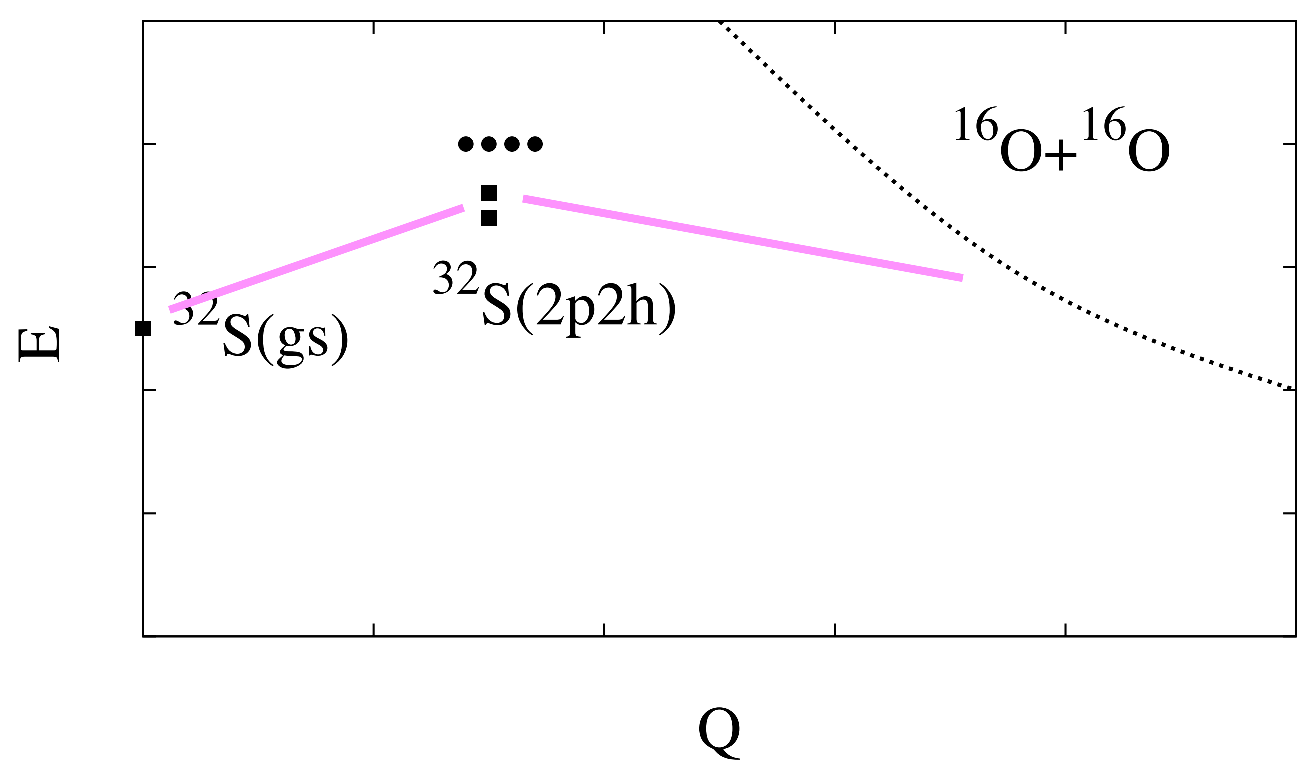
	1/2	3/2	5/2
p^+	2		
p^-	4	2	
n^+	2		
n^-	4	2	

^{16}O

=

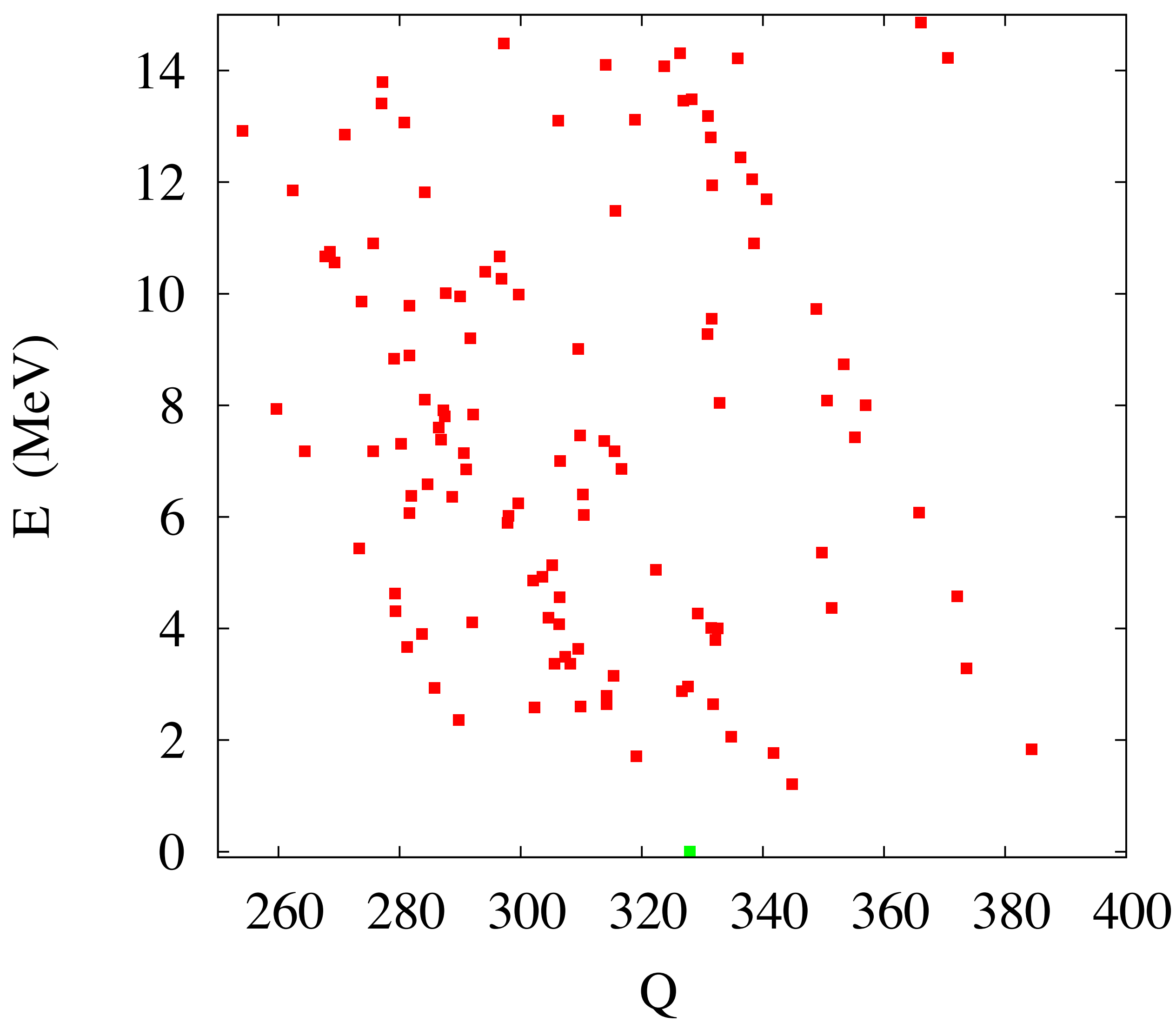
	1/2	3/2	5/2
p^+	6	2	
p^-	6	2	
n^+	6	2	
n^-	6	2	

$^{16}O + {}^{16}O$



Construct the basis by HF minimization
constraining only the K partition.

Example: partition-defined states in ^{162}Dy

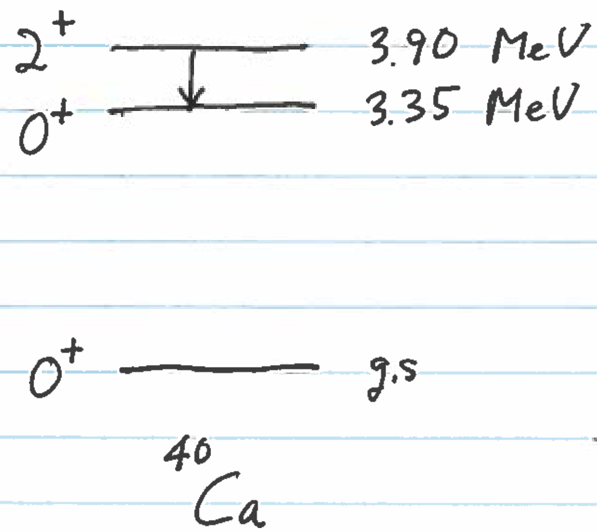


$$H = \sum \varepsilon_i a_i^\dagger a_i + \sum v_{ij,kl} a_i^\dagger a_j^\dagger a_l a_k$$

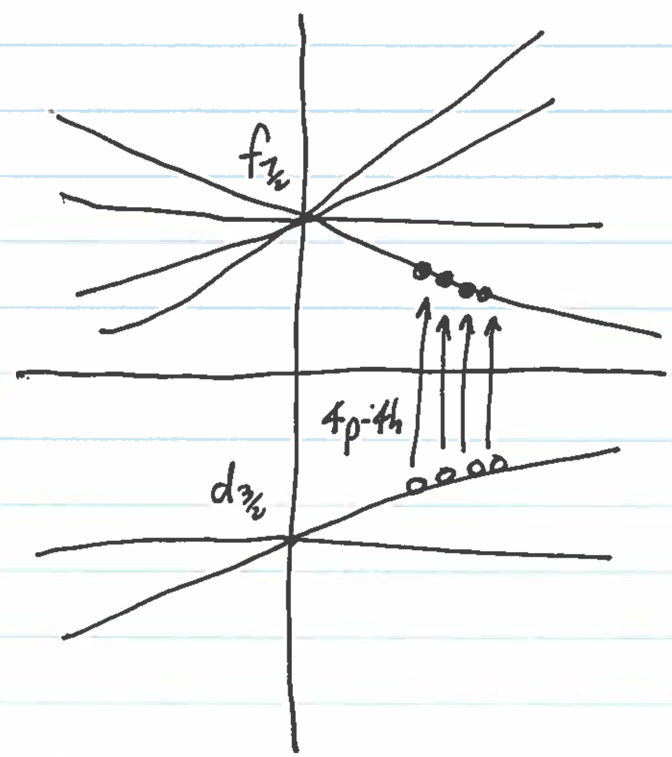
H from Y. Alhassid, et al. PRL 101 082501 (2008).

Comparison of GCM with discrete basis construction for the excited band in 40-Ca.

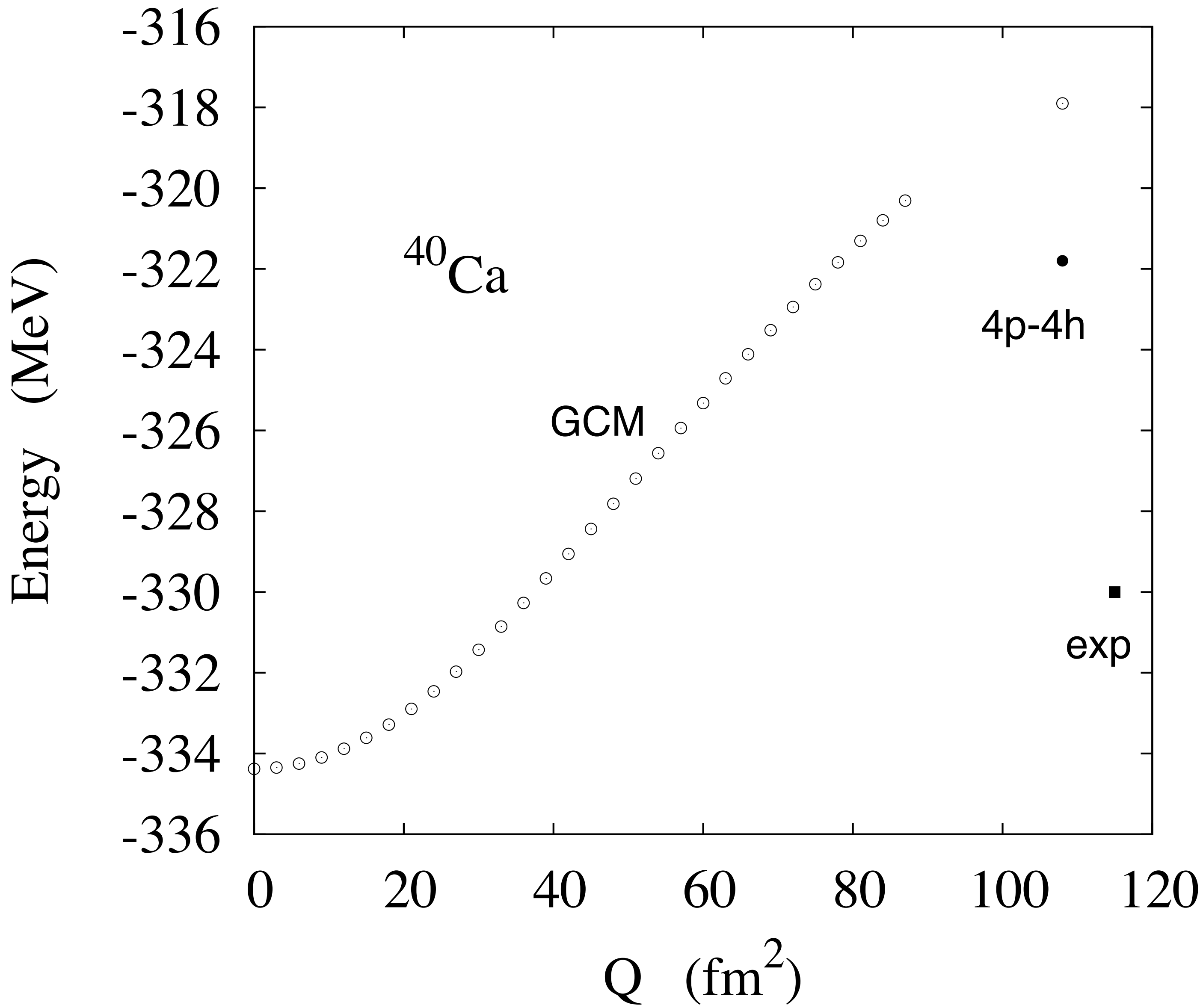
The spectrum



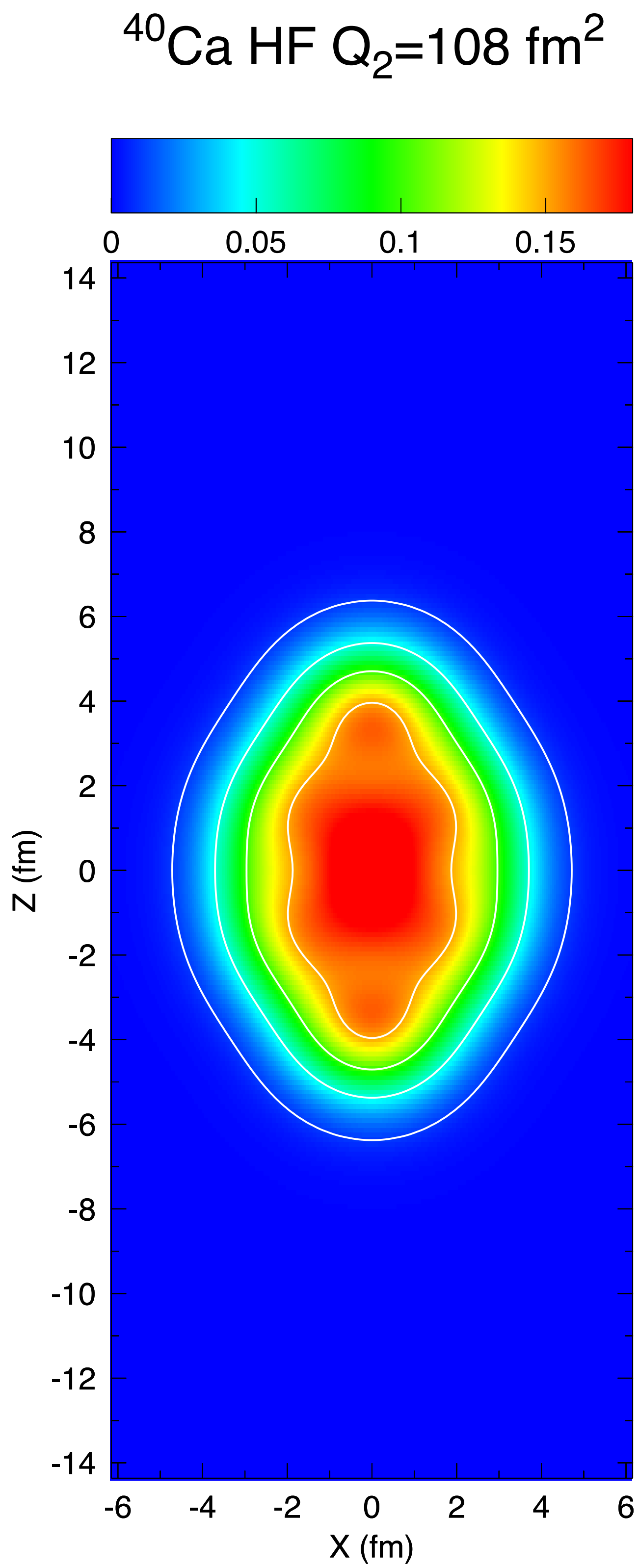
Constructing the K-pi constrained state



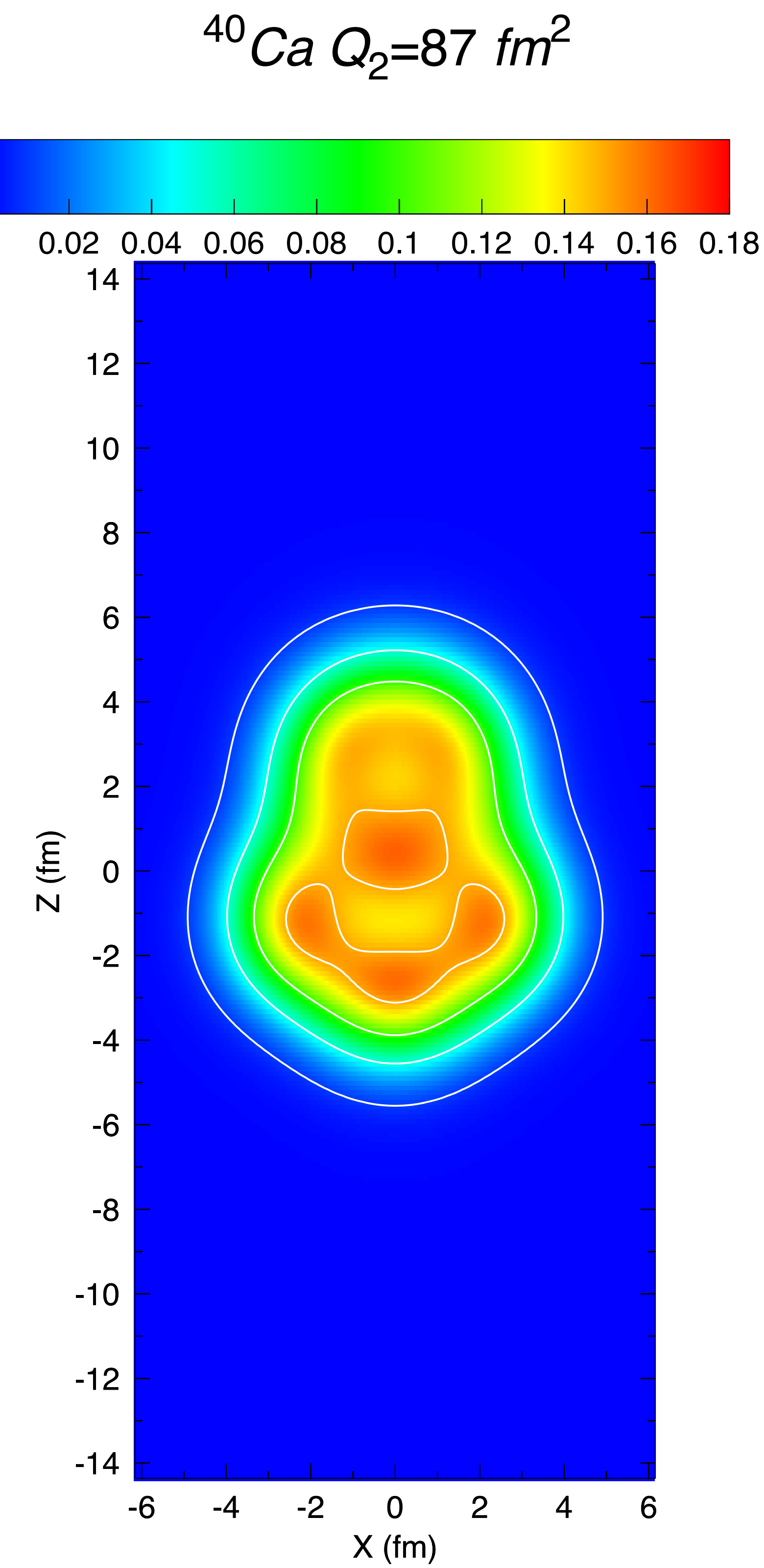
Comparison of GCM with discrete basis construction for the excited band in 40-Ca.



K-pi-constrained method might be more reliable to find the PES.



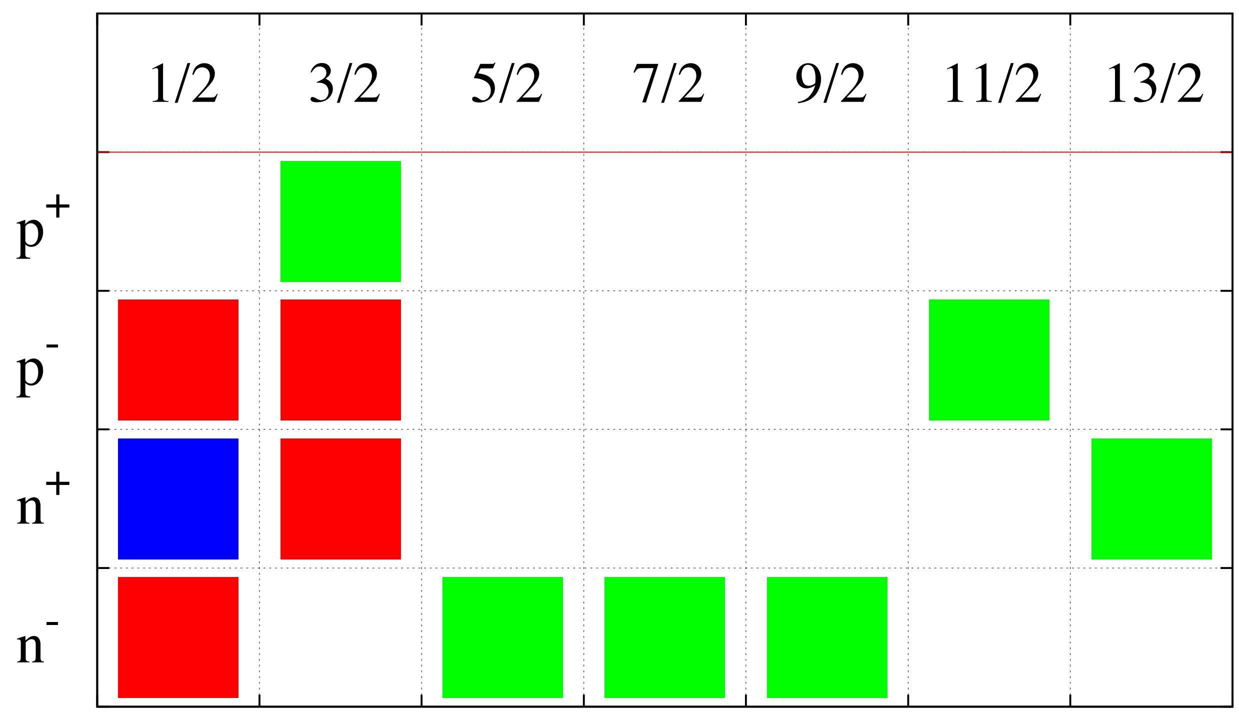
^{40}Ca HF Q_2=108 fm^2
0
0.05
0.1
0.15
Z (fm)
X (fm)



$^{40}Ca\ Q_2$=87 fm^2
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
Z (fm)
X (fm)

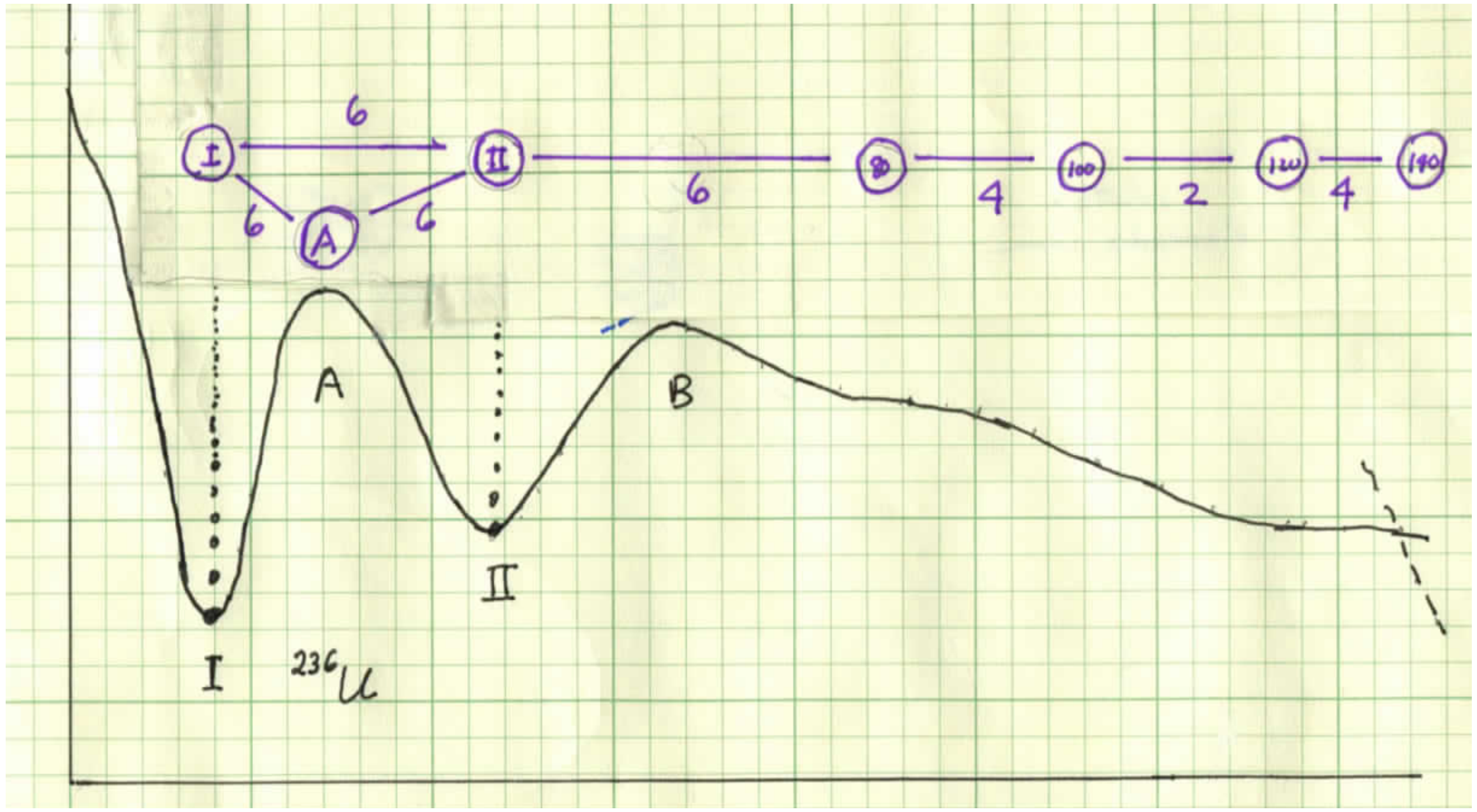
The landscape for U-236 fission, from class I to class II states

^{236}U (Möller)



Green: Class I gs occupancy one unit higher
Red: Class II gs occupancy one unit higher
Blue: Class II gs occupancy two units higher

The hopscotch fission path for ^{236}U



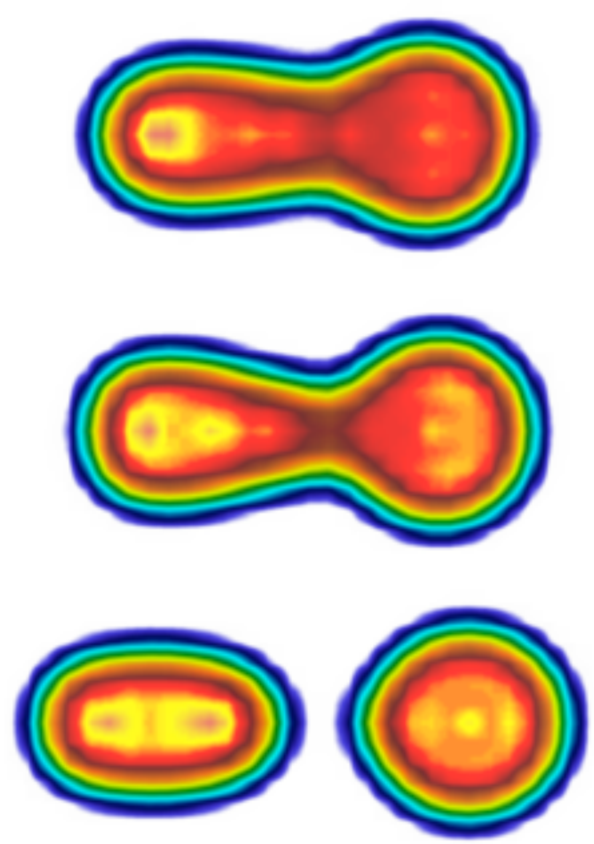
Wave functions calculated by the code HFBaxial. See
Rodriguez-Guzman and L.M. Robledo, PRC 89 054310 (2014).

A completely different approach to dynamics: time-dependent mean-field theory

PRL **116,** 122504 (2016) PHYSICAL REVIEW LETTERS week ending 25 MARCH 2016

Induced Fission of ^{240}Pu within a Real-Time Microscopic Framework

Aurel Bulgac,[1] Piotr Magierski,[1,2] Kenneth J. Roche,[1,3] and Ionel Stetcu[4]



Near-term goals

1. Code for partition-constrained DFT (Skyrme or Gogny)

2. Calculate $\rho(q, E)$

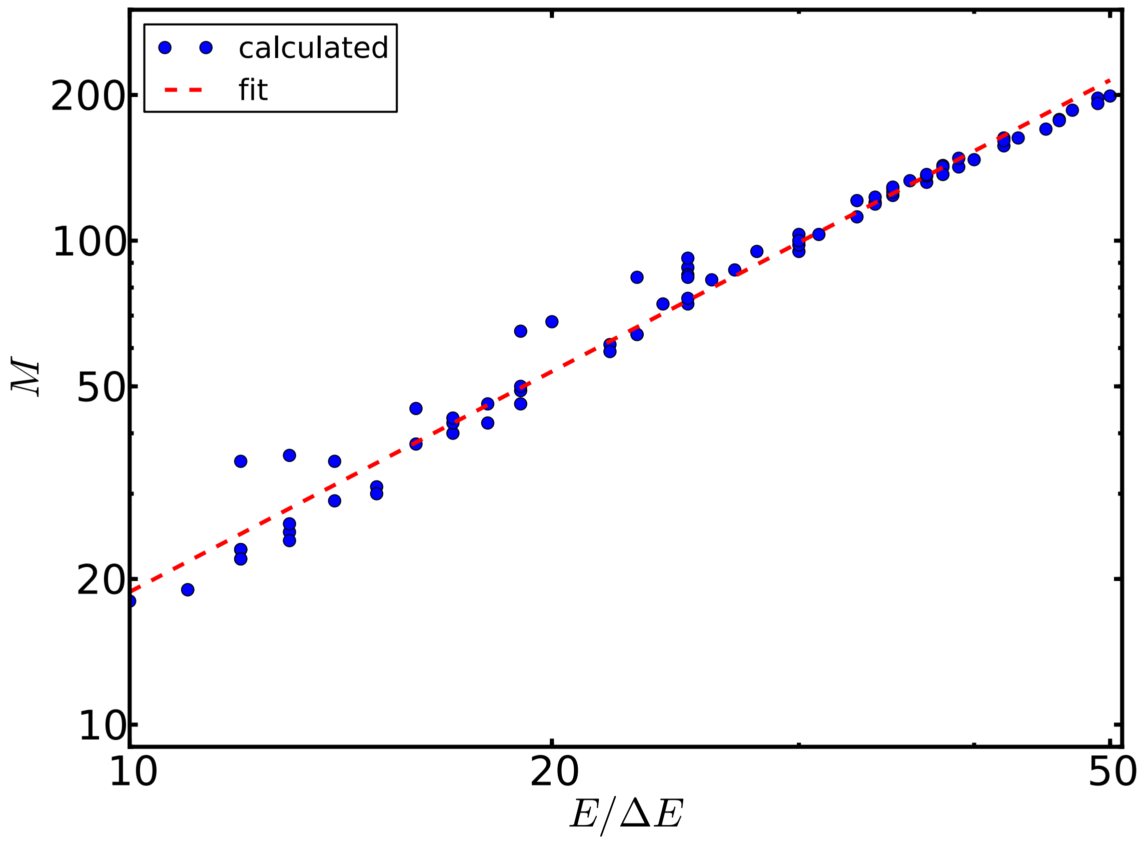
3. Estimate diffusion coefficient $D(q, E)$

The interaction between configurations

$$\langle \alpha | v | \beta \rangle = \langle pp | v | pp \rangle \det |\langle \phi_i^\alpha | \phi_j^\beta \rangle|$$

See A. Arima and S. Yoshida, Nucl. Phys 12 139 (1959).

A qualitative result: $\overline{\langle \alpha | v | \beta \rangle^2} \sim E^{3/2} / \rho(E)$ B.W. Bush et al., Phys. Rev C 45 1709 (1992).



Shows that the interaction becomes stronger with excitation and thus the dynamics approach the diffusive limit.