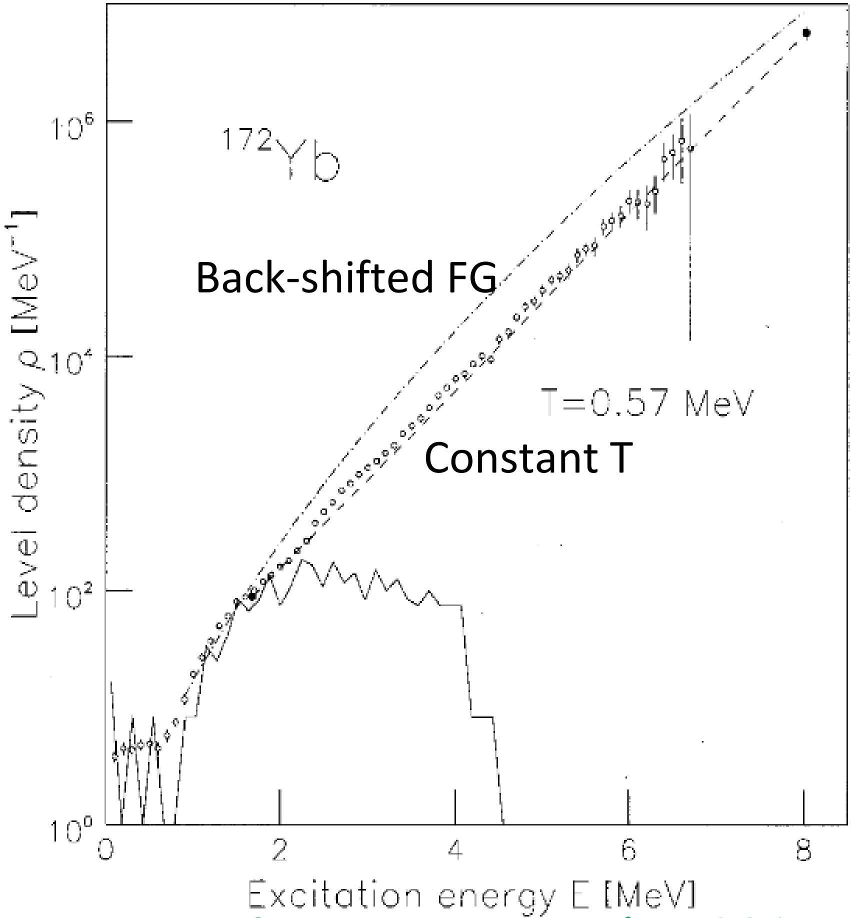
Excitation energy sorting in superfluid fission

K.-H. Schmidt and B. Jurado

CENBG, Bordeaux, France

(EFNUDAT short-term visit 2009/2010)

Constant temperature of nuclei



Guttormsen et al. 2001

Rather exact constant-temperature behaviour:

$$\rho(E^*) \propto \exp(E^*/T)$$

$$T = E^*/n_{eff} = cte.$$

Effect. Numb. of deg. of freedom

$$n_{eff} \propto E^*$$

(Melting of pairs)!

Constant temperature up to 20 MeV!!

(Voinov et al. PRC 79 (2009) 031301 (R))

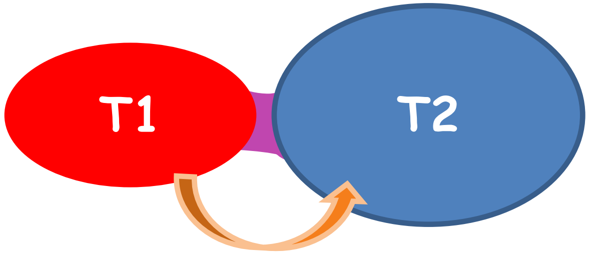
T is specific for every nucleus:

$$T = A^{-2/3} \cdot \left(17.45 - 0.51 \cdot S + 0.051 \cdot S^2\right)$$

***Empirical systematics by T. v Egidy et al. PRC* 72 (2005) 044311**

Two moderately excited nuclei in contact: Scission configuration

T1 > T2



E* flow

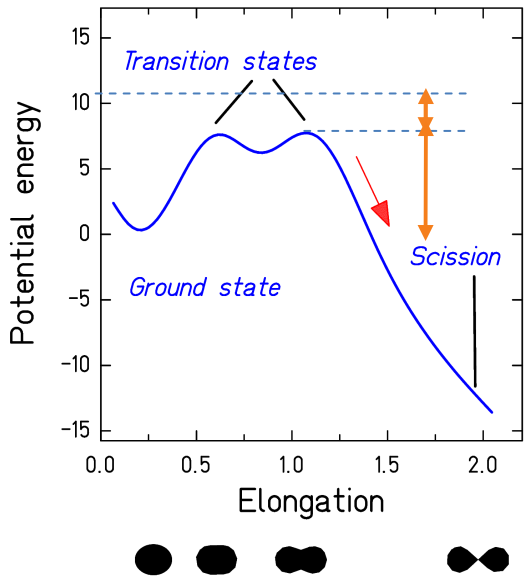
E* keeps flowing from the hot to the cold nucleus until the E* of the hot nucleus is completely exhausted!!!
-> Process of <u>excitation energy sorting</u>

<u>Unique!</u> All other objects in nature reach thermal equilibrium (T1=T2) before the hot object has exhausted all its heat

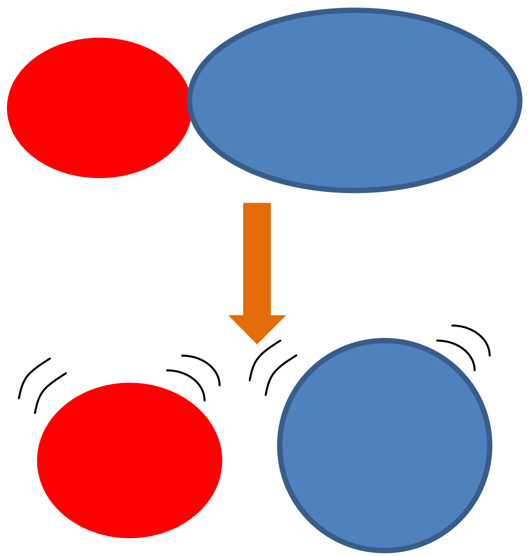
Neutron yields

E* in fiss. fragments

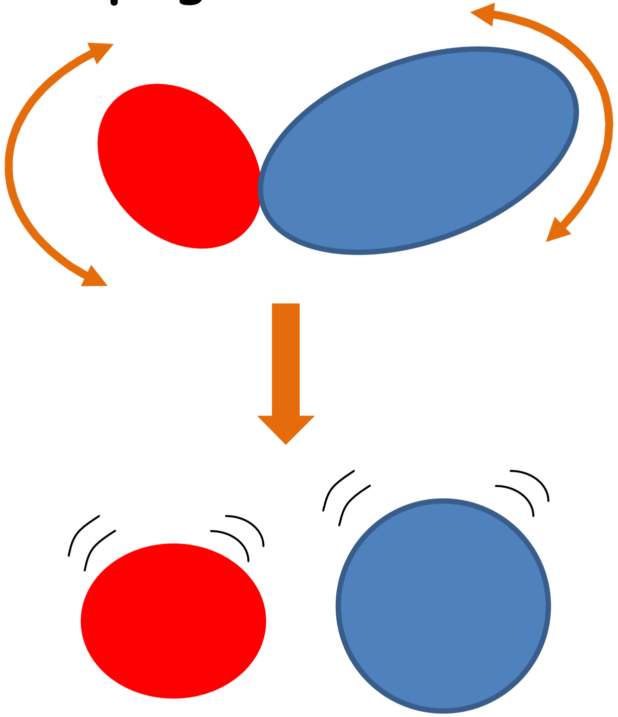
Intrinsic E*



Deformation energy

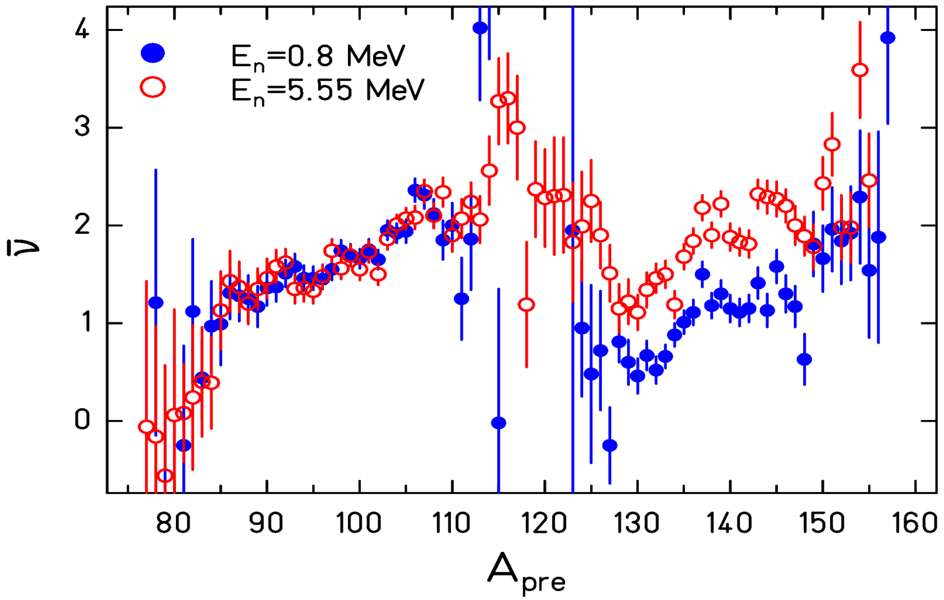


Damping of coll. modes



Neutron yields in fission: Signature of energy sorting

$^{237}Np(n,f)$



The additional energy of the neutron ends up in the heavy fragment only!!!

(Naqvi et al., PRC 34 (1986) 218)

Observation also found for ^{233}U, ^{238}U and proton-induced fission

Unexplained up to now because (Fermi-gas) level density not adapted to low E*!

Energy sorting and even-odd effect in fission

Finally, the system may eventually increase the excitation energy of the more excited nucleus by exchange of nucleons so that the fragment with zero excitation energy converts into a neighbouring **even-even nucleus** (energy gain up to 4 Δ)

↓

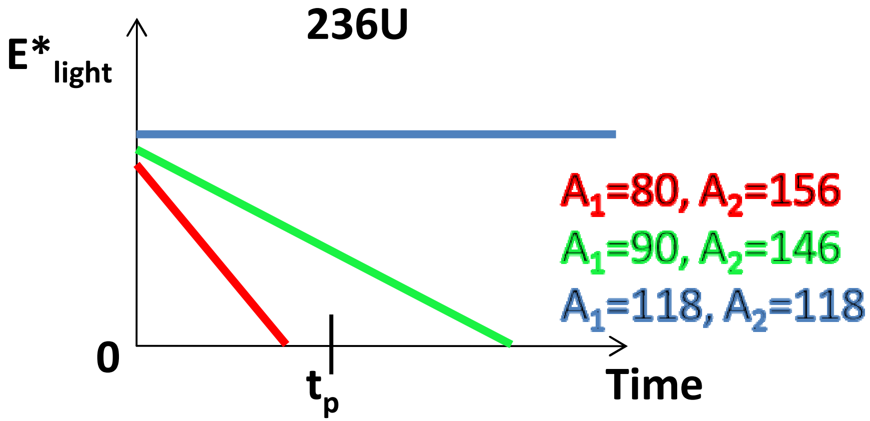
The "hotter" (generally lighter) fragment tends to be even-even!!!!!

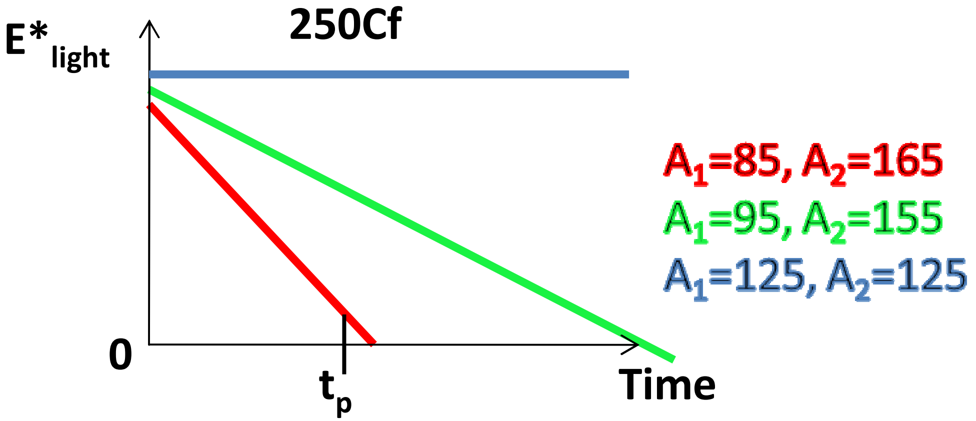
Energy sorting and even-odd (e-o) effect in fission

t→ time for E* transfer + time to transfer few protons to heavy fragment

Amount of E* to be transferred
$E^*_{light} \propto E^*_{total} = E^*_{fb} + E^*_{sad\text{-}sci}$

Temperature difference T1-T2





$t \sim E^*_{total}/(T1-T2)$ {
T1-T2 ↑ with mass asymmetry
E^*_{total} ↑ A of fiss. nucleus and beam energy

t_p→time at which the exchange of protons through the neck is very much hindered
If $t > t_p$, no even-odd effect is possible !!!

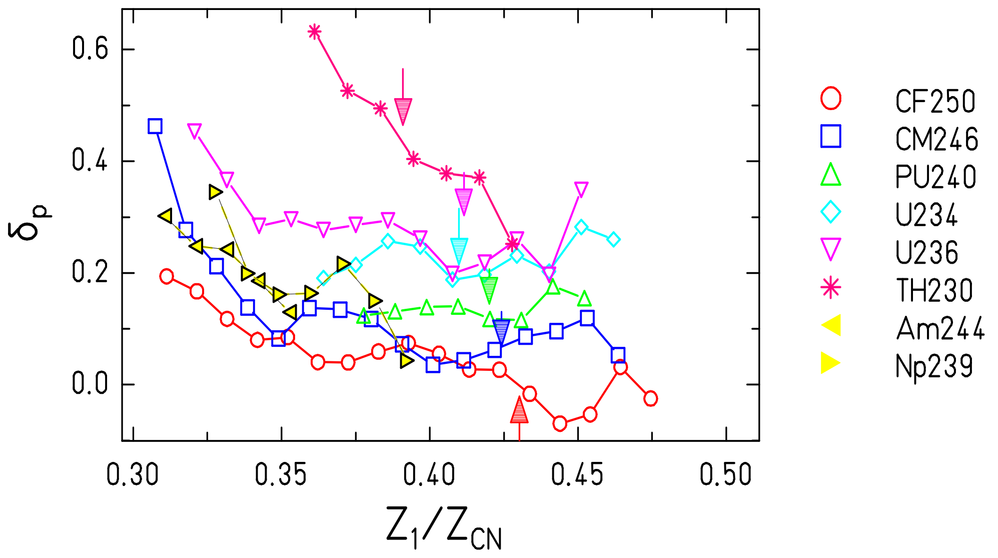
✓e-o effect sets in at a certain asymmetry {
which ↑ with A of fiss. nucleus
which ↑ with E* of fiss. nucleus

✓Equal description for even-Z and odd-Z fissioning nuclei

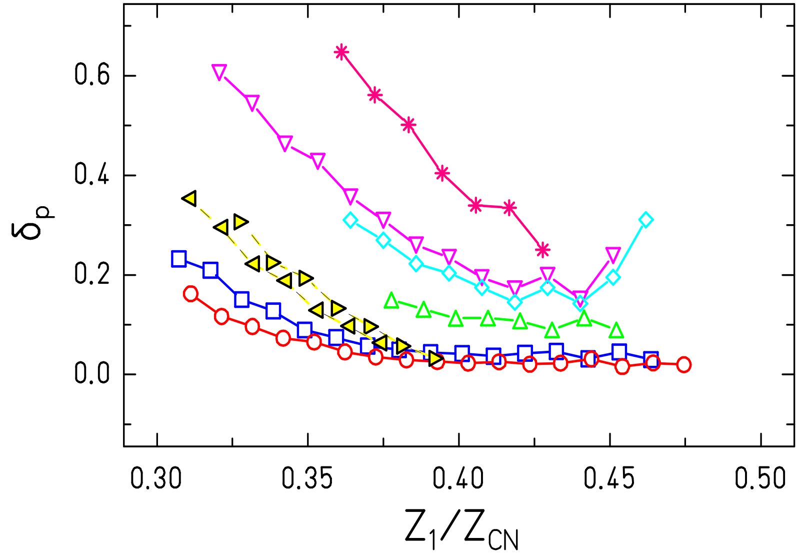
Comparison with experimental data

Experiment

Local even-odd effect



GEF calculation



(Thermal neutron-induced fission, Lohengrin)
Talk F. Rejmund

✓The e-o effect increases with asymmetry
✓The lighter the nucleus the smaller the threshold asymmetry
✓Similar behavior of even-Z and odd-Z fissioning nuclei
✓General trends nicely reproduced with GEF code (Talk K.-H. Schmidt)
✓No data to test variation of threshold asymmetry with E*

Conclusions

✓The scission configuration offers a unique opportunity to observe the behavior of two nuclei in the superfluid regime set in contact:
The hot fragment transfers all its E* to the cold one → **Excitation energy sorting!!!**

✓Energy sorting → **Clearly reflected by number of prompt neutrons vs. A**
An increase of E* translates into an increase of υ for the heavy fragment only .
This observation remained unexplained up to now!!!

✓Energy sorting **explains the dependence of the e-o effect with asymmetry and with the A of the fiss. nucleus**:
e-o effect sets in at a threshold asymmetry that ↑ with A and E* of fiss. nucleus

✓**Need for more experimental data** on prompt neutrons and e-o effect

More information:

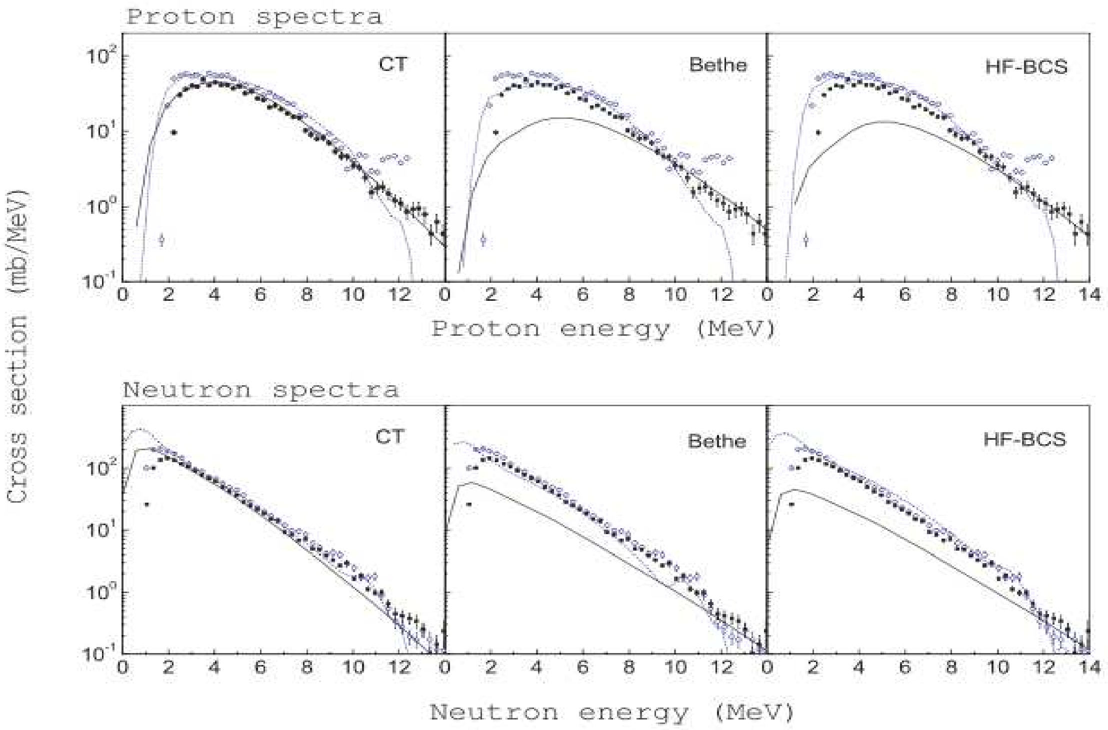
K.-H. Schmidt and B. Jurado accepted for publication in Phys. Rev. Lett.
GEF web site (www.cenbg.in2p3.fr/GEF) (Talk K.-H. Schmidt)

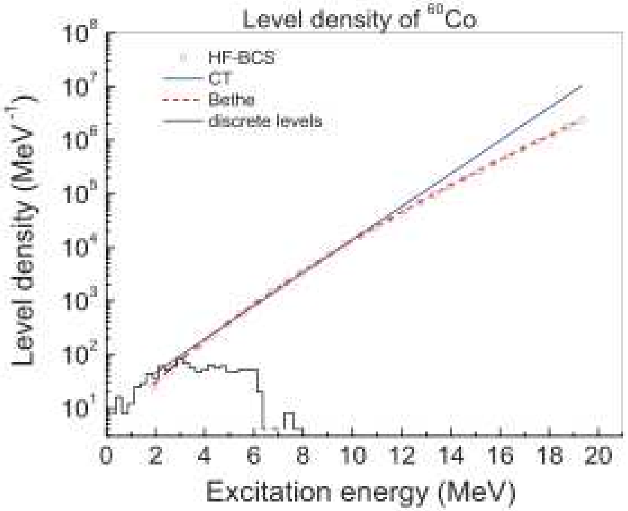
PHYSICAL REVIEW C **79**, 031301(R) (2009)

Nuclear excitations at constant temperature

A. V. Voinov,[1,*] B. M. Oginni,[1] S. M. Grimes,[1] C. R. Brune,[1] M. Guttormsen,[2] A. C. Larsen,[2]
T. N. Massey,[1] A. Schiller,[1] and S. Siem[2]
[1]*Department of Physics and Astronomy, Ohio University, Athens, Ohio 45701, USA*
[2]*Department of Physics, University of Oslo, N-0316 Oslo, Norway*

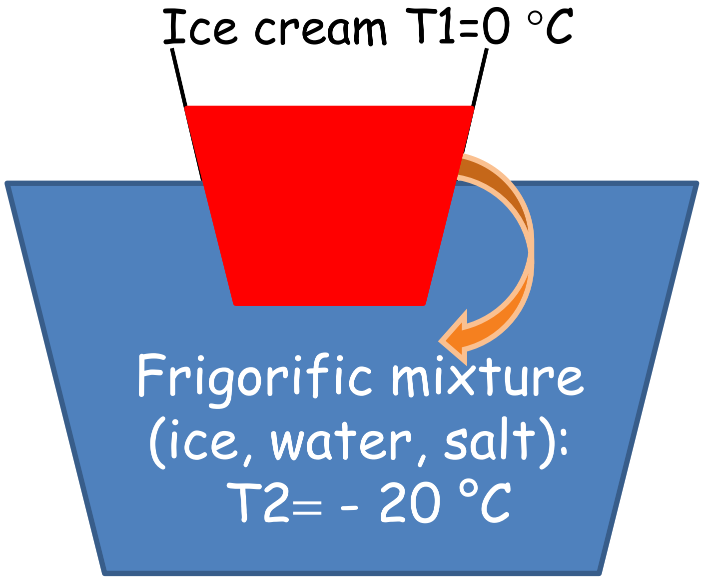
(Received 2 July 2008; revised manuscript received 1 December 2008; published 5 March 2009)





Evidence for constant-temperature behaviour up to *E**=20 MeV.

Technical analogon:
The classical ice machine



When ice cream has become ice → T1 is not cte. and T1=T2 before T1≈ 0°!

Energy sorting in fission:
General phenomenon without a convincing explanation.

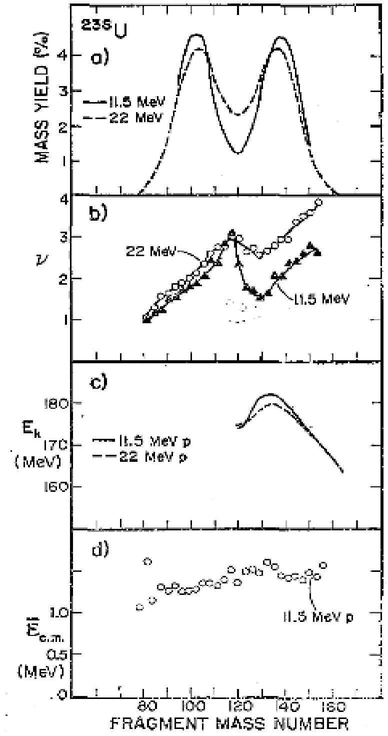


Fig. 3. The fission mass yield (a) neutron yield (b) total fragment kinetic energy (c) and average neutron c.m. energy (d) are illustrated as a function of the initial fragment mass for proton-induced fission of ^{238}U.

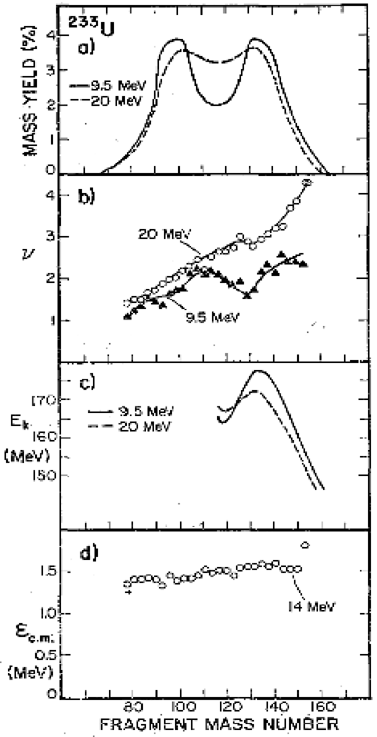


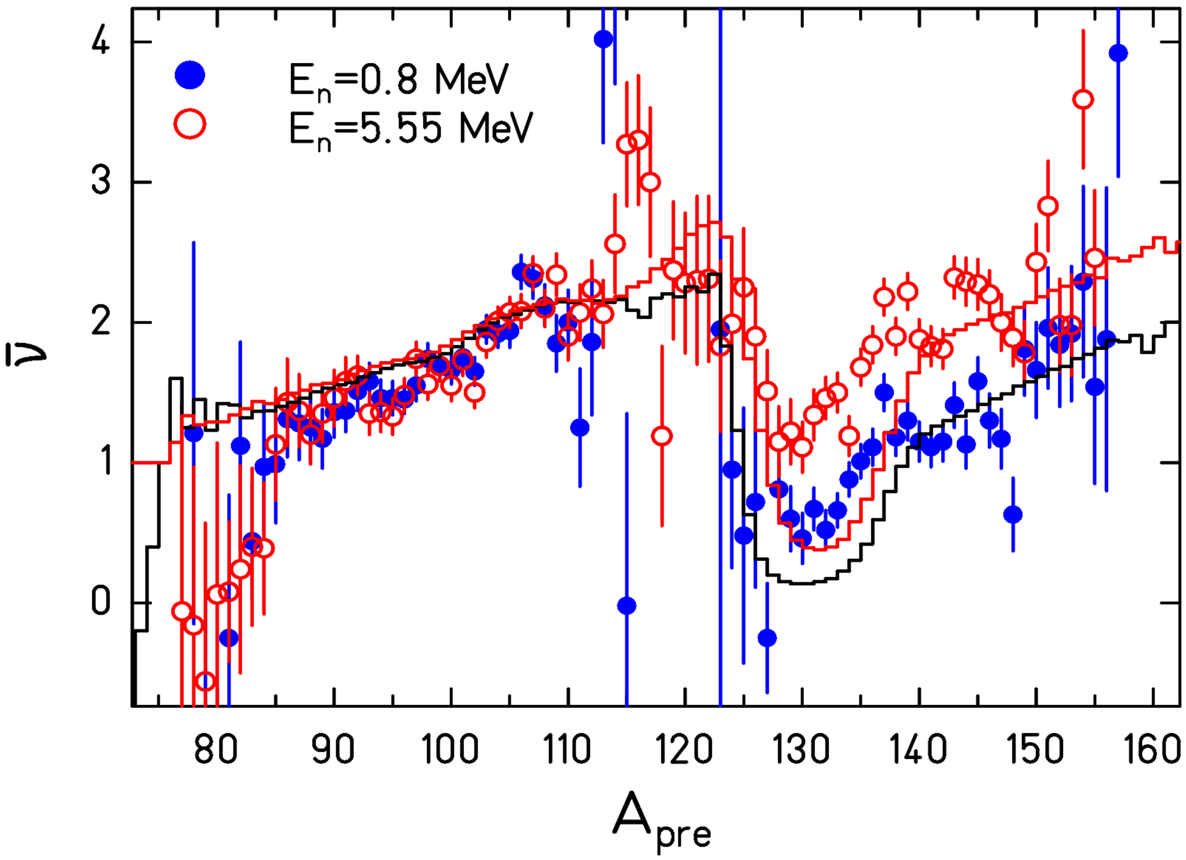
Fig. 4. The fission mass yield (a) neutron yield (b) total fragment kinetic energy (c) and average neutron c.m. energy (d) are illustrated as a function of the initial fragment mass for proton-induced fission of ^{233}U.

(From Bishop et al., 1970)

They used the wrong level density

Is this Maxwell's demon on the nuclear level?

GEF Calculation



Contributions to neutron yields

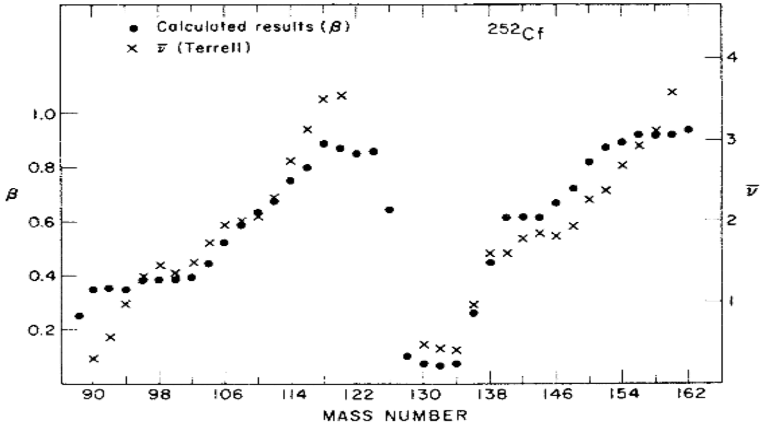
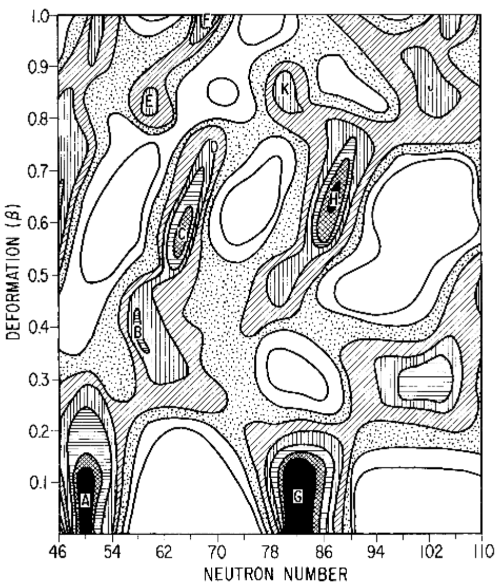


FIG. 9. The average deformation β of the fragments (symbol ●) calculated for the fissioning system ^{252}Cf compared with the results of Terrell (Ref. 32) for $\bar{\nu}(A)$ in ^{252}Cf(sf) (symbol ×).

B. D. WILKINS, E. P. STEINBERG, AND R. R. CHASMAN



Sawtooth shape reflects deformation at scission due to shell effects. (Wilkins et al. 1976)

Variation of E*initial : TKE = const.
-> Contribution of deformation to neutron yield stays constant!

Energy removed by gamma emission is small and stays constant.
-> We may neglect it.

Other contributions to neutron yields:

- Collective excitations (normal modes)
- Intrinsic excitations

Nuclear level density: Independent-particle model (approximative)

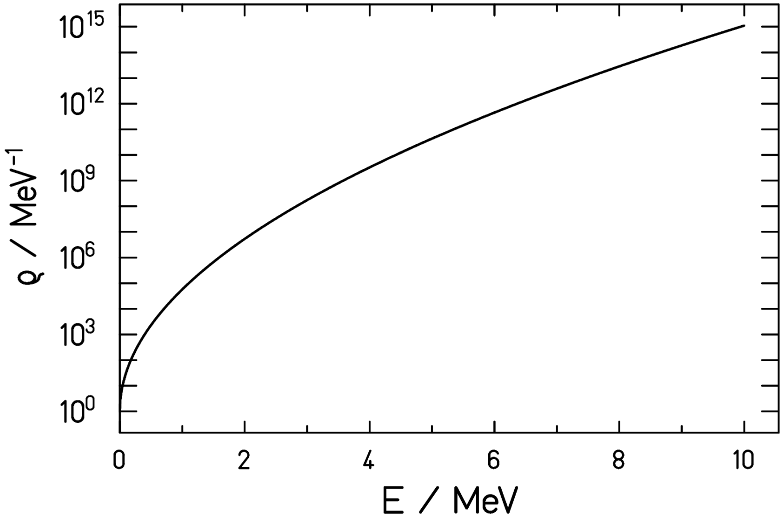
Combinatorics of different particle-hole configurations

numerical (e.g. Hilaire et al.)

analytical (Bethe, "Fermi gas", better “equidistant model”)

$$\rho \propto \exp\left(2\sqrt{(aE)}\right)$$

$$T = \left(d\,\frac{(ln\rho)}{dE} \right)^{-1}$$



$E = a\,T^2$

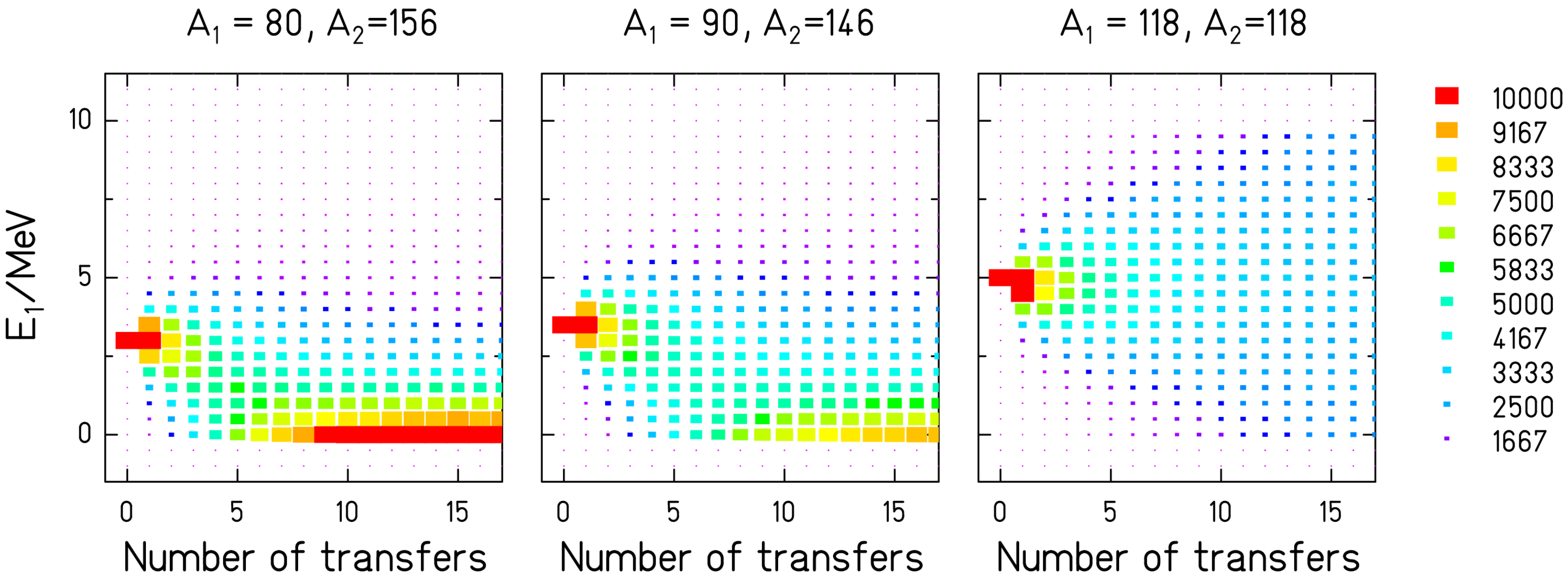
$a = A/10$

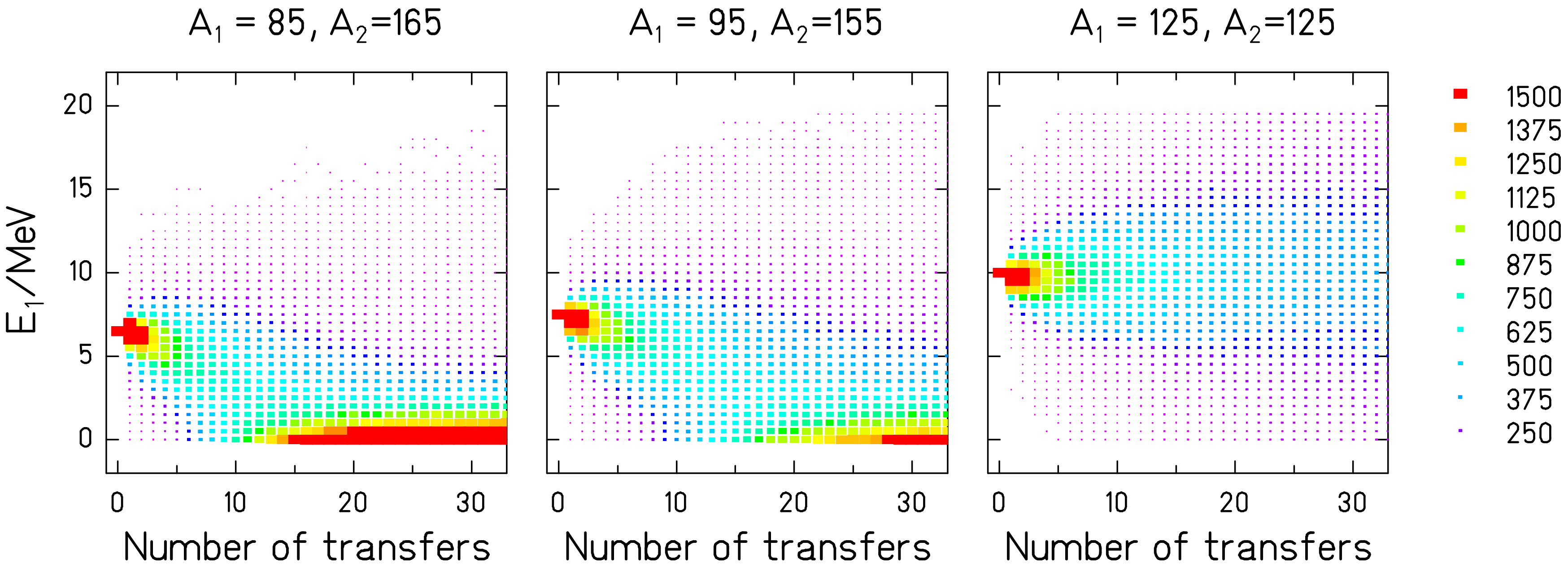
$E = T^2\,A/10$

This leads to:

$E_1/E_2 = A_1/A_2$

Generally used!


A1 = 80, A2=156
A1 = 90, A2=146
A1 = 118, A2=118
E1/MeV
10
5
0
0
5
10
15
Number of transfers
10000
9167
8333
7500
6667
5833
5000
4167
3333
2500
1667


A1 = 85, A2=165
A1 = 95, A2=155
A1 = 125, A2=125
E1/MeV
20
15
10
5
0
0
10
20
30
Number of transfers
1500
1375
1250
1125
1000
875
750
625
500
375
250

Division of E^*_{intr} at scission: Assumption of thermal equilibrium

Assumption:
Collective motion in fission direction is slow enough that thermal equilibrium of intrinsic excitations is maintained until scission.

Individual properties of fragments establish well before scission:
Shell effects (Maruhn, Mosel, Greiner)
Congruence energy (Myers, Swiatecki)
Pairing strength (Myers, Swiatecki)

Partition of energy governed by level density

$$T_1 = T_2$$

$$\beta = 1/T = \mathrm{d}(\ln\rho)/\mathrm{d}E^*$$

Thermodynamical interpretation

Fundamental meaning of *T*:

🗐 ❍ean energy per (effective) degree of freedom

Ideal gas: T 🗐 E

Constant number of degrees of freedom: n = const.

(Translational degrees of freedom of point-like mass objects.)

Fermi gas: T 🗐 sqrt(E)

Number of degrees of freedom n_{eff} 🗐 sqrt(E).

(Great part of nucleons are frozen by Pauli blocking.)

Constant temperature: T = const.

Number of degrees of freedom n_{eff} 🗐 E

(Energy is used for melting pairs.)

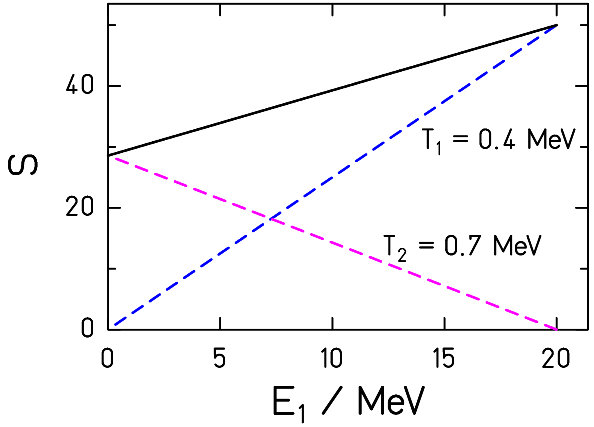
Entropy considerations

♎💧📫♎▱ ♓⬧ [illegible]
♍□●●♏♍⧫♓❖♏ ♎♓⬧⬧♓□♋⧫♓❖♏ ❍□⧫♓□■📬
☎☝♏■♏❒♋● ♐♏♋⧫◆❒♏ □♐ ☹♋■♑♏❖♓■
♏❑◆♋⧫♓□■⬧📬✆

💧📂 🖫 ☜📂🖂📪❄📂 💧🗏 🖫 ☜🗏🖂📪
☜🗏🖂 🖫 ☜🖂⧫□⧫

♎☎💧📂 🖃 💧🗏✆ 📪 ♎☜📂 ♓⬧ ♏
⌘♏❒□📫

☜■♏❒♑⍓ ⬧□❒⧫♓■♑ ♓⬧ ♏■⧫❒□◻



✋⧫ ♓⬧ ❍□❒♏ ♏♐♐♓♍♓♏■⧫ ☎♓■ ⧫♏❒❍⬧ □♐
♏■⧫❒□◻⍓✆ ⧫□ ♓■❖♏⬧⧫ ♋●● ♏■♏❒♑⍓ ♓■
⧫♒♏ ♍□●♎♏❒ ☎♒♏♋❖♓♏❒✆ ♐❒♋♑❍♏■⧫
⧫♒♋■ ⧫□ ⬧♒♋❒♏ ♋■⍓ ◻□❒⧫♓□■ □♐
♏■♏❒♑⍓ ⬥♓⧫♒ ⧫♒♏ ♒□⧫⧫♏❒ ☎●♓♑♒⧫♏❒✆
♐❒♋♑❍♏■⧫📬

Hindrance for proton exchange through the neck

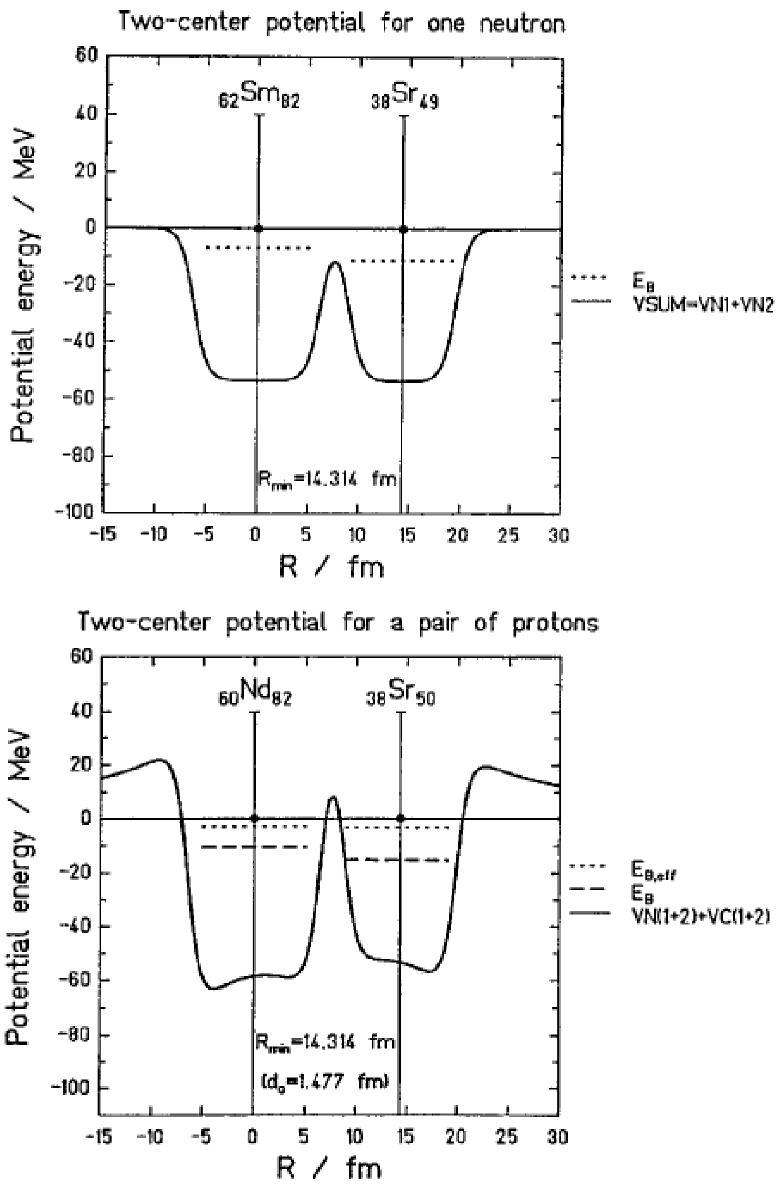


Figure 16. Two-centre wells for neutrons and protons for the system ^{88}Sr + ^{144}Sm for the same internuclear distances (given by d_0 values) corresponding to different heights of the internal barrier. The binding energies (and E_{eff} for the protons) are indicated.

Zu Deiner Frage, wie der Asymmetrie-assoziierte Gerade-Ungerade-Effekt in GEF ausgerechnet wird: Bei gerade-Z spaltenden Kernen gibt es zunächst einmal einen Gerade-Ungerade-Effekt, der konstant ist über den ganzen Z-Bereich.

Der restliche Bereich (bis zu 100%) wird mit einem skalierten Gauß-Integral parametrisiert.

Sie setzt sich auf dem allgemeinen Gerade-Ungerade-Effekt auf und wächst bis 100%.

(Die Error-Funktion ist eine etwas andere Funktion, die von dem Gauß-Integral abgeleitet ist.)

Der Schwellenwert (der Wert, an dem das Gauß-Integral den Wert 1/2 hat) ist gegeben durch die Bedingung, dass die Energie-Sortierungs-Zeit (proportional zu E*/(T2-T1)) gleich dem "dynamischen Zeitfenster" ist. Dieses dynamische Zeitfenster ist durch die kollektive Spaltdynamik gegeben.

Sie beginnt, wenn die beiden Kerne ihre individuellen Temperaturen ausbilden und sie endet, wenn der Widerstand für Protonentransport durch den Hals zu groß wird. Der Wert ist für alle der gleiche. Er ist an die Daten angepasst. Die Breite des Gaußintegrals wächst proportional zu |T2-T1|. (Ich hatte mir überlegt, dass diese Proportionalität physikalisch sinnvoll ist. Es ist einfach eine Skalierung.) Der Proportionalitätsfaktor ist wieder an die Daten angepasst.