Synthesis of super-heavy-elements: what can we predict?

David BOILLEY,
Hongliang LÜ (吕宏亮) and Barthołomé CAUCHOIS
GANIL and Normandie Université

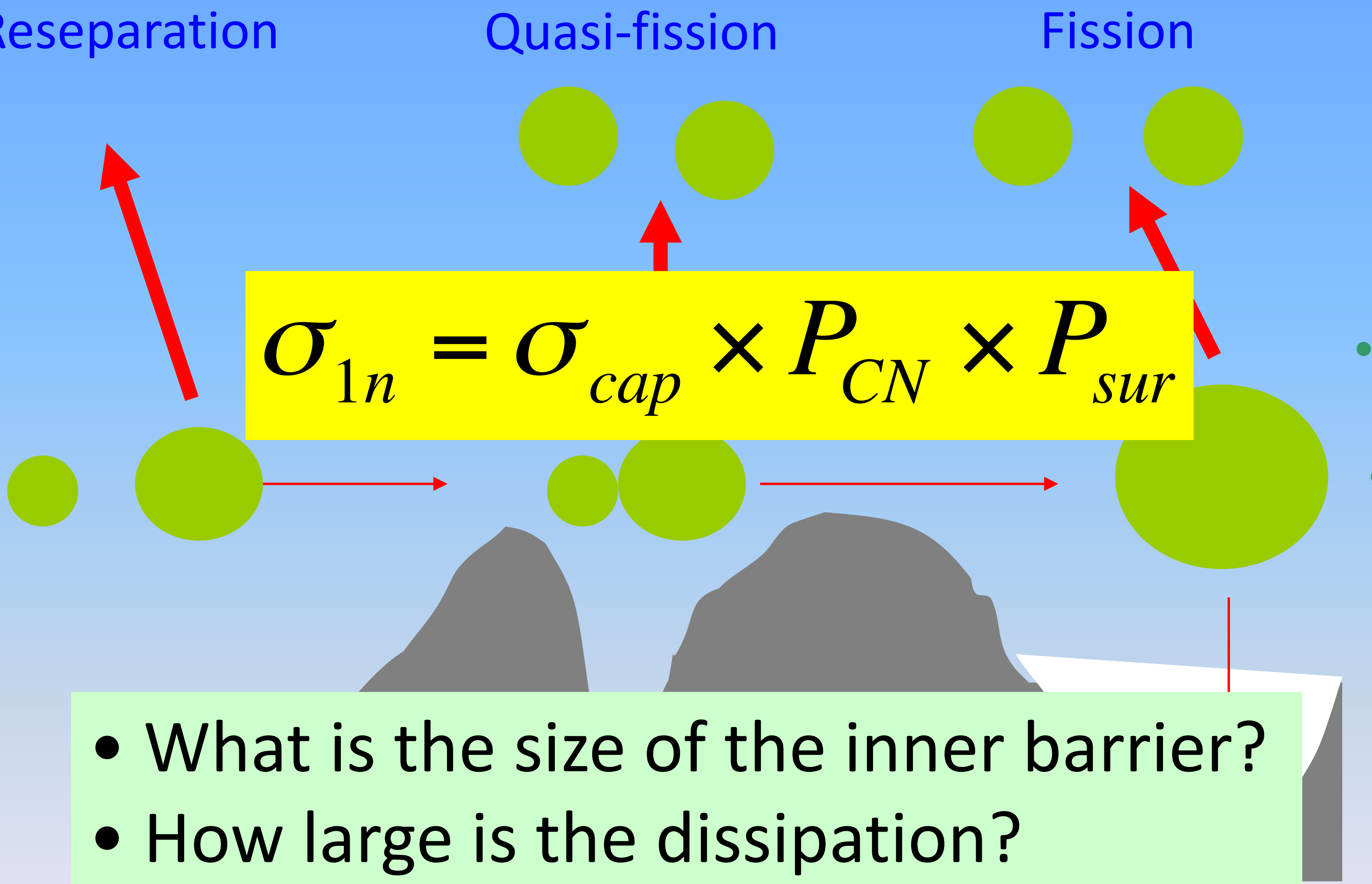
Yasuhisa ABE (阿部恭久)
RCNP, Osaka
(大阪大学核物理研究センター)

Caiwan SHEN (沈彩万)
Huzhou University
(湖州师范学院)

Anthony MARCHIX
CEA/DRF/IRFU Saclay

Guy Royer
Subatech and Univ. De Nantes

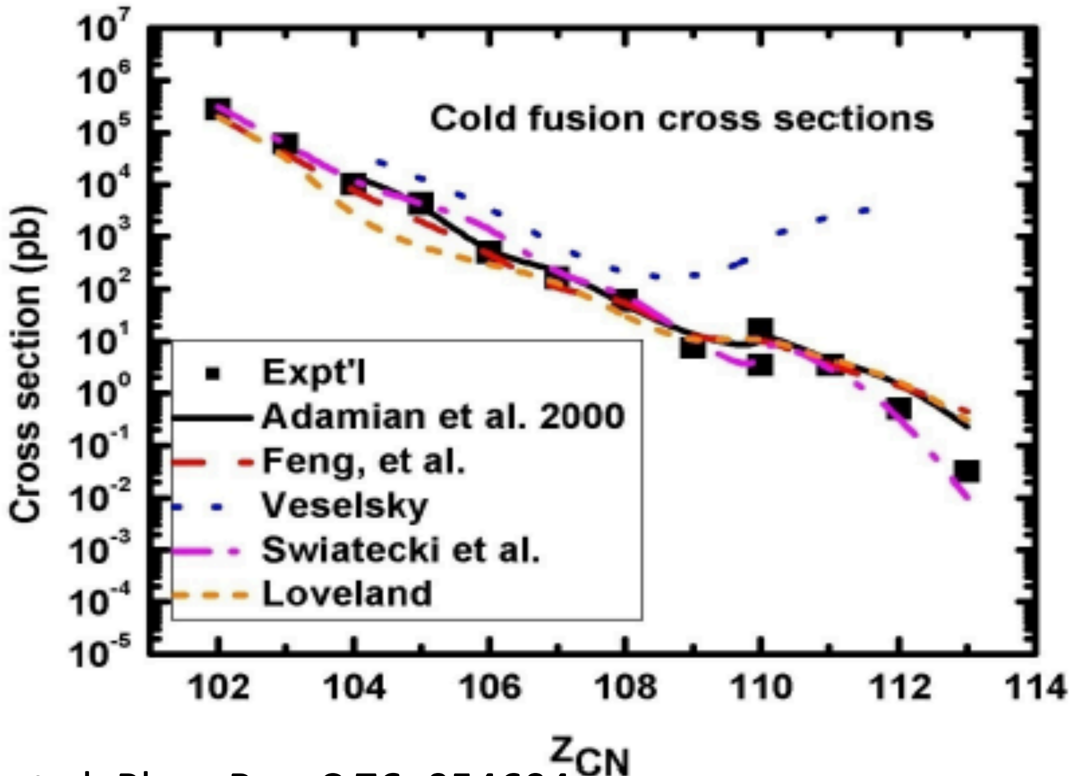
Hindered fusion reaction



$$\sigma_{1n} = \sigma_{cap} \times P_{CN} \times P_{sur}$$

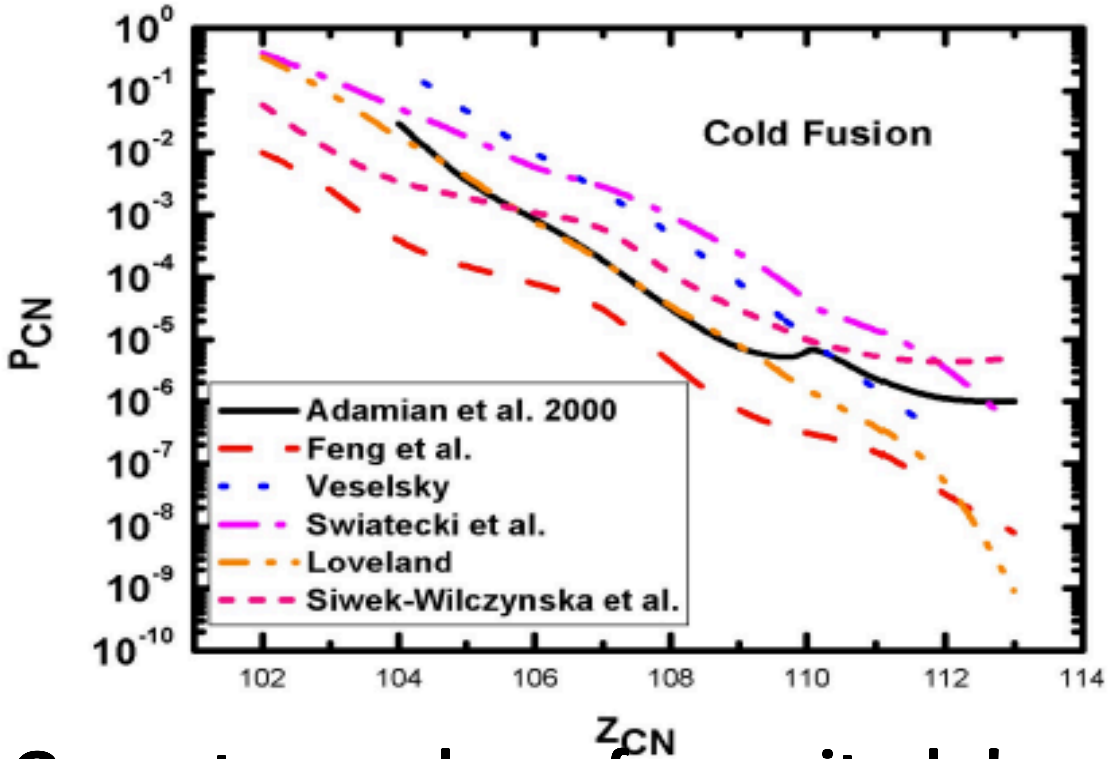
- What is the size of the inner barrier?
- How large is the dissipation?
- Correct dynamical description?
- *No reliable data*

Let's look at this more carefully



Naik, Loveland et al, Phys. Rev. C **76**, 054604

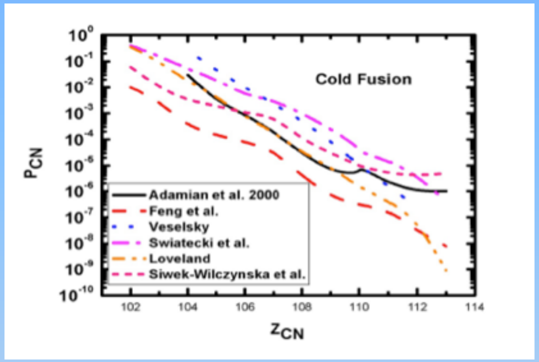
Despite correctly predicting σ_{EVR} correctly, the values of P_{CN} (and W_{sur})differ significantly



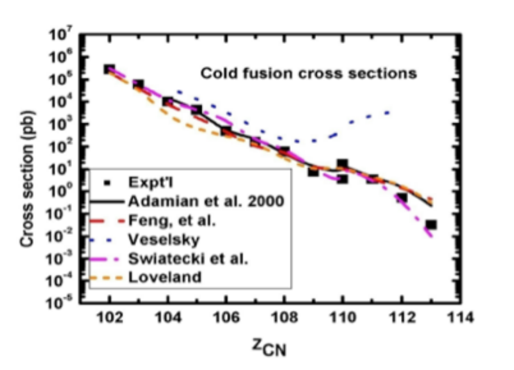
One – two orders of magnitude!

What's the problem?

σ_{Cap} x



x P_{sur}=



The best known part has the same discrepancies as the less known part!

What's the problem?

- The best known part has the same discrepancies as the less known part!
- Is it due to uncertainties?

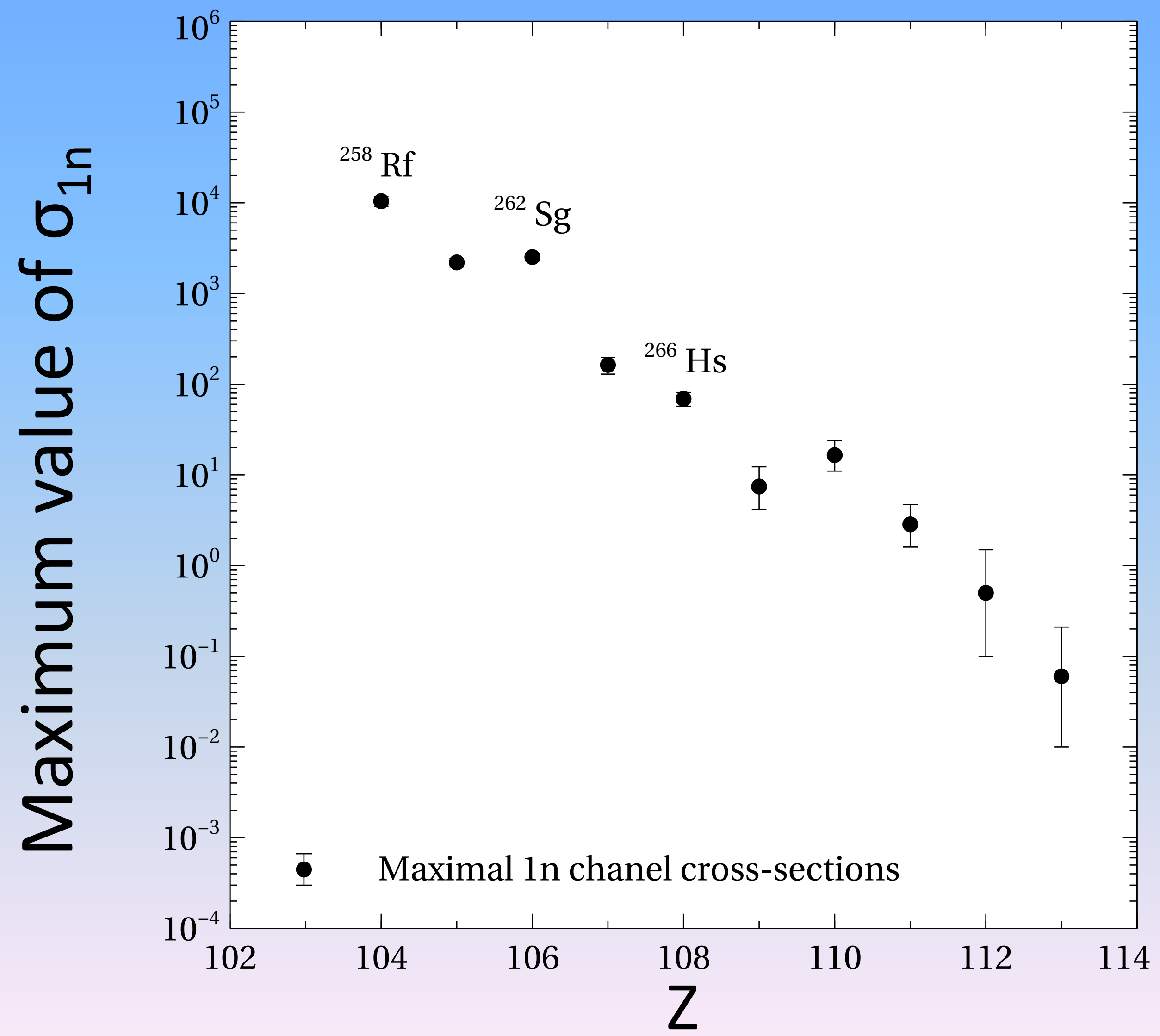
$$\sigma_{1n} = \sigma_{cap} \times P_{CN} \times P_{sur}$$

$$P_{CN} = \frac{\sigma_{1n}}{\sigma_{cap} \times P_{sur}}$$

Experiments

Models

Experimental uncertainties



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KEWPIE2: A cascade code for the study of dynamical decay of excited nuclei☆

Ho

JCGM 100:2008

GUM 1995 with minor corrections

Evaluation of measurement data — Guide to the expression of uncertainty in measurement

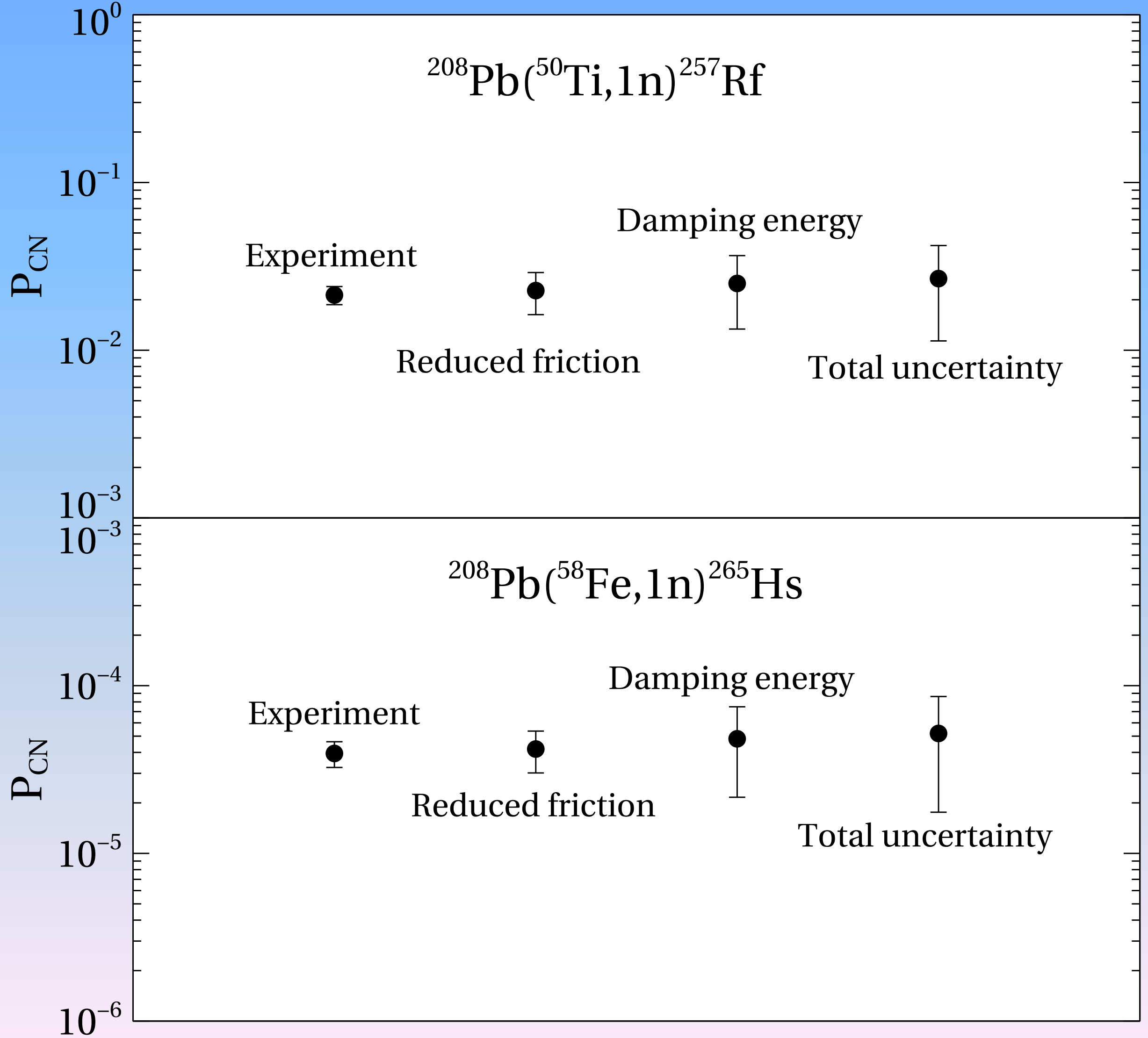
Évaluation des données de mesure — Guide pour l'expression de l'incertitude de mesure

Survival probability

$$P_{sur} = \frac{\Gamma_n}{\Gamma_n + \Gamma_f}$$

- **B_f < B_n => Fission dominates**:
  - Parameters entering the fission width have a great influence
  - Fission barrier is most sensitive parameter
  - Nuisance parameters:
    - Damping energy: $11 < Ed < 19 \text{ MeV}$
    - Friction coefficient: $1 < \beta < 5 \text{ zs}^{-1}$

Nuisance parameters



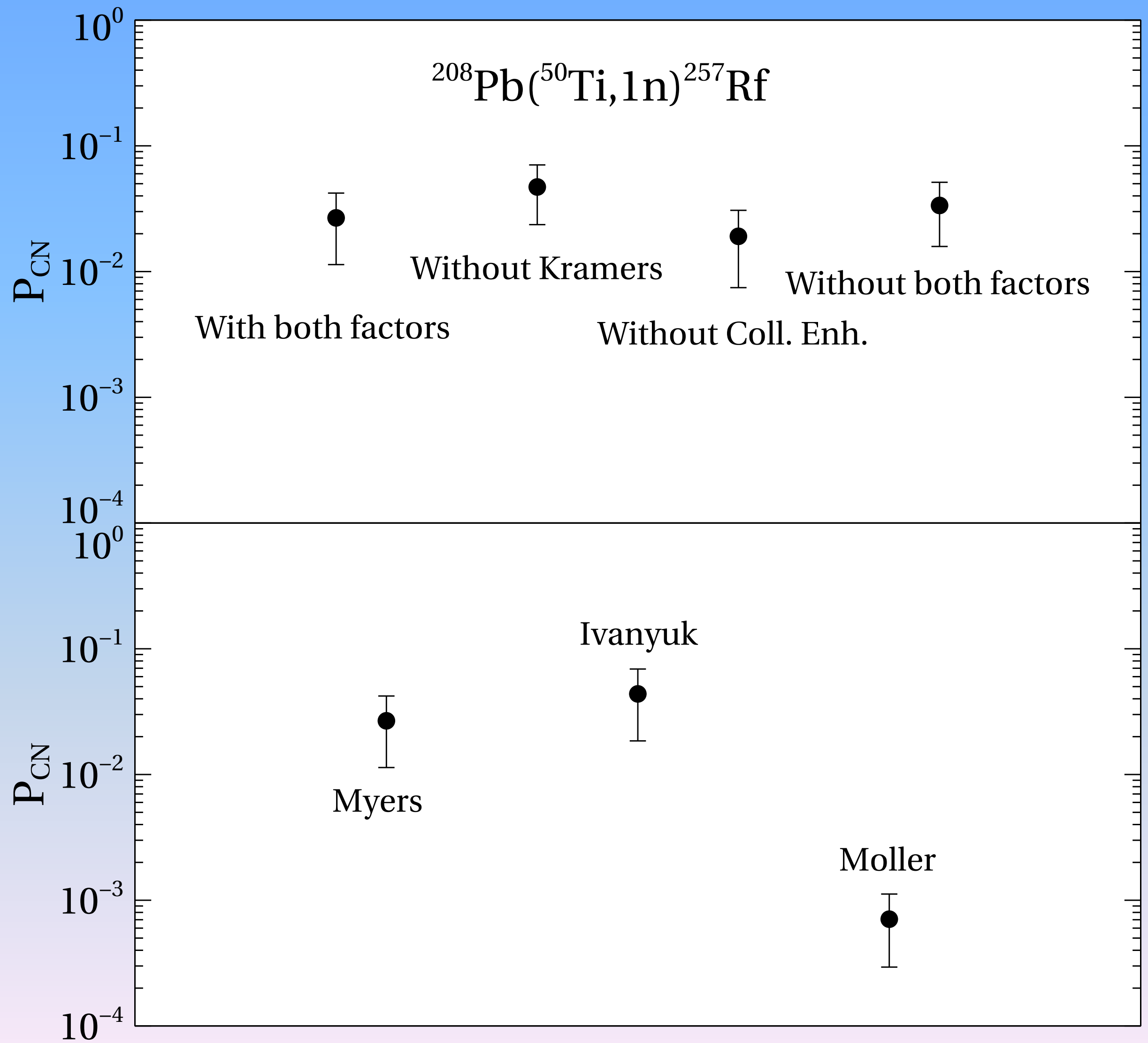
Fission barriers

- In the past:

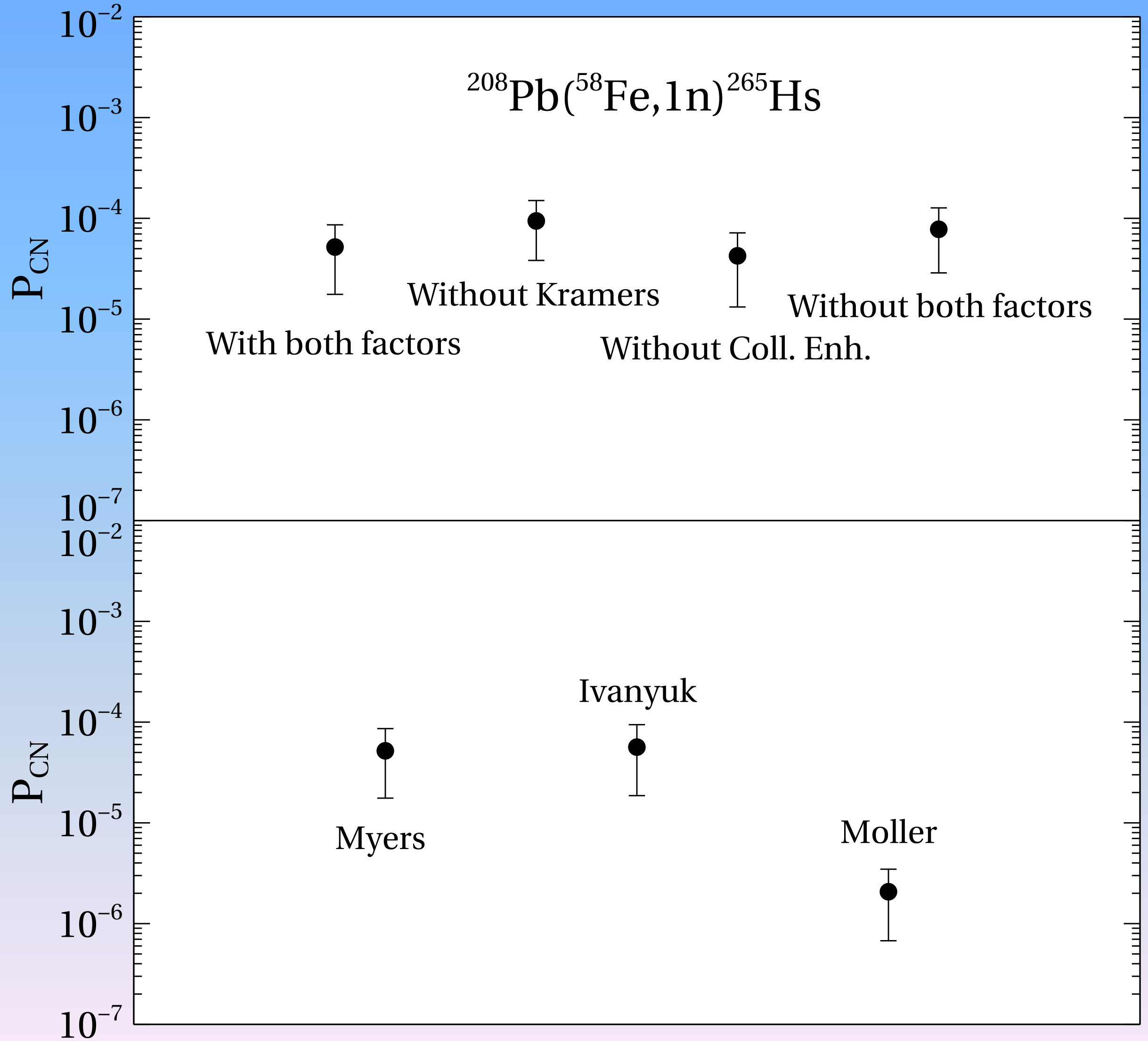
$$Bf \approx B_{LDM} - \Delta E_{shell}$$

- Nowadays:
  - Tables: Moller et al, M. Kowal et al…

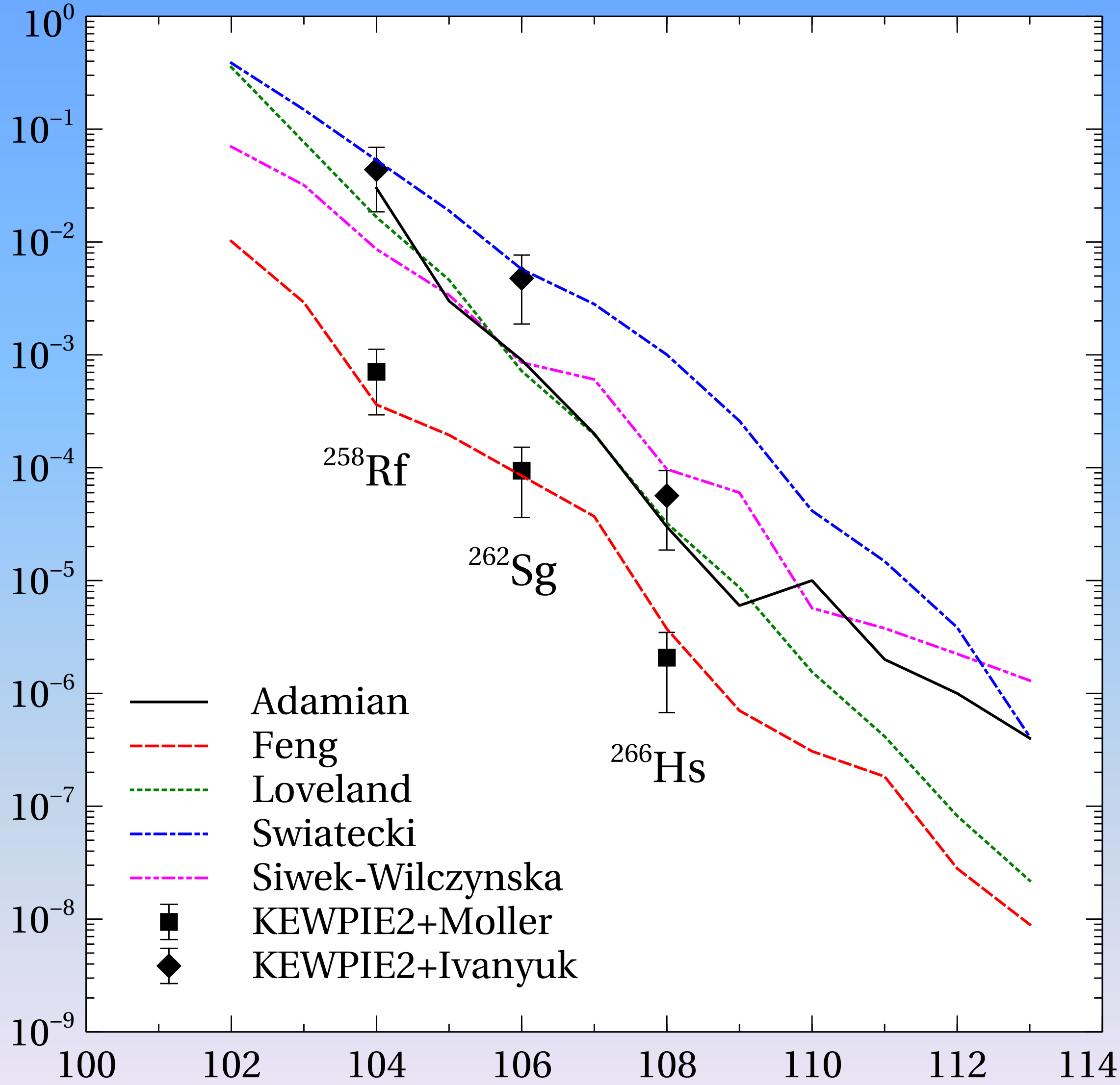
Various models



Various models (2)



Summary



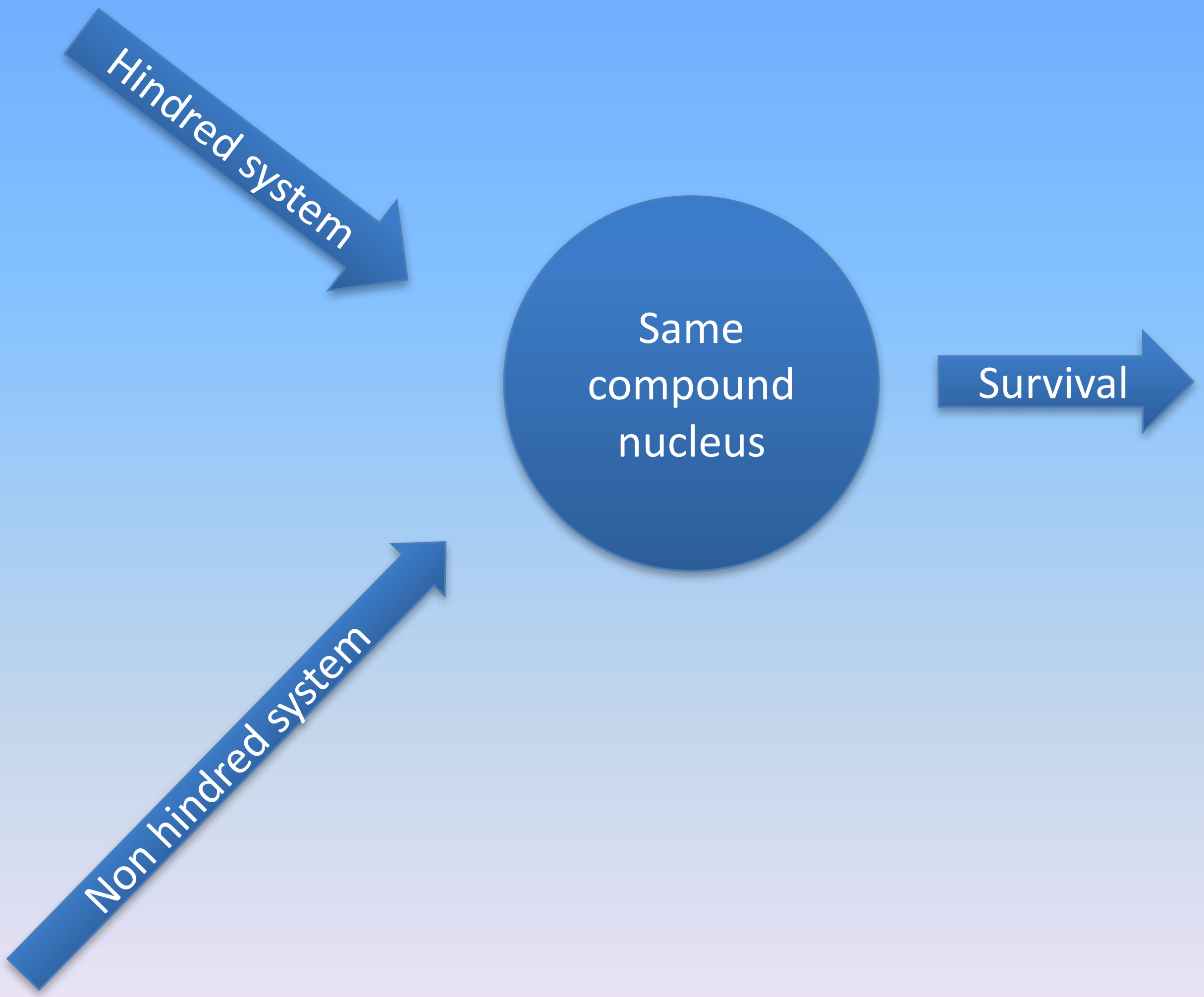
Lü et al, PRC94 (2016) 034616

Partial conclusions

- Fusion hindrance and fission barriers are both unknown

- Can we assess them separately?

Need for specific experimental programme:



And fission barriers?

- Fusion hindrance and fission barrier dominate
- Fission barriers are difficult to calculate and to measure
- Focus on ΔE_{shell}

Experimental masses

$$^{291}_{116}\mathrm{Lv} \rightarrow {}^{287}_{114}\mathrm{Fl} \rightarrow {}^{283}_{112}\mathrm{Cn} \rightarrow \ldots \rightarrow {}^{267}_{104}\mathrm{Rf}$$

- Can be obtained from Q_α

Nuclei	Q_α	Δm^{Exp}
$^{267}_{104}$		
$^{271}_{106}$		
$^{275}_{108}$		
$^{279}_{110}$		
$^{283}_{112}$		
$^{287}_{114}$		
$^{291}_{116}$		

Table 2. Experimental mass excess correlation matrix

1.00	0.99	0.99	0.98	0.97	0.97	0.96
0.99	1.00	0.99	0.99	0.98	0.98	0.97
0.99	0.99	1.00	0.99	0.99	0.98	0.98
0.98	0.99	0.99	1.00	0.99	0.99	0.98
0.97	0.98	0.99	0.99	1.00	0.99	0.99
0.97	0.98	0.98	0.99	0.99	1.00	0.99
0.96	0.97	0.98	0.98	0.99	0.99	1.00

Mass fit and uncertainties

- We fit: $$M_{\exp} - \Delta E_{shell}$$

-> LDM coefficients are obtained by simple linear regression

-> Uncertainty evaluation assumes that errors are Gaussian

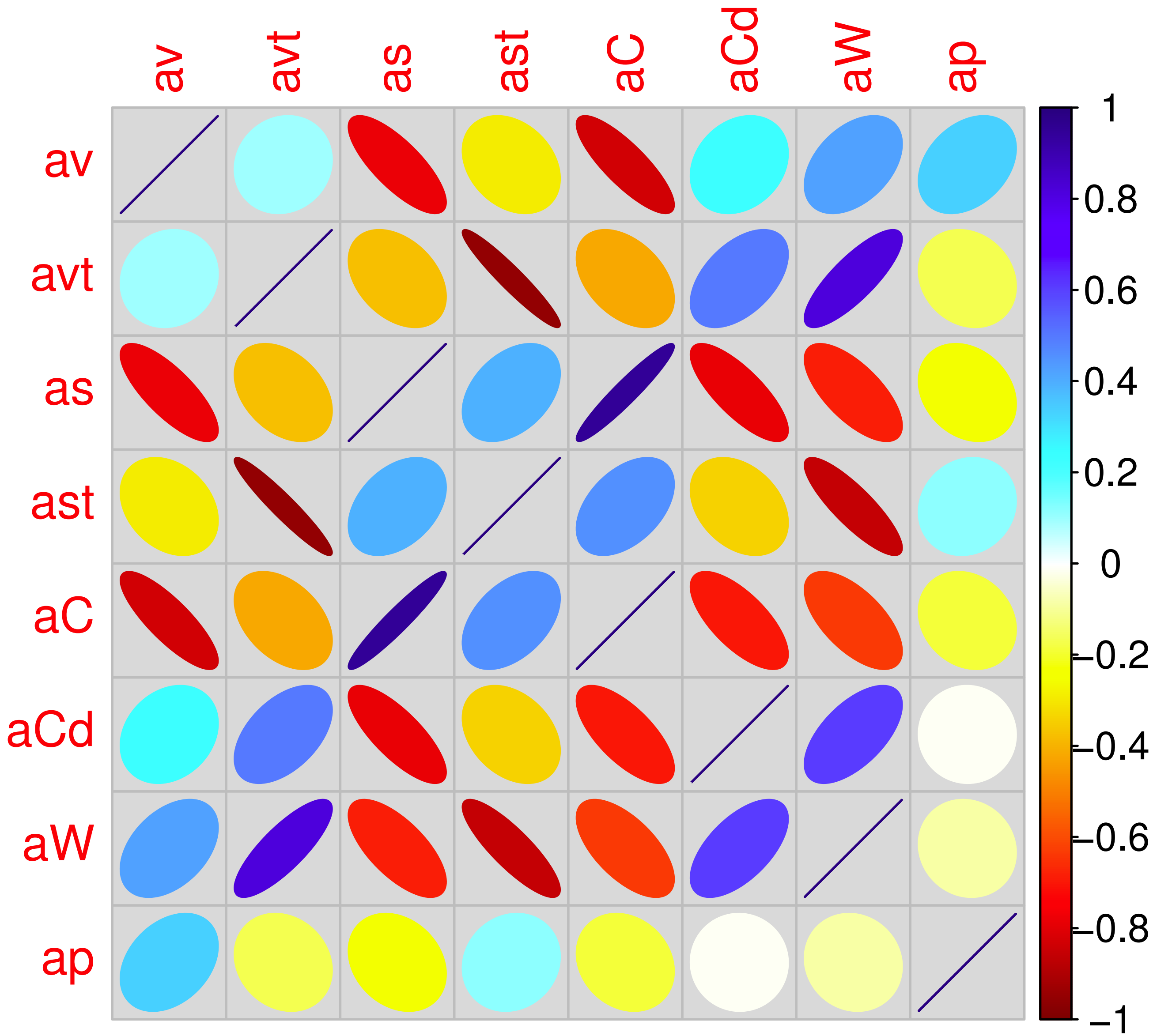
$$LDM = (M_{\exp} - \Delta E_{shell}) + e$$

$$B_n(A,Z) = \left(a_v A + a_{vt}\left(\frac{A-2Z}{A}\right)^2\right)A + \left(a_s + a_{st}\left(\frac{A-2Z}{A}\right)^2\right)A^{2/3}$$
$$+ a_C\frac{Z^2}{A^{1/3}} + a_{Cd}\frac{Z^2}{A} + a_W\frac{|A-2Z|}{A} + a_p\frac{\delta_{np}(A,Z)}{A^{1/3}}$$

G. Royer, NPA917 (2013) 1

	Estimate	Std. Error
a_v	15.63700	0.02364
a_{vt}	-29.53200	0.26727
a_s	-18.55500	0.12740
a_{st}	46.97700	1.67080
a_C	-0.71636	0.00211
a_{Cd}	1.40110	0.09989
a_W	-42.77700	3.56280
a_p	6.92040	0.38306

Correlation matrix



Results

Nuclei	Q_α	Δm^{Exp}	Δm^{LD}	SCE
$^{267}_{104}$Rf				
$^{271}_{106}$Sg				
$^{275}_{108}$Hs				
$^{279}_{110}$Ds				
$^{283}_{112}$Cn				
$^{287}_{114}$Fl				
$^{291}_{116}$Lv				

Table 4. SCE correlation matrix

1.00	0.99	0.98	0.98	0.97	0.97	0.96
0.99	1.00	0.99	0.99	0.98	0.98	0.97
0.98	0.99	1.00	0.99	0.99	0.98	0.98
0.98	0.99	0.99	1.00	0.99	0.99	0.98
0.97	0.98	0.99	0.99	1.00	0.99	0.99
0.97	0.98	0.98	0.99	0.99	1.00	0.99
0.96	0.97	0.98	0.98	0.99	0.99	1.00

Results with no uncertainty on the last nucleus of the chain

With uncertainty

SCE
-3.687±0.578
-3.576±0.584
-3.307±0.588
-3.243±0.591
-3.947±0.595
-4.751±0.599
-5.409±0.605

Without

SCE
-3.687±0.058
-3.576±0.101
-3.307±0.121
-3.243±0.138
-3.947±0.154
-4.751±0.169
-5.409±0.188

Conclusions and perspective

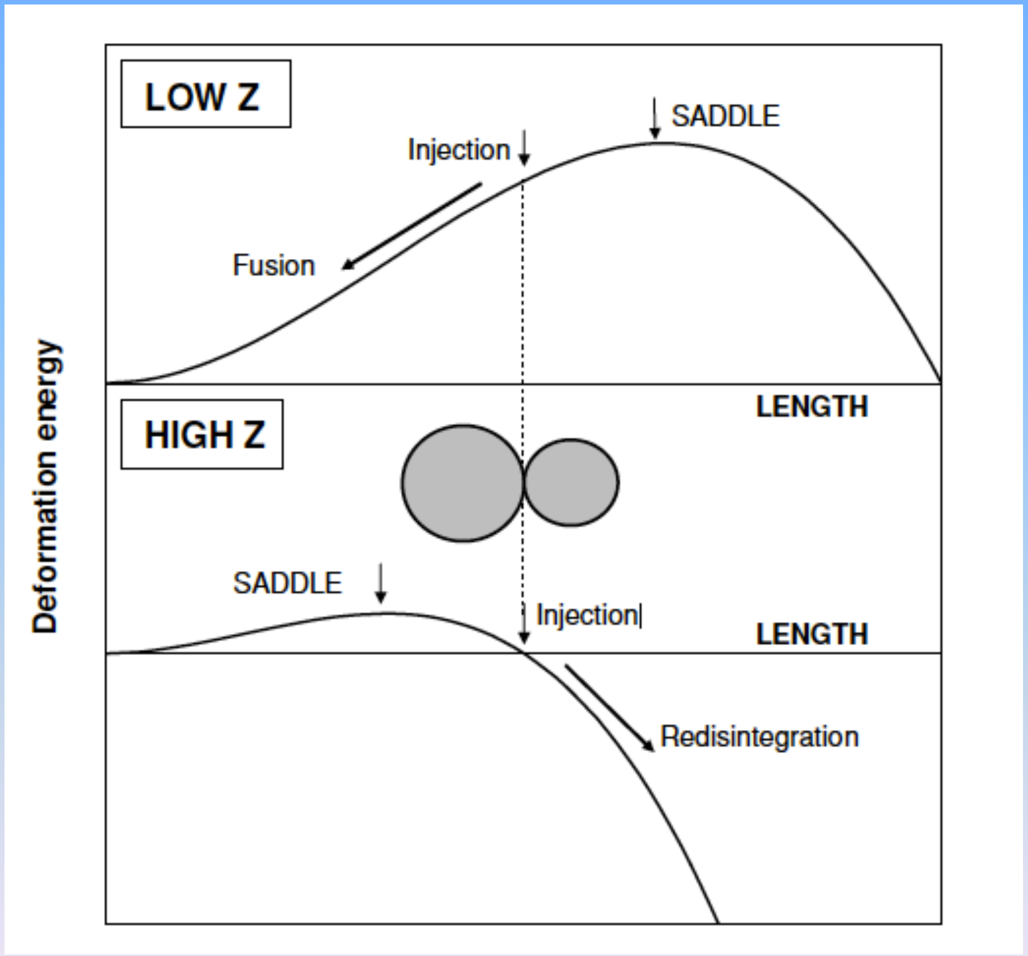
- Limited predictive power of the models
- Hindrance and fission barriers dominates uncertainties
- One should assess them separately
- Necessity of dedicated experiments to improve the prediction of dynamical models

“In this world nothing can be said to be certain, except death and taxes”

Benjamin Franklin (1789)

Thank you for your attention!

Fusion hindrance threshold



Swiatecki et al, Fusion by diffusion

PHYSICAL REVIEW C **83**, 054620 (2011)

Fusion hindrance in reactions with very heavy ions: Border between normal and hindered fusion

Caiwan Shen,[1] David Boilley,[2,3] Qingfeng Li,[1] Junjie Shen,[1,4] and Yasuhisa Abe[5]