# Fission Barrier Landscape

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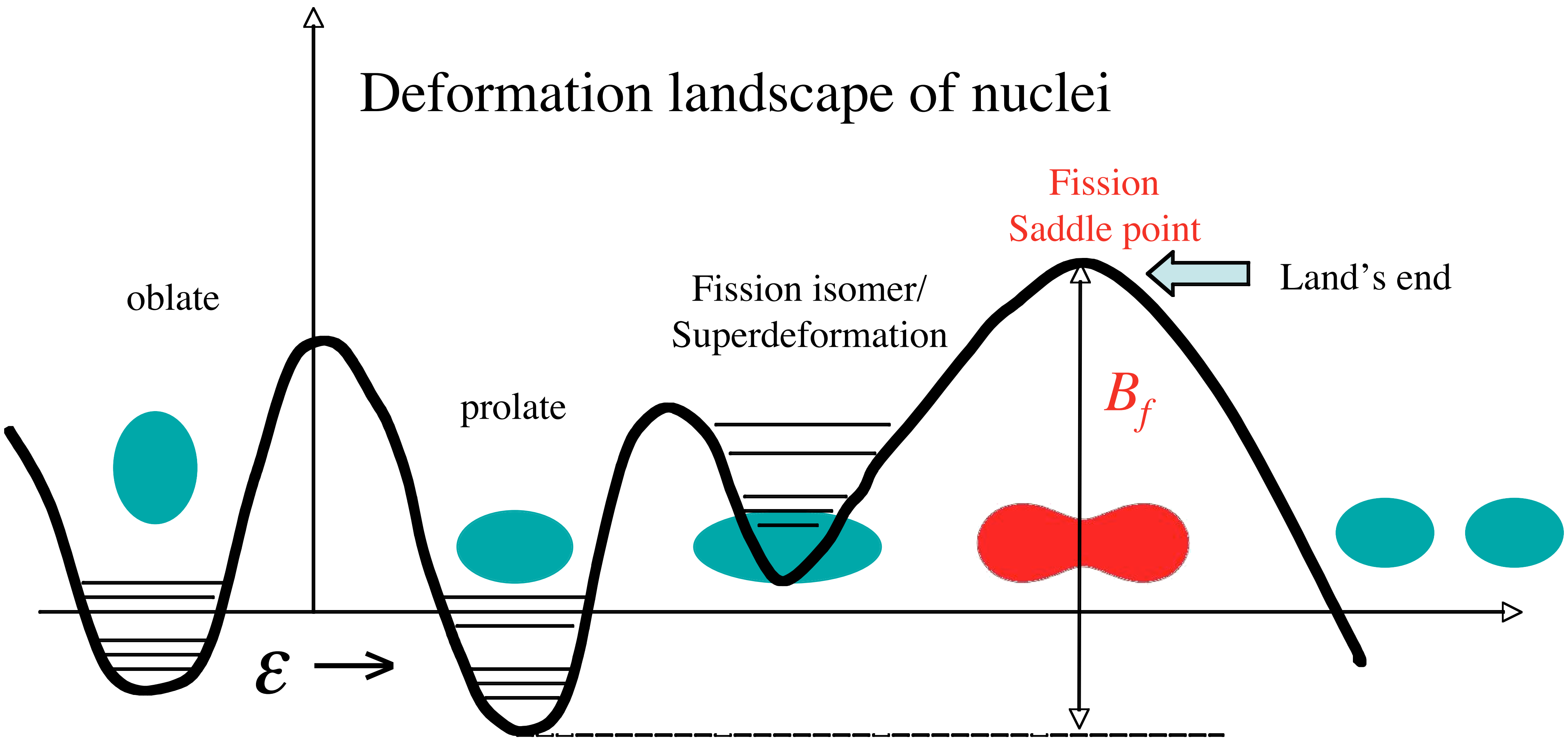
# Motivation:
# Structure of deformed objects




Stationary point:

$\Longrightarrow$ Fission spectroscopy

Fission barrier $B_f$: mass of saddle

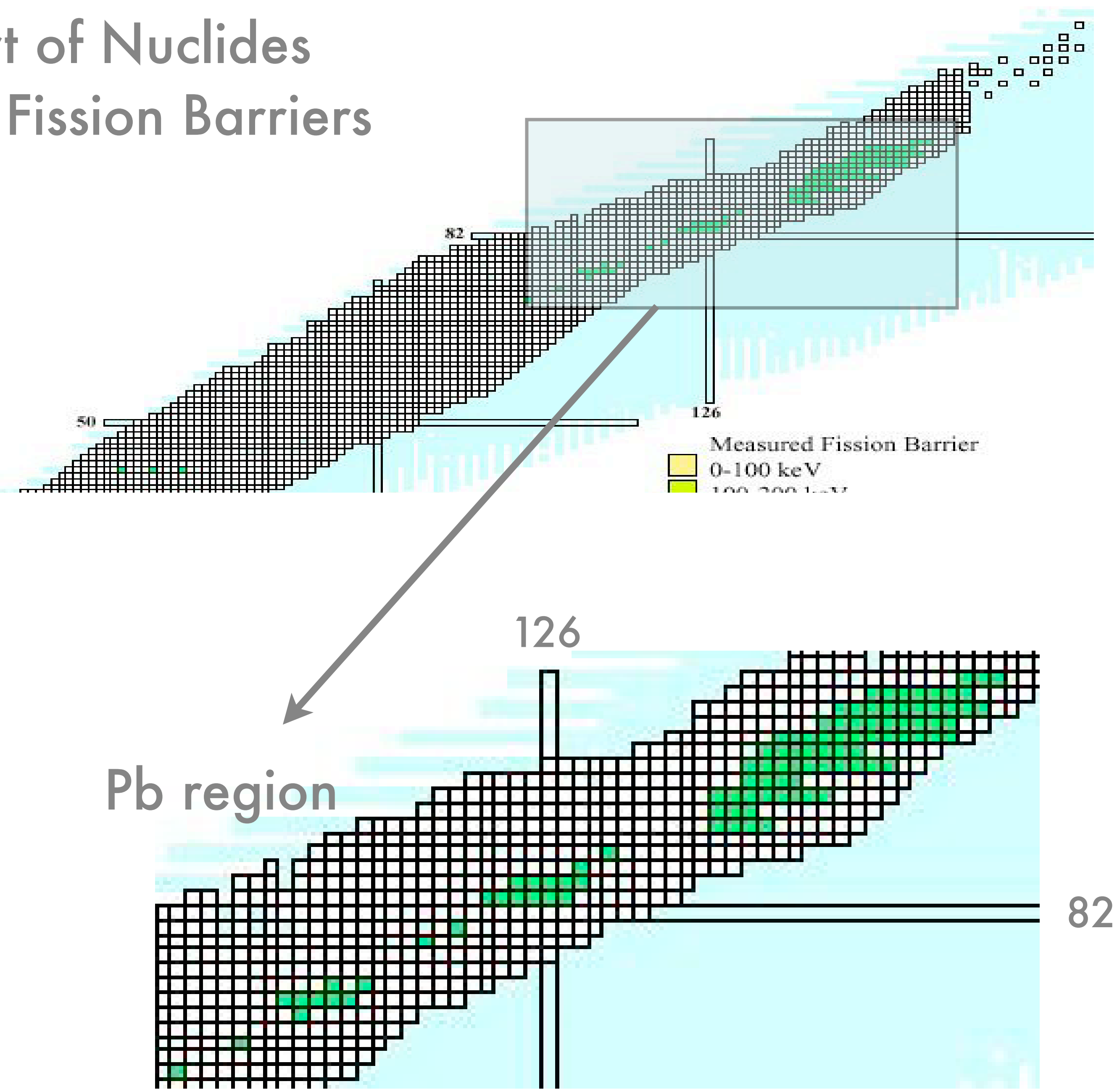
$$M_S = M_{gs} + B_f$$

Pairing ($\Delta_0$)
shell corrections ($\Delta_{shell}$)
single particle level density ($g$)
Congruence Energy (Wigner term masses)

# What is known about the detailed properties of the saddle point?

- Very little compared to ground state.
- ~100 known barriers
  - Typically restricted to very heavy nuclei
  - Poor precision

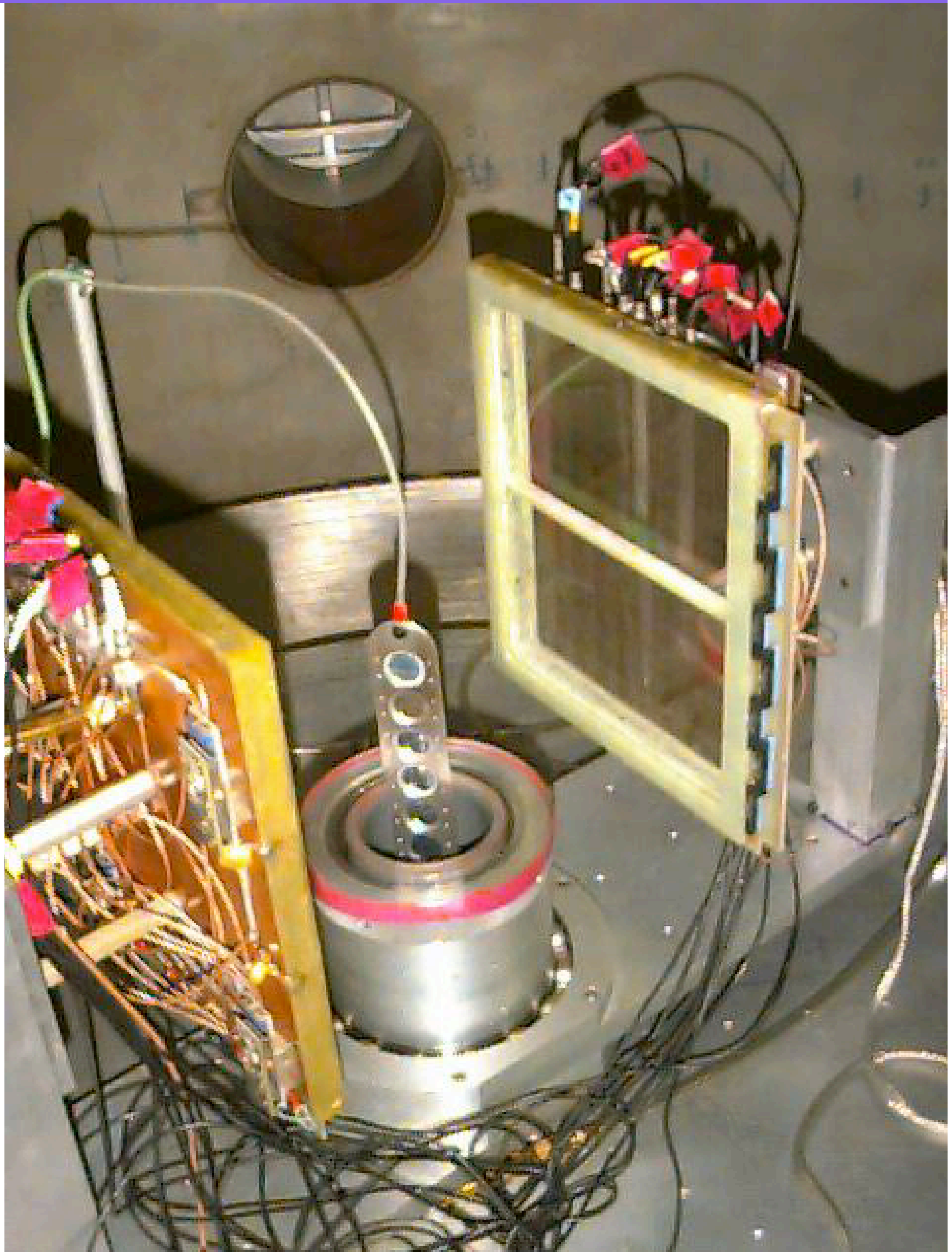
Chart of Nuclides
Known Fission Barriers



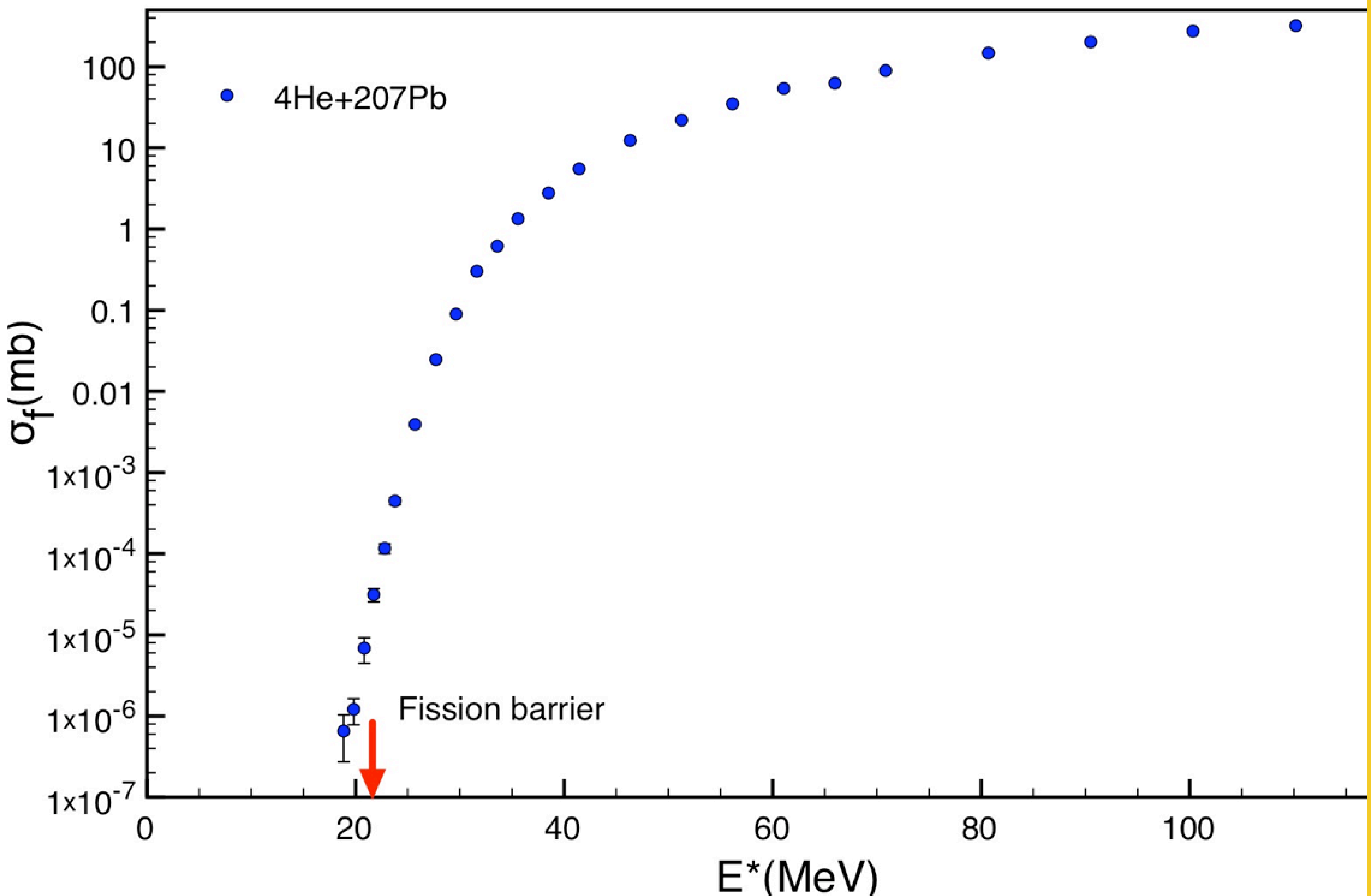
# Systematic data sets

- Precision data
  - High purity targets
  - Parts per billion uranium
  - High purity beams

| Year | Reaction | Compound Nucleus |
|---|---|---|
| 1997 | $^{3}$He + $^{182184,186}$W | $^{185-187,189}$Os |
| 1997 | $^{3}$He + $^{206-208}$Pb | $^{209-211}$Po |
| 1999 | $^{3}$He + $^{204}$Pb | $^{207}$Po |
| 1999 | d + $^{204,206-208}$Pb | $^{206,208-210}$Bi |
| 1999 | $^{4}$He + $^{204,206-208}$Pb | $^{208,210-212}$Po |
| 2000 | p + $^{204,206-208}$Pb | $^{205,207-209}$Bi |
| 2002 | $^{3}$He+$^{192,194-196,198}$Pt | $^{195,197-199,201}$Hg |
| 2002 | $^{4}$He+$^{192,194-196,198}$Pt | $^{196,198-200,202}$Hg |



# Example of data



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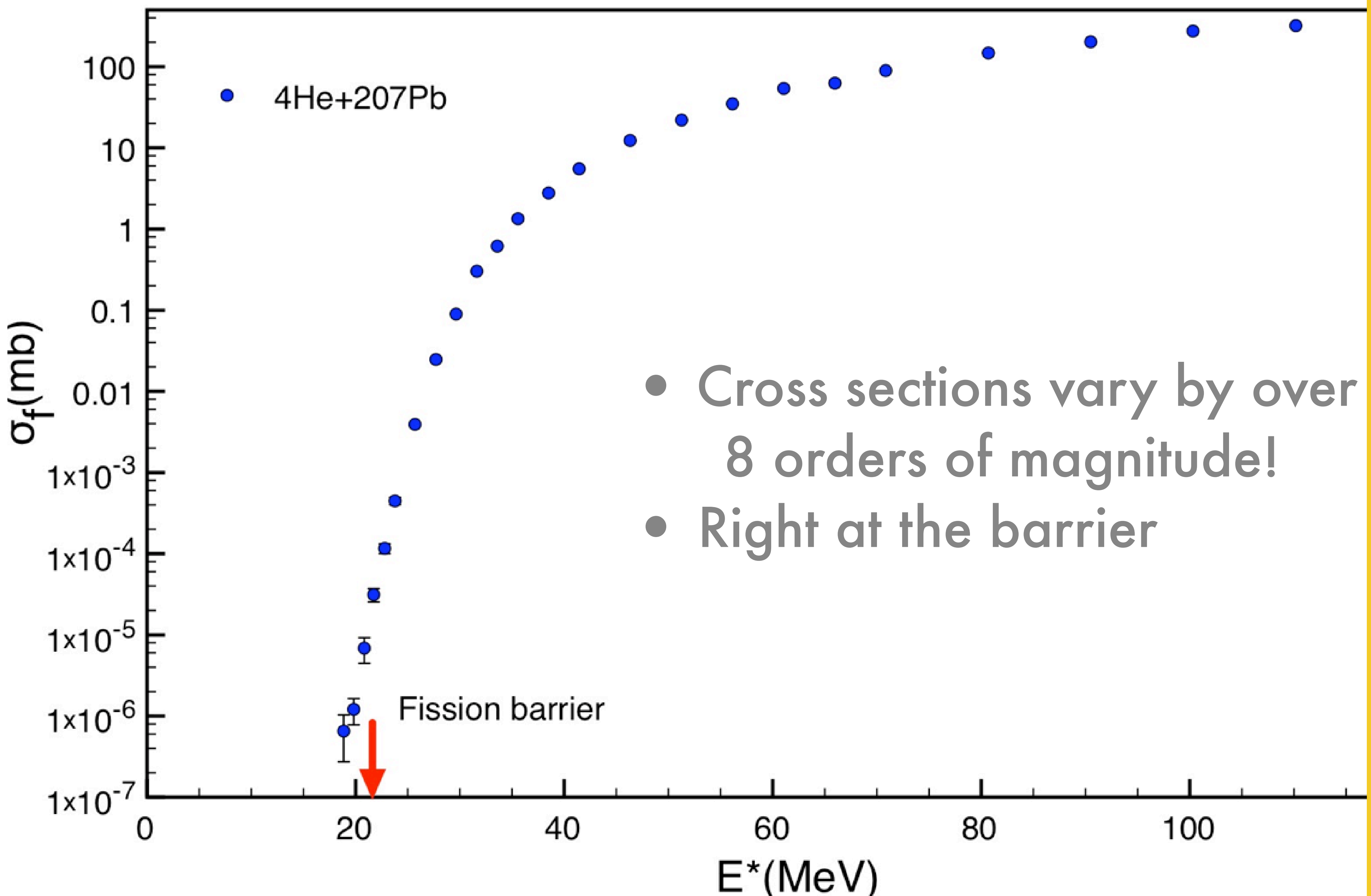
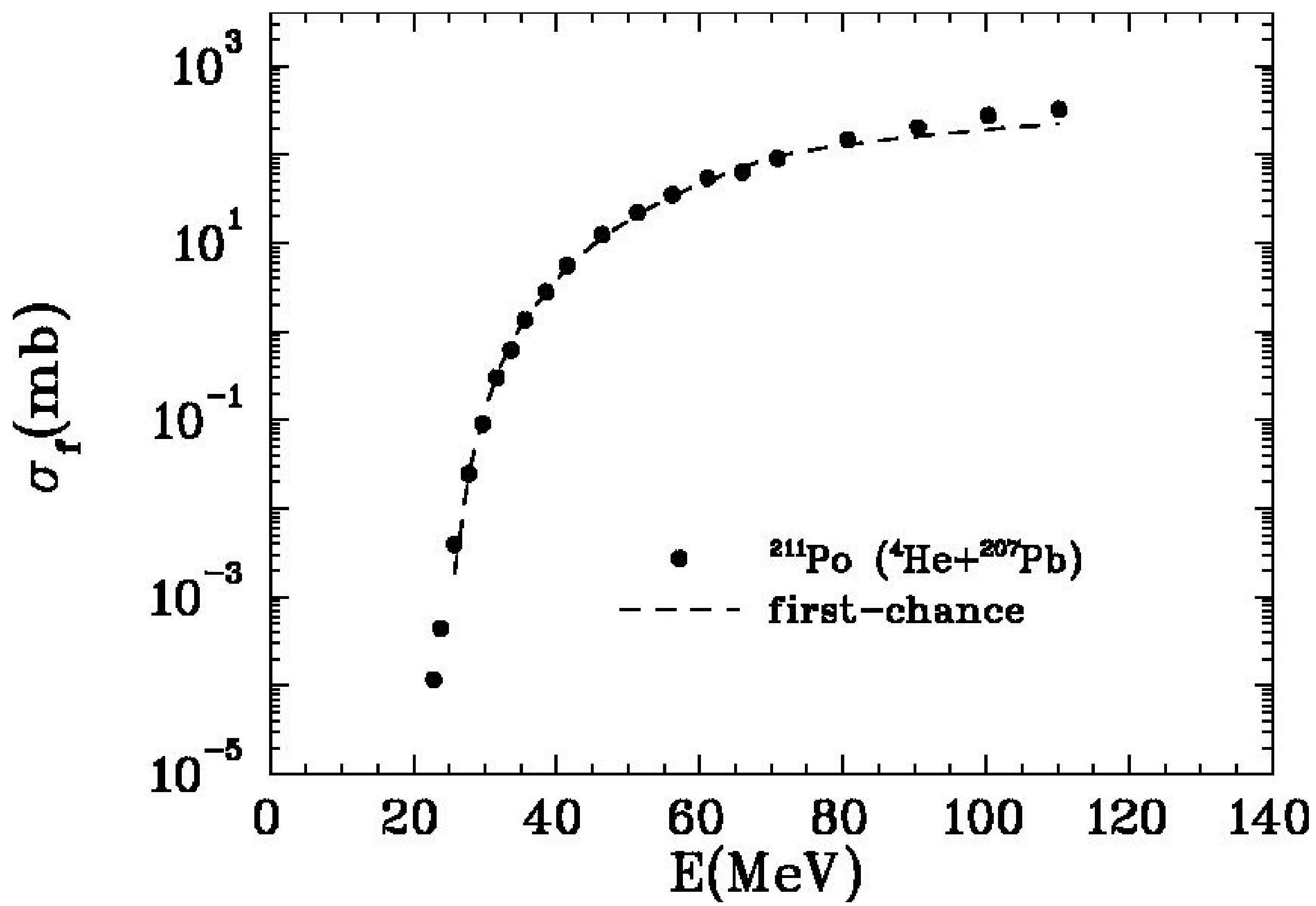



- Cross sections vary by over 8 orders of magnitude!
- Right at the barrier

# Old vs. New analysis

- Assumptions: old analysis
  - Single compound nucleus
  - Only two channels: n emission & fission
  - First chance fission only



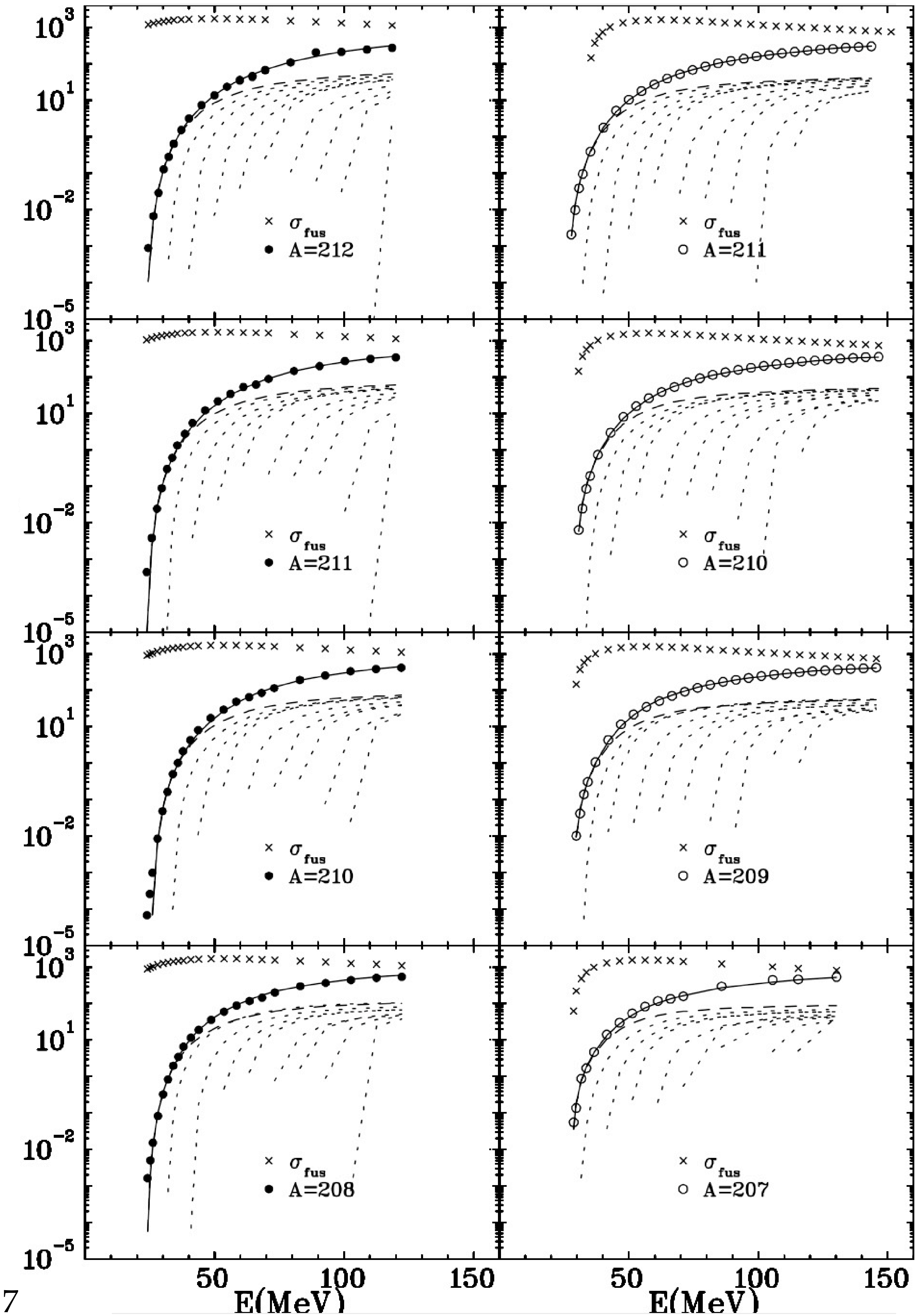

$$P_f(E) \propto \frac{\Gamma_f}{\Gamma_n} \propto \frac{\rho_f\left(E - B_f - E_r^S\right)}{\rho\left(E - B_n - E_r^{gs} - \Delta_{\text{shell}}^{n-1}\right)}$$

# New analysis

- Fit a chain of neighboring compound nuclei
- Multiple chance

$$\sigma_f = \sum_{i=0} \sigma_f^{(i)} = \sum_{l=0}^{l_{\max}} \sum_{i=0} (2l+1)\pi\lambda\!\!\!^{-2} P_f^{(i)}(l)$$

Each $n$ carries $B_n$+2T



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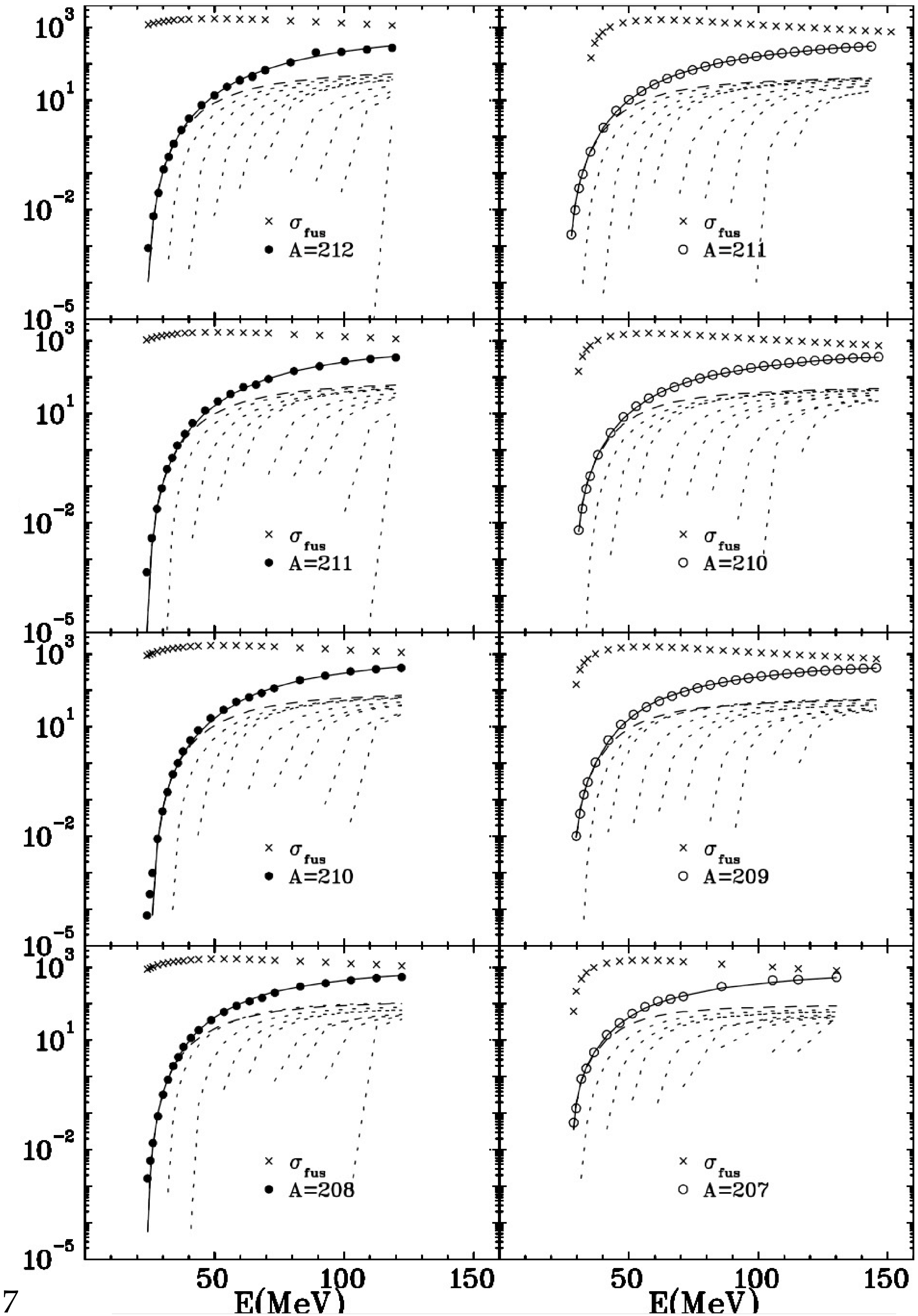
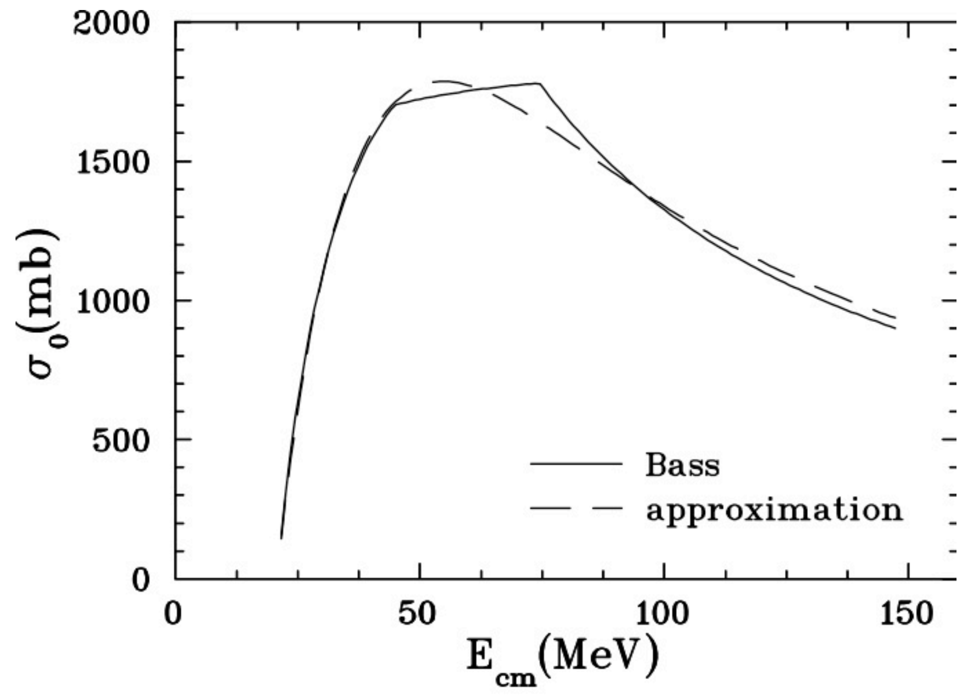
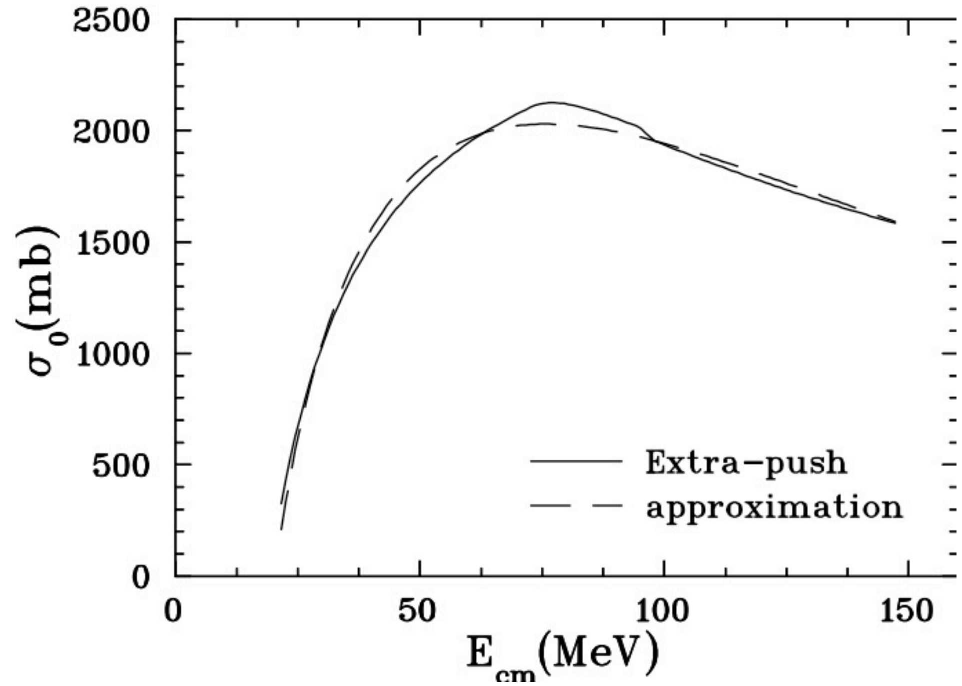


# Fusion cross sections




- Useful to make the Bass model more general and include it as part of the fit.
  - Low energy part: $\sigma_0 = \pi R^2 (1 - V/E)$
  - High energy part: $\sigma_0 E = \pi R^2 (E_2 - V)$
- Marry the two behaviors: adds two more parameters to fit ($R$, $E_2 - V$)

$$\sigma_0 = \left(E_2 - V\right) \frac{\pi R^2}{E} \tanh\left(\frac{E - V}{E_2 - V}\right)$$

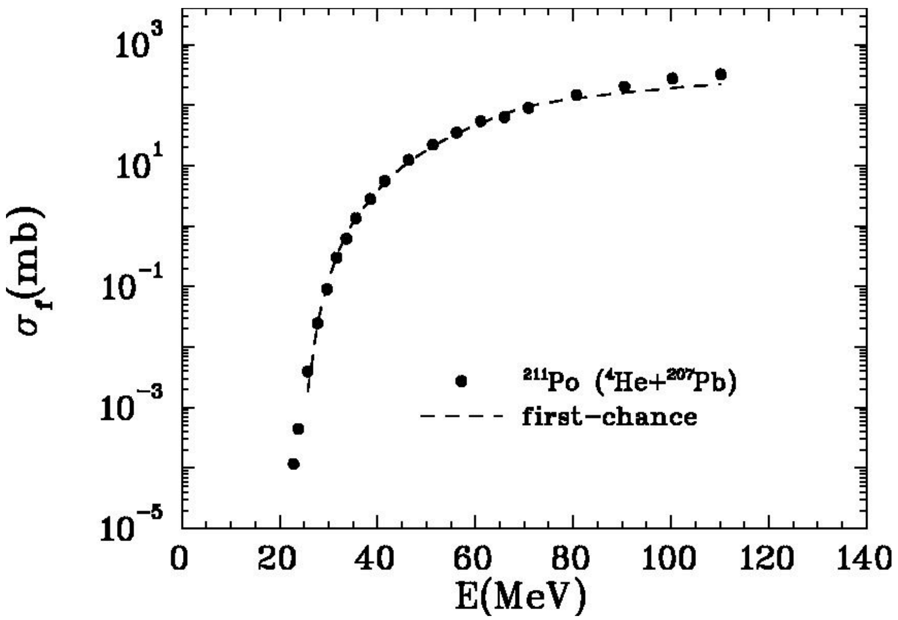
# Summary of parameters

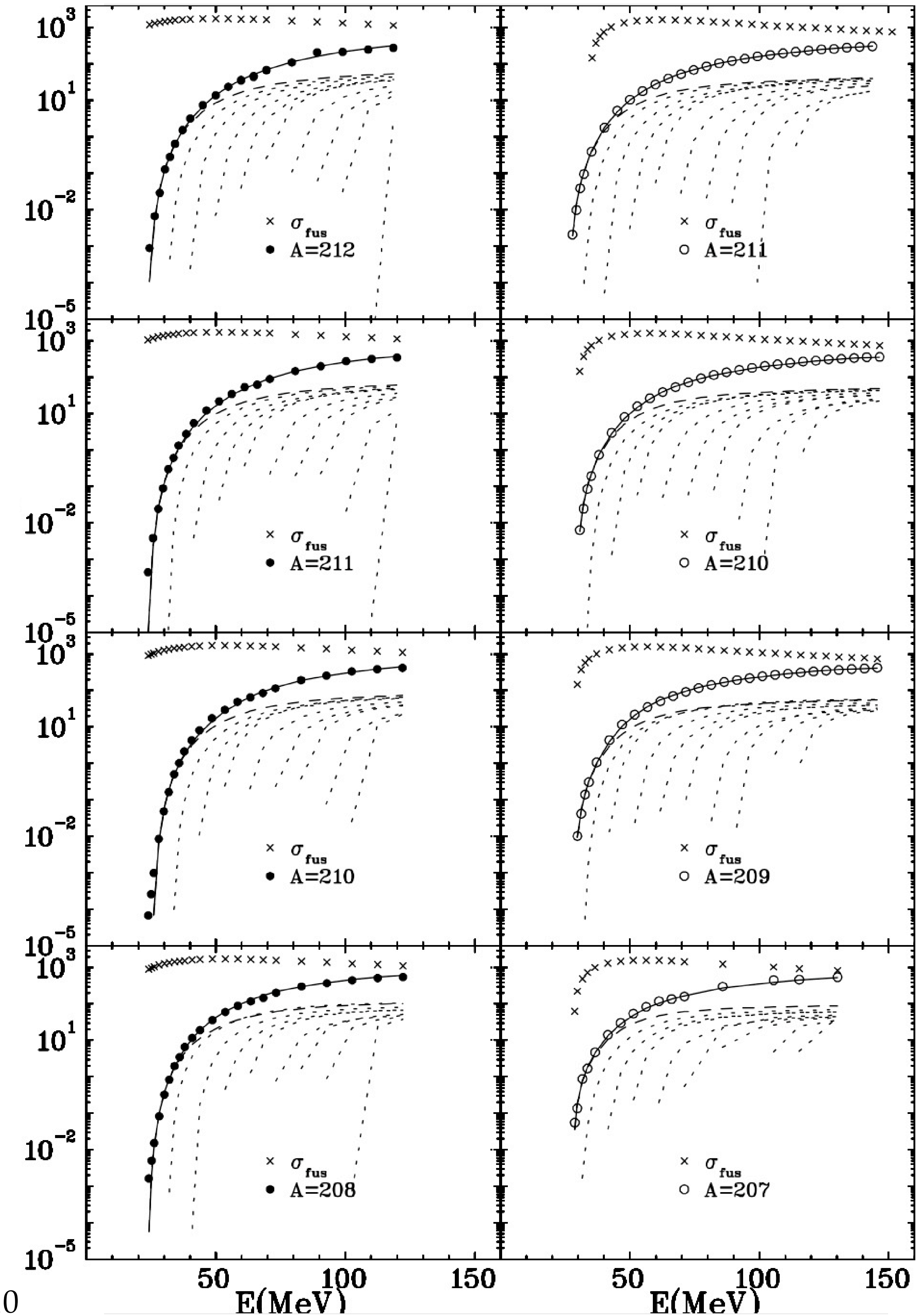
| Parameter | Name | Nominal value |
|---|---|---|
| Fission barrier | $B_f$ | $B_{macro}$-$\Delta_{shell}$ |
| Shell correction | $\Delta_{shell}$ | nominal |
| Ratio level density parameters | $a_f/a_n$ | 1.0 – 1.07 |
| Geometric cross section | $\pi(r_0(A_b^{1/3}+A_t^{1/3}))^2$ | 1.2-1.5 fm |
| Characteristic velocity | $E_2\text{-}V=1/2\mu v^2$ | |

- 6 Po compound nucleus data sets: $^{207\text{-}212}$Po
- 2 overlapping sets: $^{211,210}$Po
- 9 free parameters

# Fit quality

- The fits are not so different in quality. However, the fit parameters are very different.



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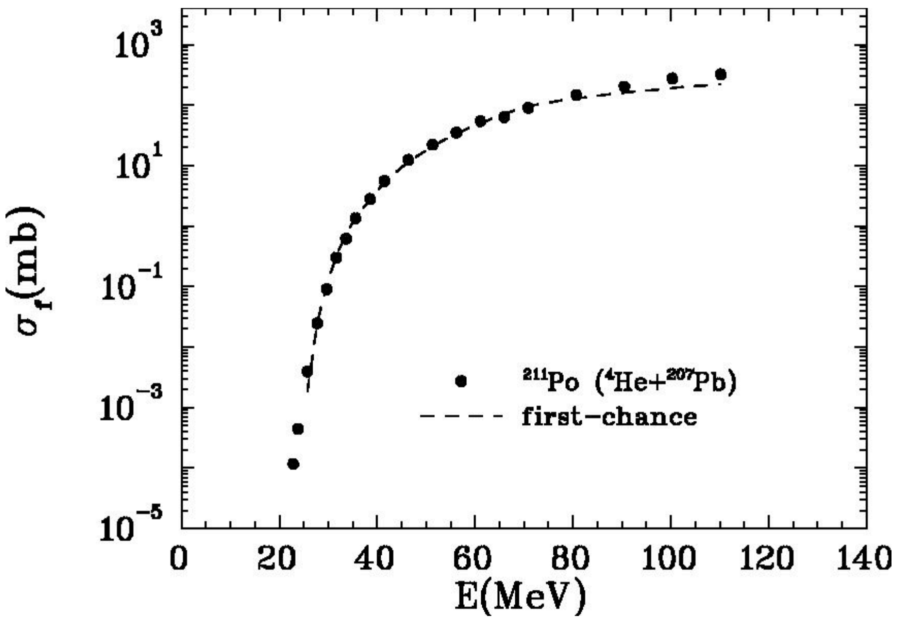


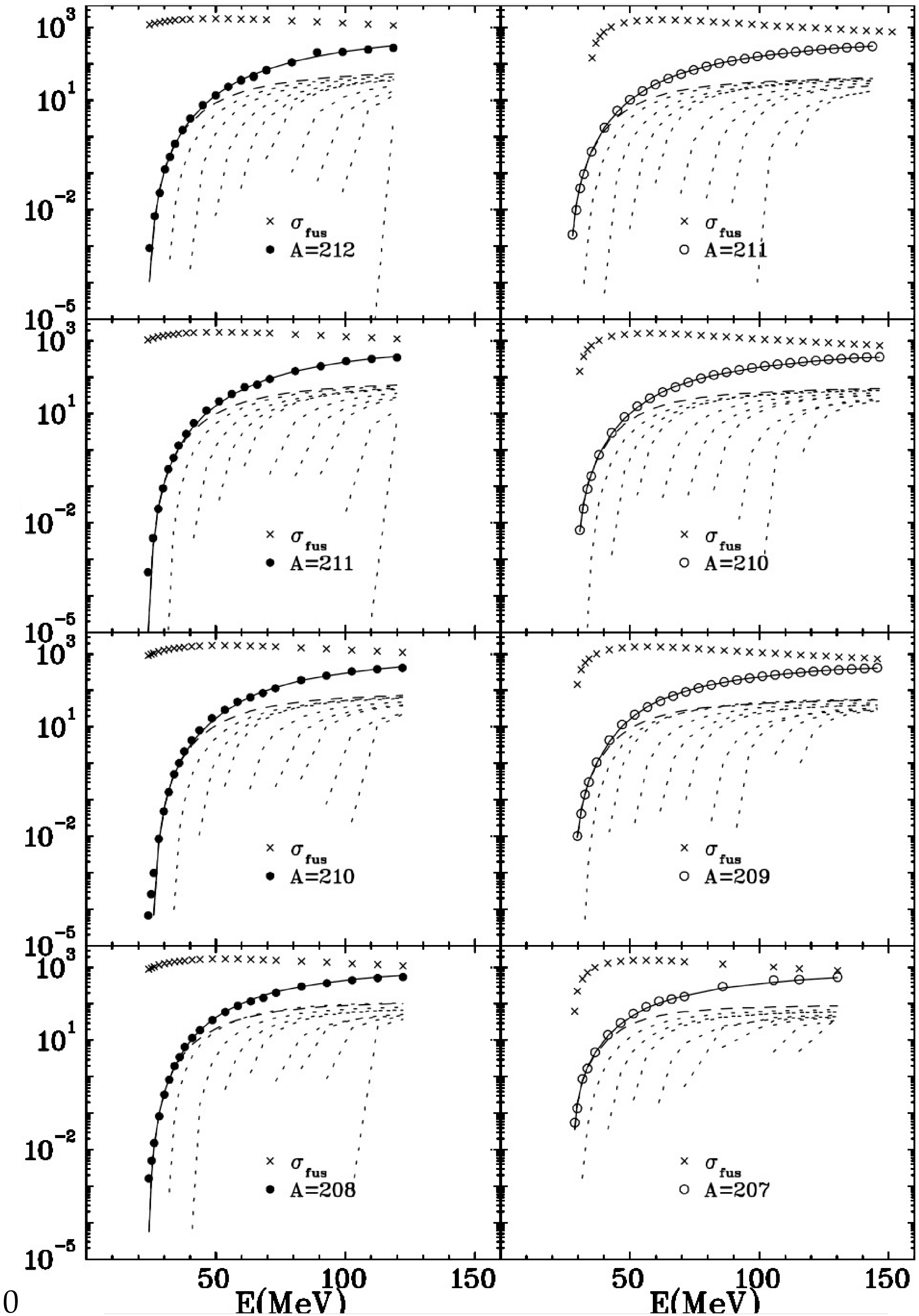

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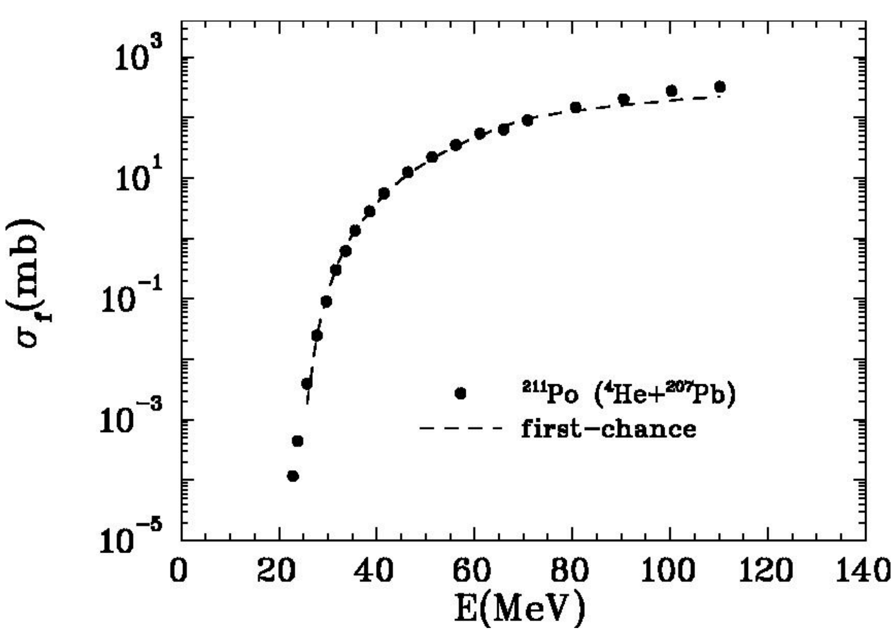
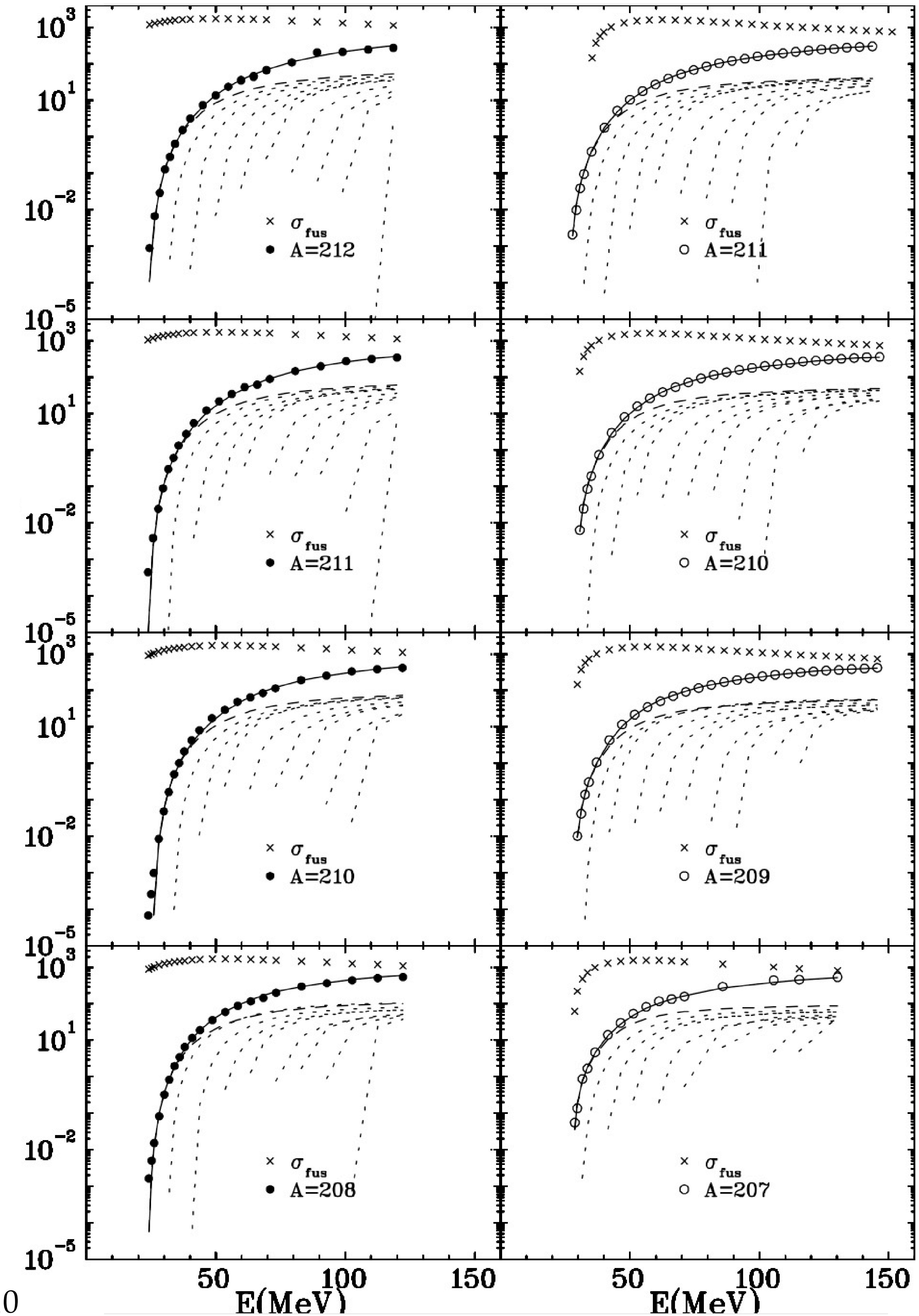
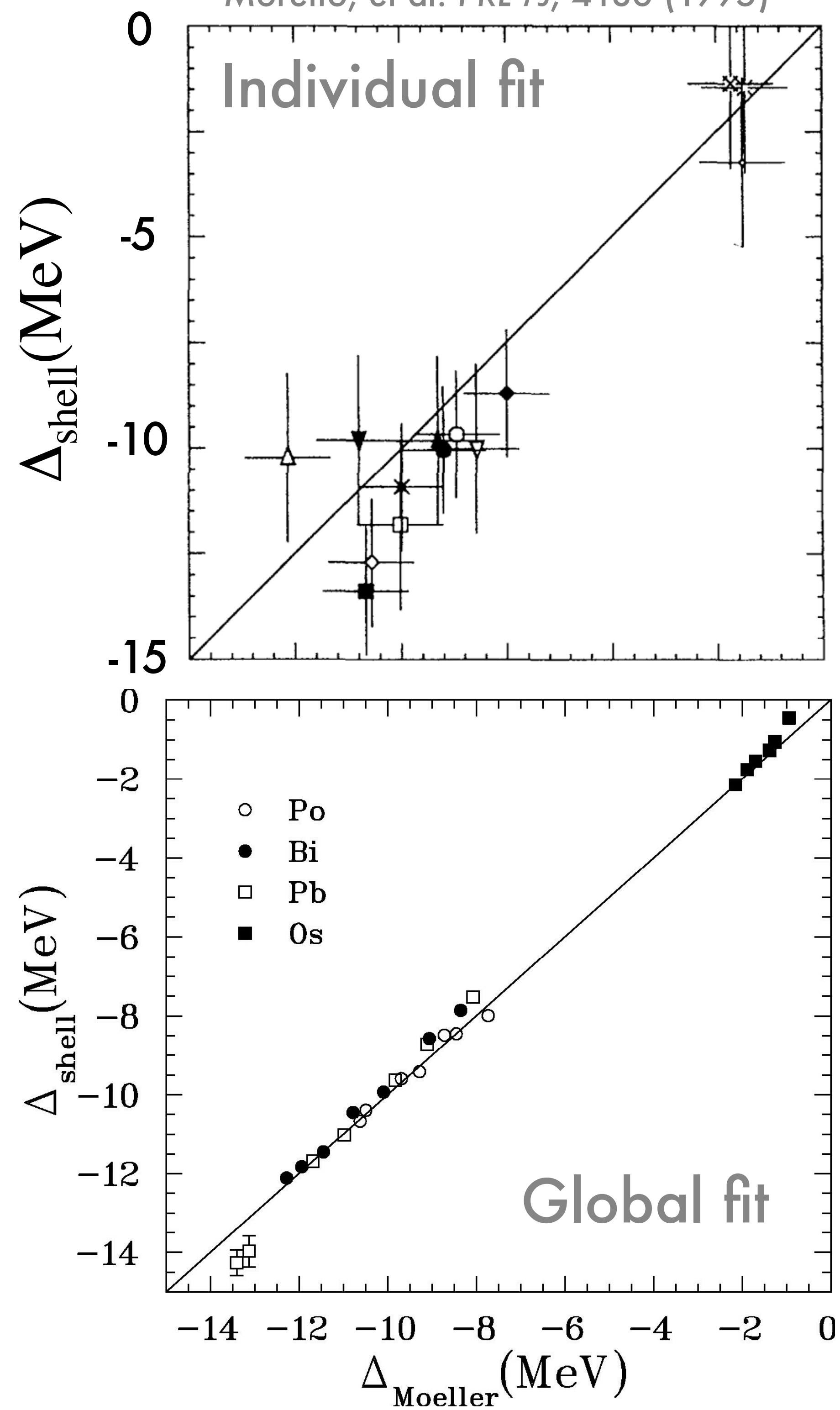


# Test: ground state shell correction

- Po, Bi, Pb, Os chains
- "Old" fits (single system, first-chance fission only) have large errors: ±2MeV
- "New" fits: tens of keV. Agreement better than 100 keV
- "Local" measures of shell
- Equivalently accurate fission barriers

Moretto, et al. *PRL 75*, 4186 (1995)



# Potential analyses

- Pairing
- Shell corrections
- Congruence energy
- Level density
- Fission delay times

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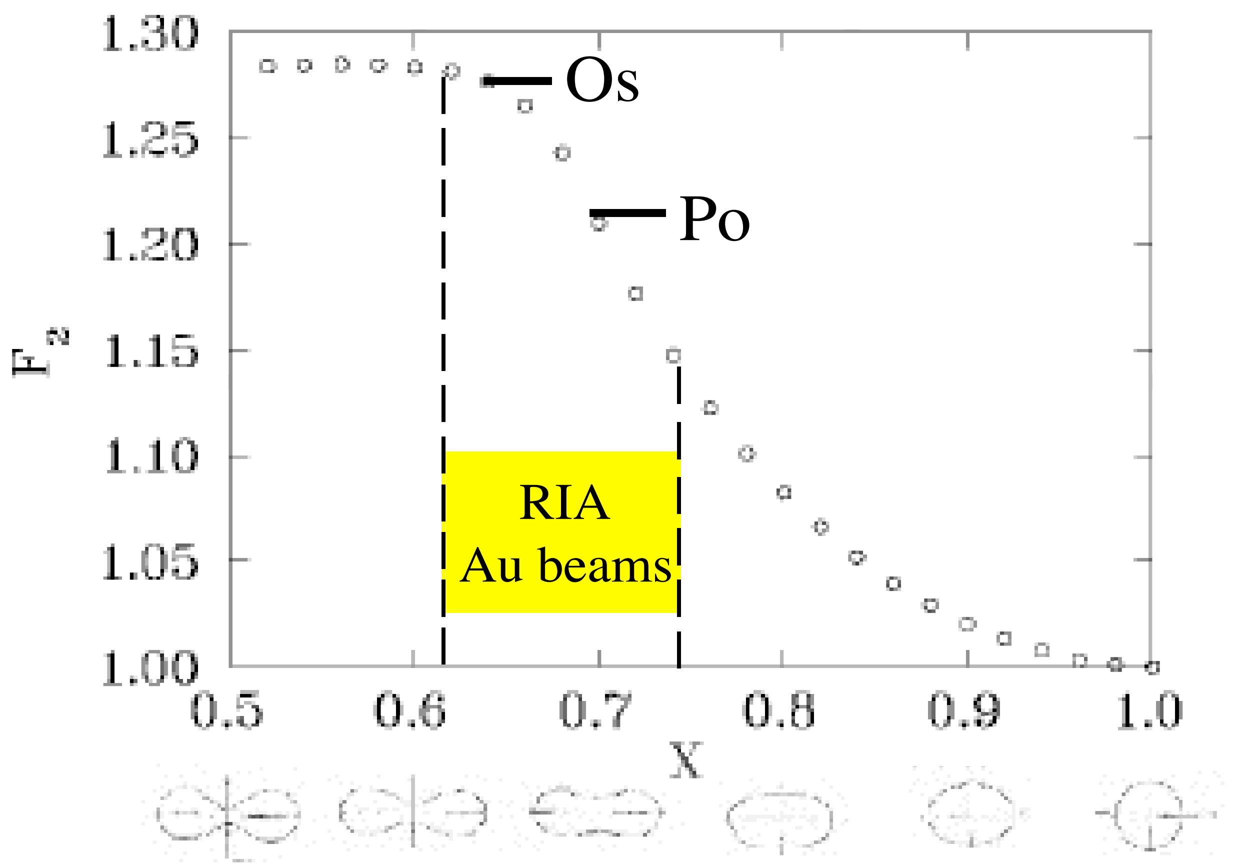
# Level density at the saddle

- Studying the surface area dependence of the level density parameter *a*

| Isotopes | $a_f/a_n$ | estimate |
|---|---|---|
| Os | 1.062 | 1.095 |
| Po | 1.028 | 1.079 |

Toke & Swiatecki, Nucl. Phys. A372, 141 (1981)

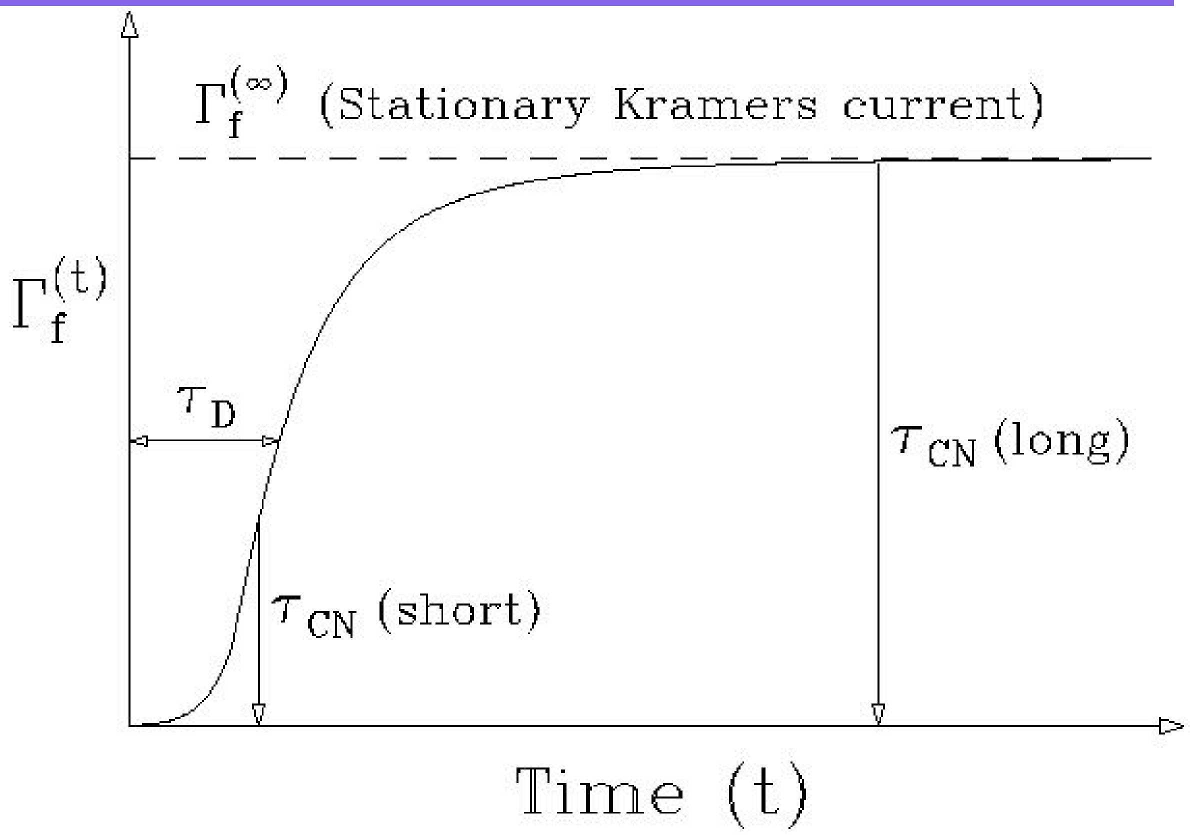
$$a = \frac{A}{14.61\ \text{MeV}}\left(1 + \frac{4}{A^{1/3}}F_2\right)$$




F2 is the surface area in units of a sphere

# Fission delay time

- Fission decay width is suppressed during the time it takes to get to the saddle configuration.
- Fission probability is suppressed.
- Approximate suppression with step function



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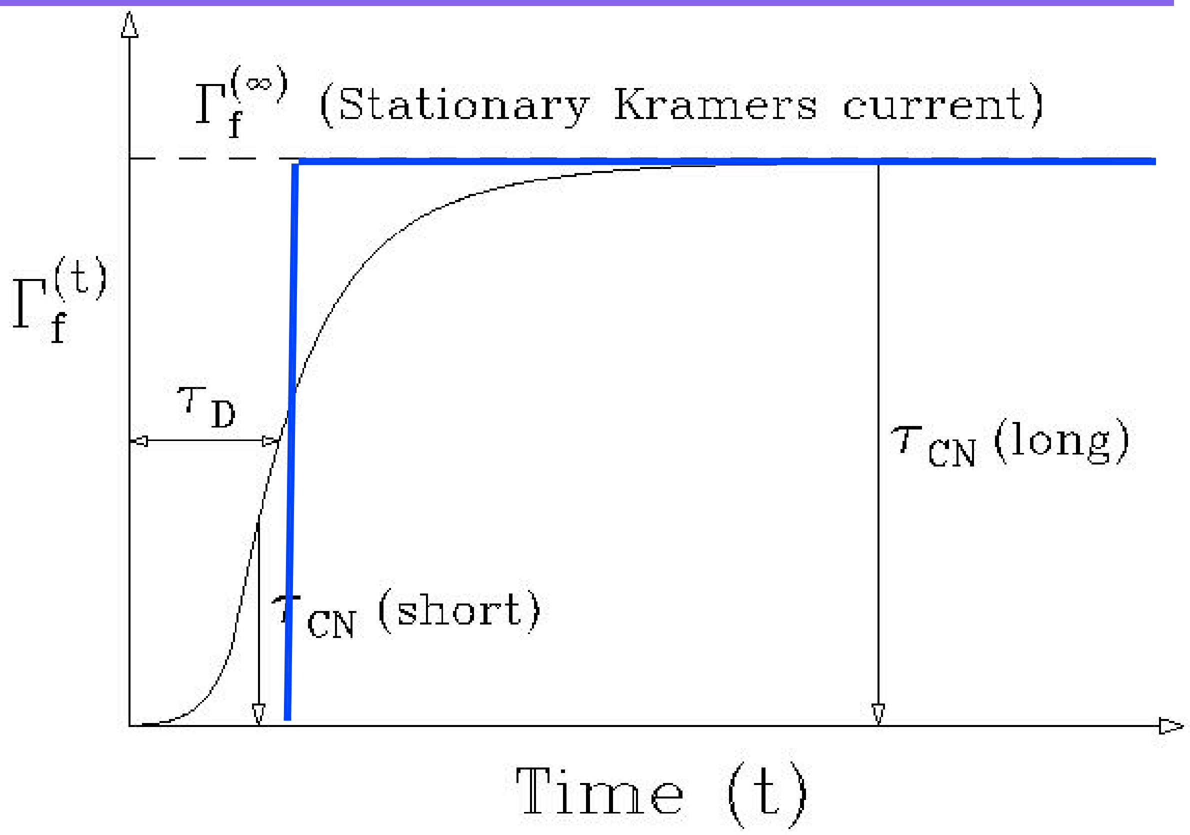



$$\Gamma_f = \Gamma_f^{(\infty)} \int_0^{\infty} \zeta(t) \frac{N(t)}{N_0} \lambda_{CN}\, dt = \Gamma_f^{(\infty)} \int_{\tau_D}^{\infty} \frac{N(t)}{N_0} \frac{dt}{\tau_{CN}}$$

# Introducing fission delay time $\tau_D$

Balance equations:

$$\frac{dN_i(t)}{dt} = \lambda_n^{(i-1)} N_{i-1}(t) - \lambda_n^{(i)} N_i(t), \qquad (t \le \tau_D)$$
$$\frac{dN_i(t)}{dt} = \lambda_n^{(i-1)} N_{i-1}(t) - \lambda_{CN}^{(i)} N_i(t), \qquad (t \ge \tau_D)$$

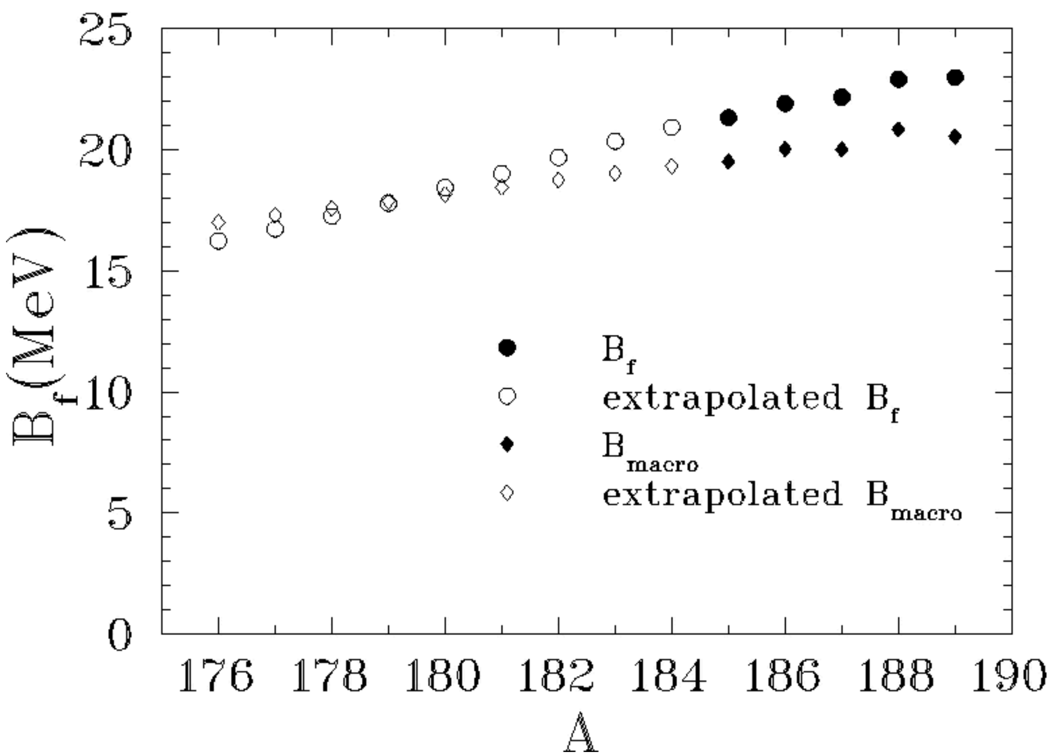
$$\frac{N_i(t)}{N_0} = \sum_{j=0}^{j=i} a_{i,j} \exp(-\lambda_n^{(j)}\, t), \qquad (t \le \tau_D)$$
$$a_{i,j} = \frac{\lambda_n^{(i-1)} a_{i-1,j}}{\lambda_n^{(i)} - \lambda_n^{(j)}}, \qquad j = 0, 1, 2, \cdots, i-1,$$
$$a_{i,i} = -\sum_{j=0}^{j=i-1} a_{i,j}\,,$$
$$a_{0,0} = 1.0\,;$$
$$\frac{N_i(t)}{N_0} = \sum_{j=0}^{j=i} b_{i,j} \exp(-\lambda_{CN}^{(j)}\, t), \qquad (t \ge \tau_D)$$
$$b_{i,j} = \frac{\lambda_n^{(i-1)} b_{i-1,j}}{\lambda_{CN}^{(i)} - \lambda_{CN}^{(j)}}, \qquad j = 0, 1, 2, \cdots, i-1,$$
$$b_{i,i} = \exp(\lambda_{CN}^{(i)} \tau_D) \left[ \frac{N_i(\tau_D)}{N_0} - \sum_{j=0}^{j=i-1} b_{i,j} \exp(-\lambda_{CN}^{(j)} \tau_D) \right]$$
$$b_{0,0} = \exp\Big( (\lambda_{CN}^{(0)} - \lambda_n^{(0)})\, \tau_D \Big)\,.$$

$$P_f^{t} = \sum_{i=0} P_f^{(i)}, \longleftarrow \text{Unmodified } P_f$$

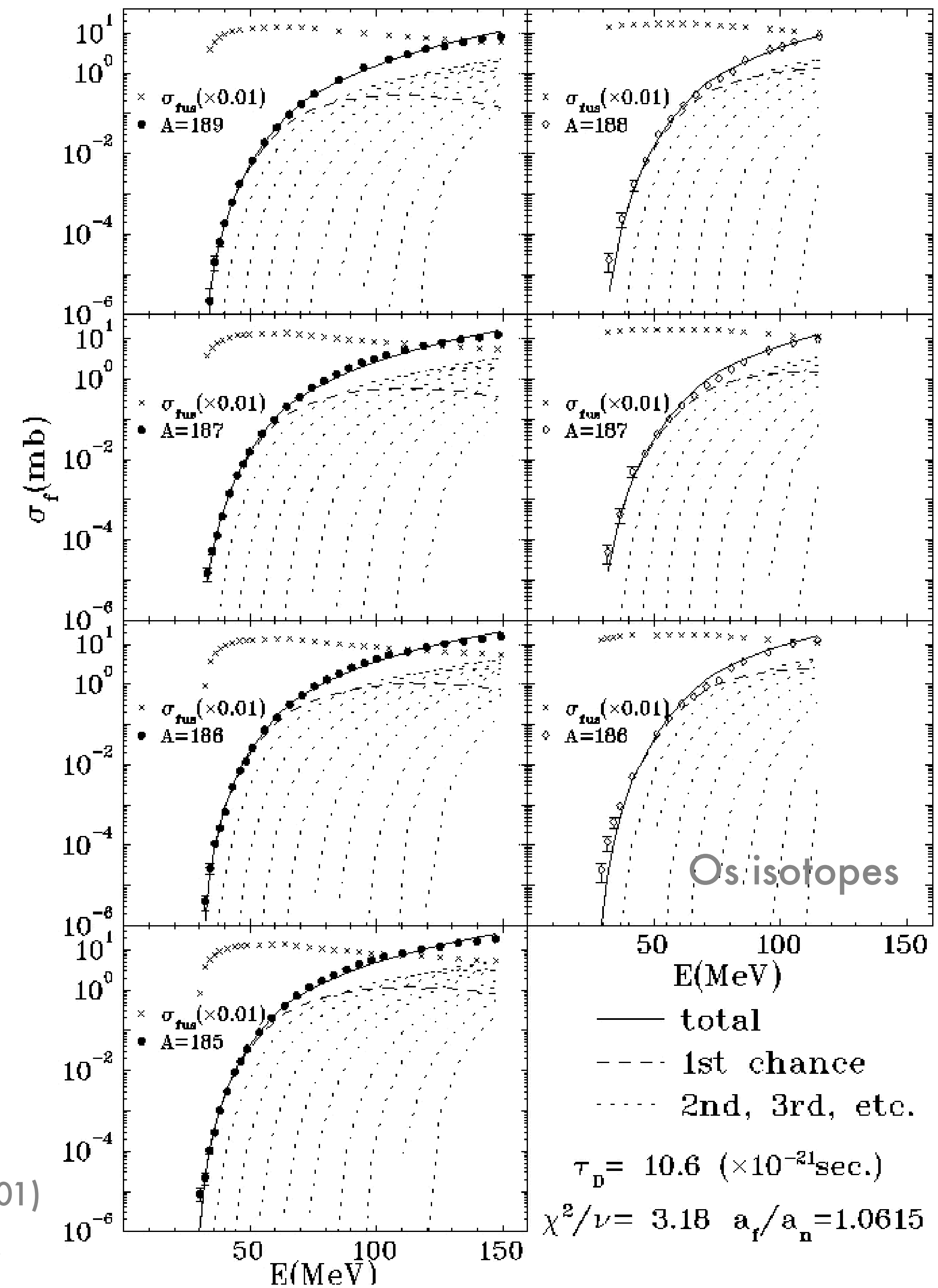
$$P_f^{(i)} = \int_{\tau_D}^{\infty} \lambda_f^{(i)} \frac{N_i(t)}{N_0}\, dt = P_f(Z, A-i, E - \sum_{j=1,i} \Delta E_j)$$
$$\boxed{\times \sum_{j=0}^{j=i} b_{i,j} \frac{\lambda_{\mathrm{CN}}^{(i)}}{\lambda_{\mathrm{CN}}^{(j)}} \exp(-\tau_D/\tau_{\mathrm{CN}}^{(j)}),}$$

Correction

# Estimate of $\tau_D$




- Assume experimental shell
- Add delay time $\tau_D$ (step function)
- Suppresses first chance fission
- $\tau_D = 10 \times 10^{-21}$ seconds

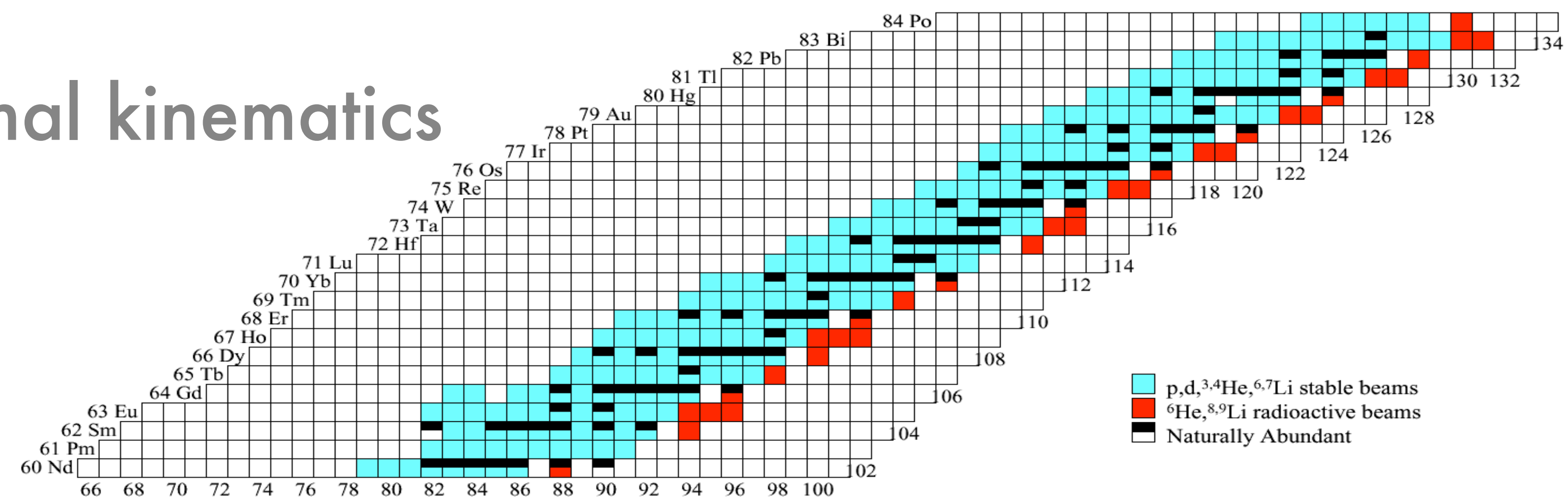



*Physics Letters B 518, 221 (2001)*

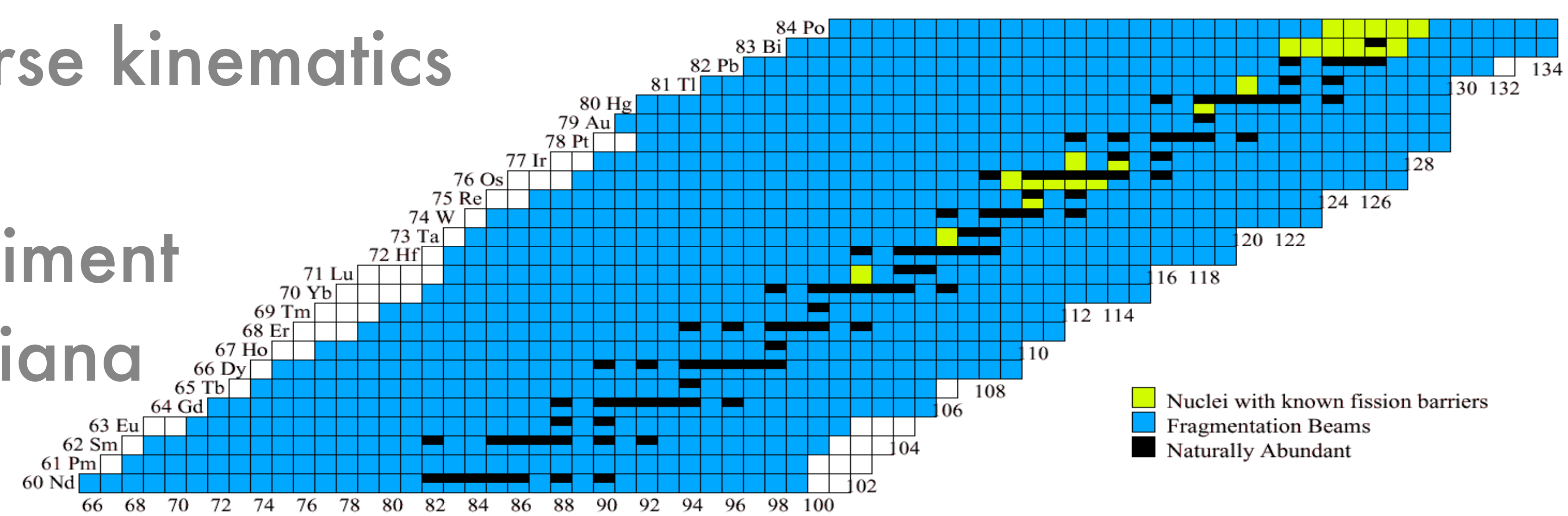
# Now and the Future

- Near future: Normal kinematics at 88-Inch cyclotron
- Long term: Reverse kinematics at RIBF
- Approved experiment at MSU led by Indiana

Fission Barrier Measurements with Stable and Radioactive Beams




Fission Barrier Measurements with Fragmentation Beams from RIA



# Conclusions & Outlook

- Saddle mass surface still largely unexplored
- Program of systematic fission measurements and systematic analysis (global fits)
- Successes so far:
  - Accurate $B_f$
  - Ground state shell (determined "locally")
  - Time delay $\tau_D$=10x10$^{-21}$ seconds
- Future:
  - Congruence energy (shape dependence)
  - Single particle level densities at the saddle
  - Pairing at the saddle
  - Shell effects at the saddle