Stability of V&SHE:
fission barrier measurements

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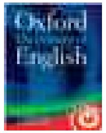
PRL 113, 262505 and beyond...

Fission



Fission: noun, from Latin *fissio*, from *findere* 'to split'.
Division or splitting into two or more parts.

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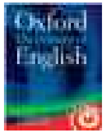

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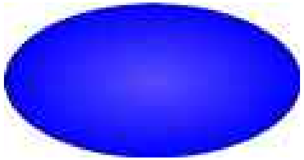

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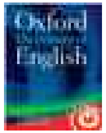

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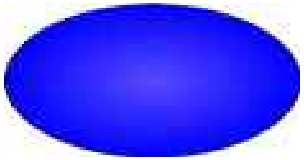

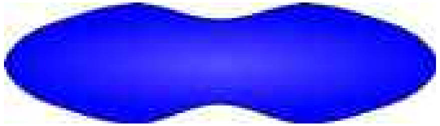

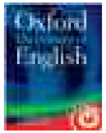

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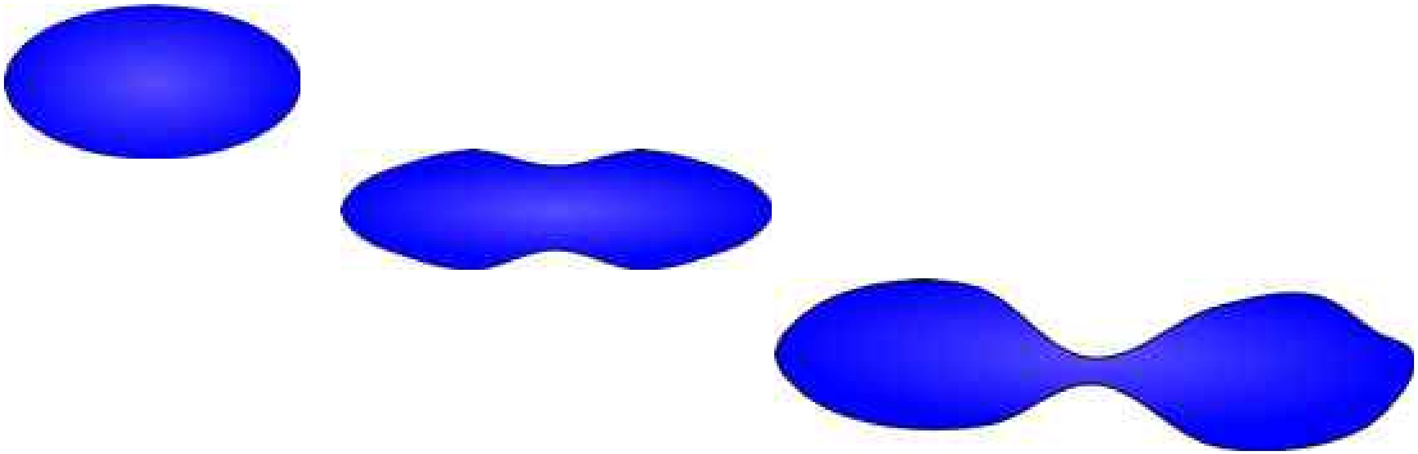

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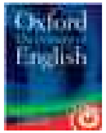

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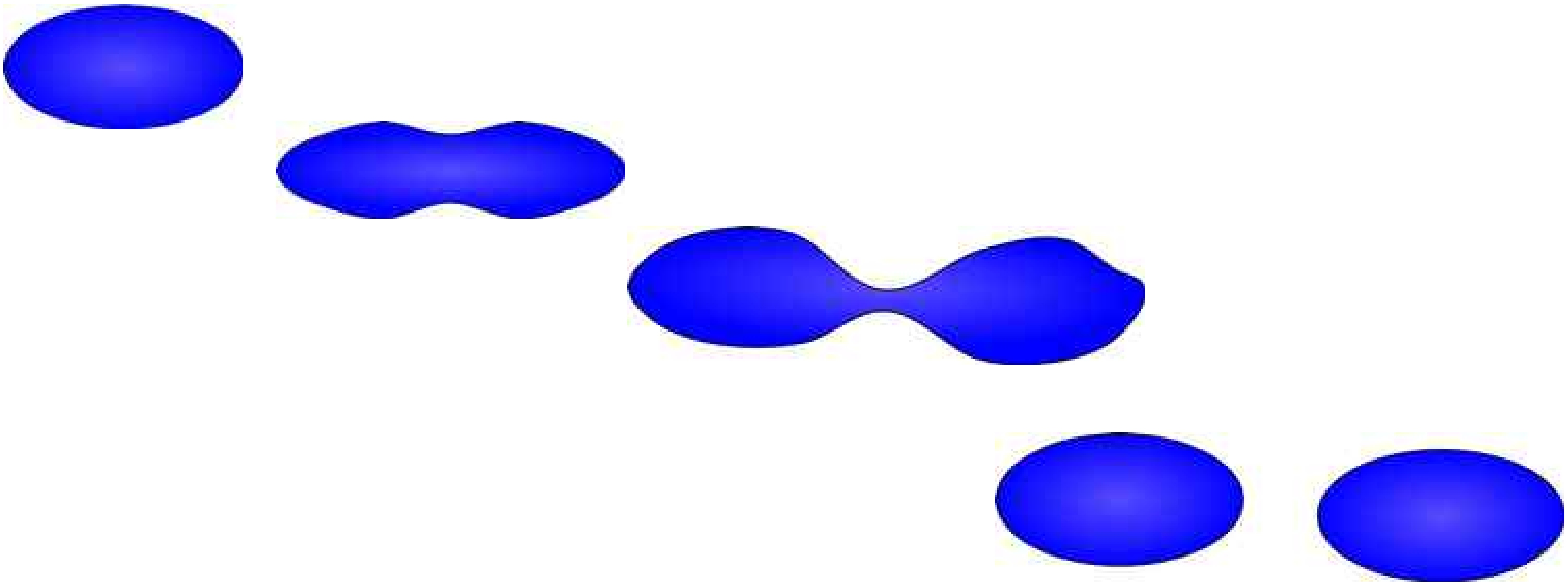

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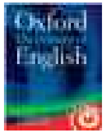

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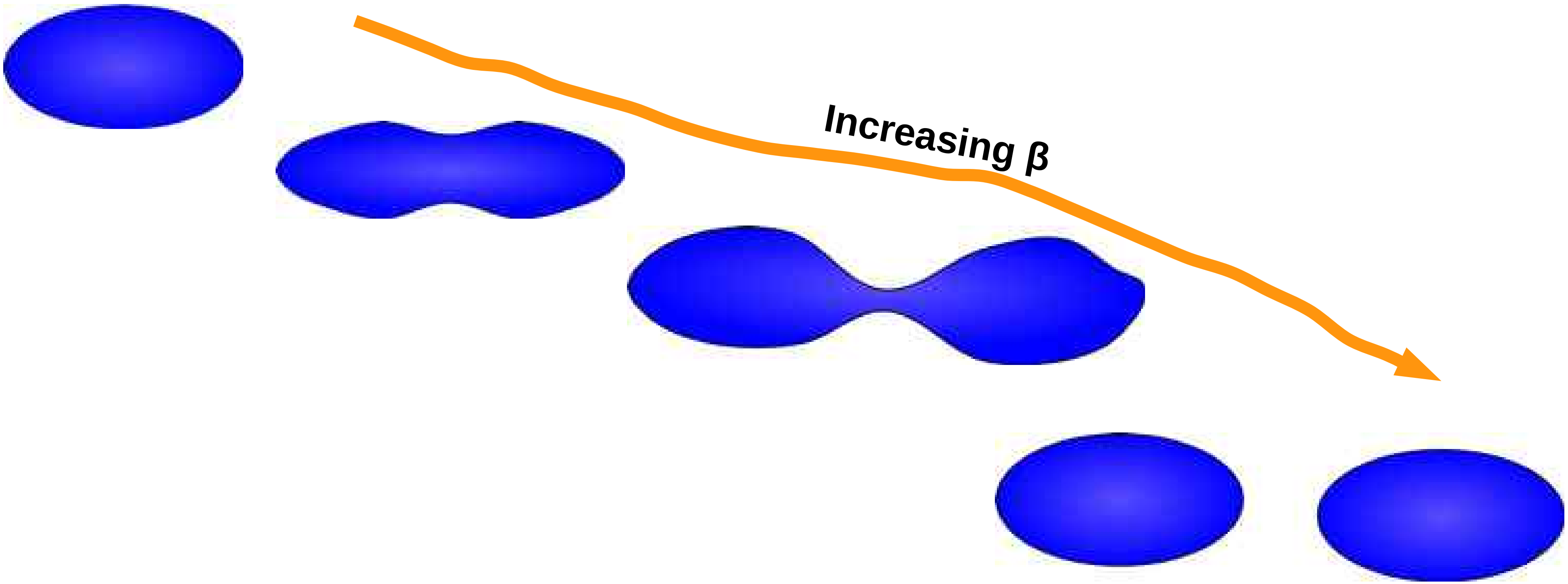

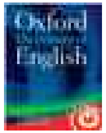

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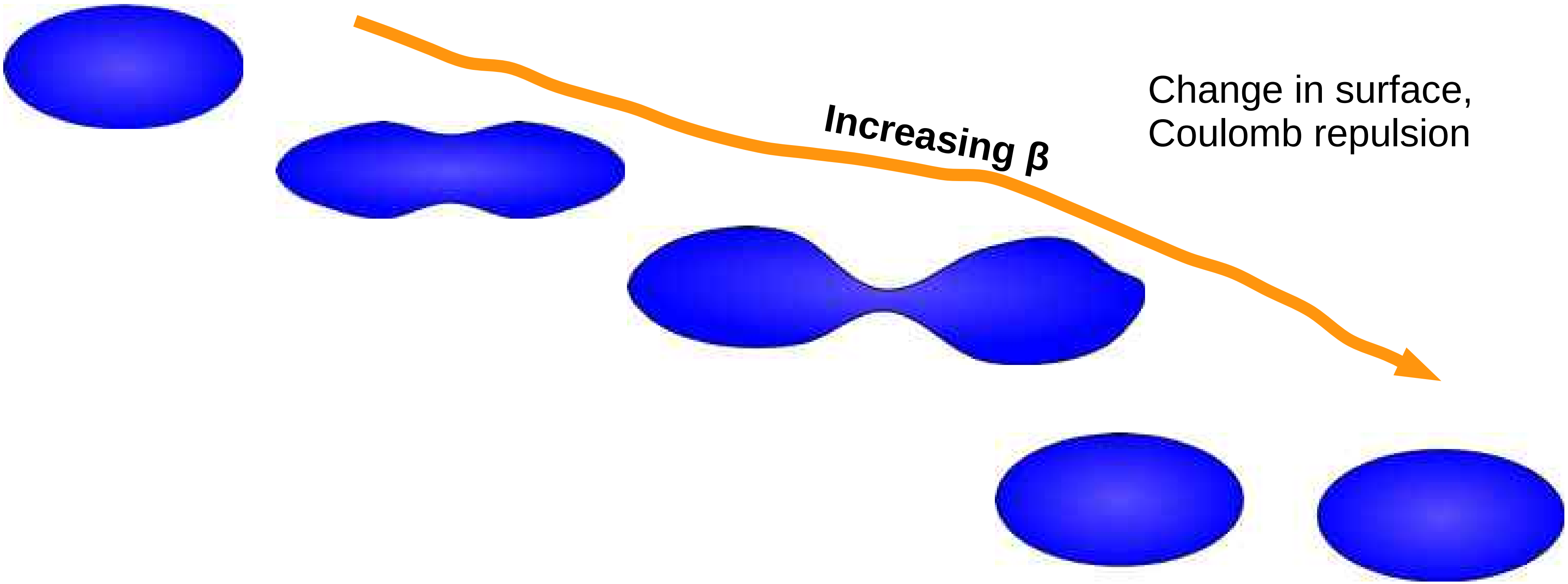
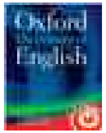


Change in surface,
Coulomb repulsion

Fission



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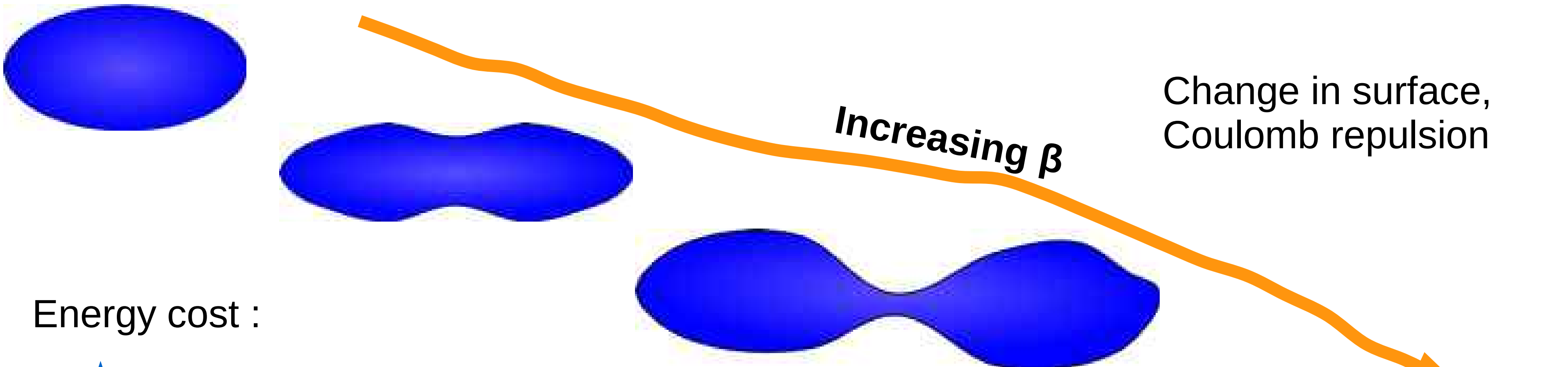
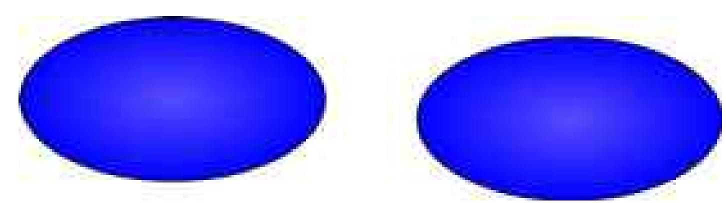
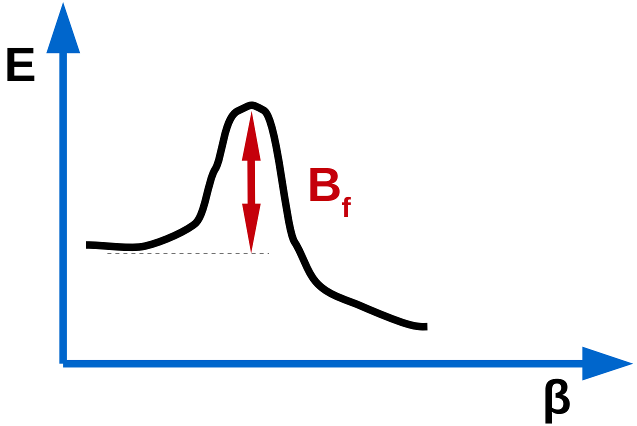




Energy cost :



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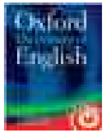

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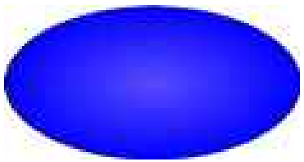

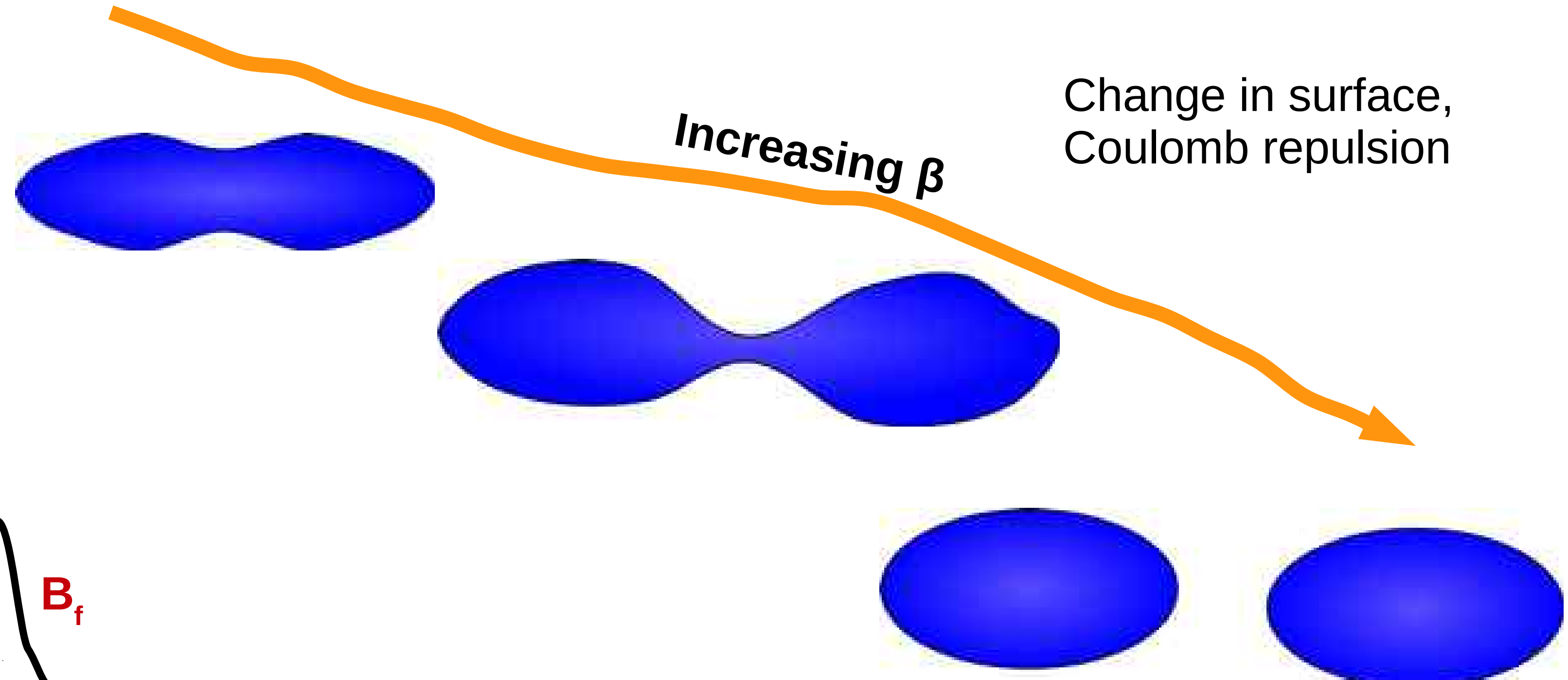

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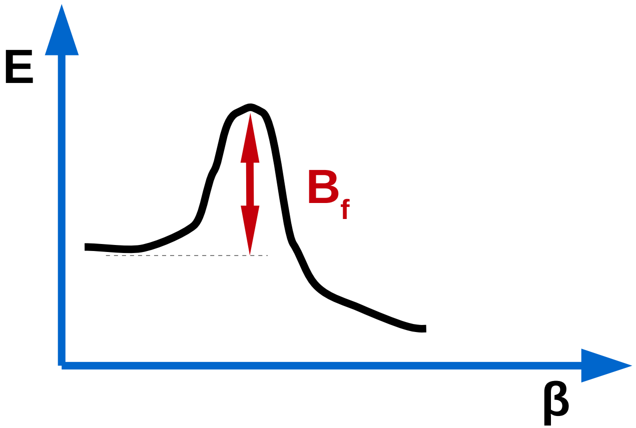

B_f can be calculated within the liquid drop model.

Fission

But: The nucleus is a quantum object!

➔ Tunneling through the barrier,

➔ *Shell effects* are present. (Actually: Z protons and N neutrons in Coulomb and nuclear interaction at the quantum scale.)

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→ **Calculation of B_f is not that easy...**

Fission

But: The nucleus is a quantum object!

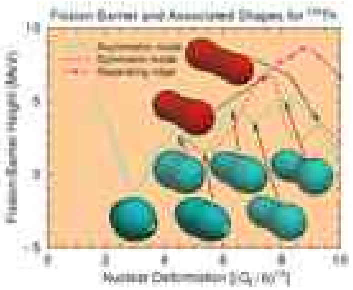
➔ Tunneling through the barrier,

➔ *Shell effects* are present. (Actually: Z protons and N neutrons in Coulomb and nuclear interaction at the quantum scale.)

→ **Calculation of B_f is not that easy...**

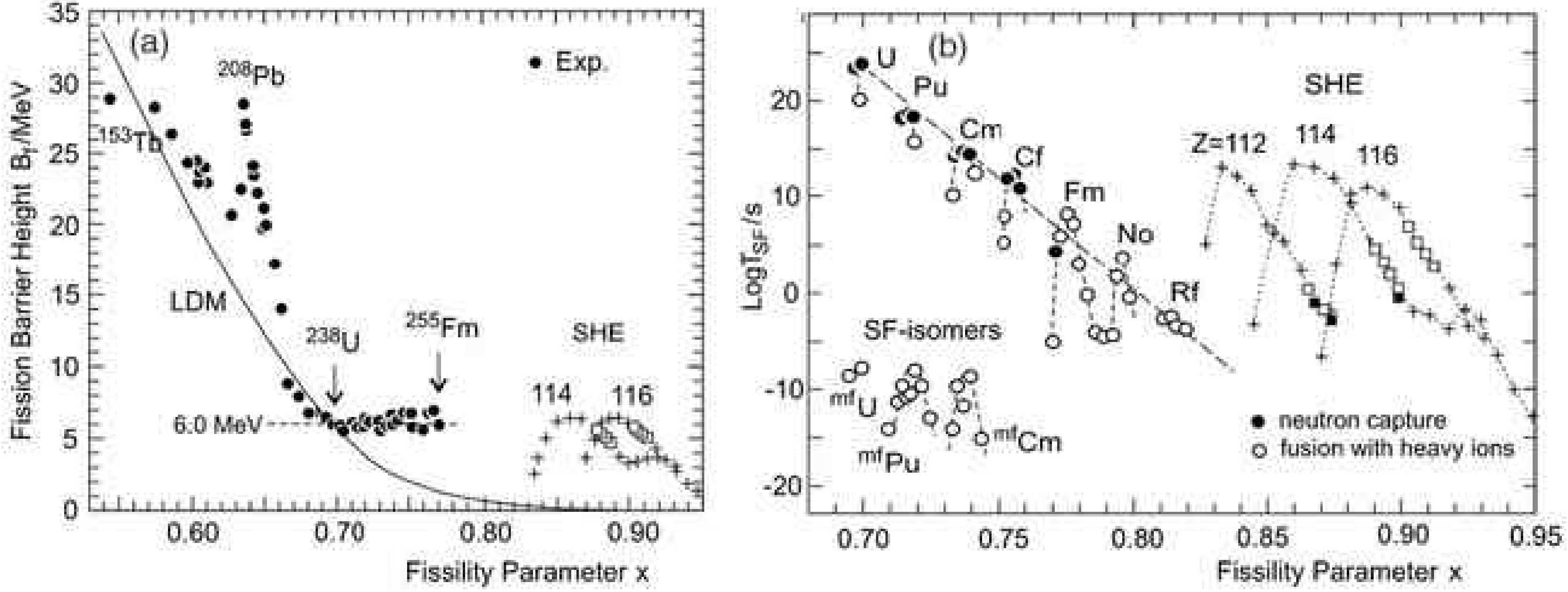
Several frameworks for calculation/determination:

- Microscopic-Macroscopic
- Density functional theory
- Phenomenological determination



B_f and SHE synthesis

B_f is a key parameter for the stability of SHE



Yuri Oganessian
J. Phys. G: Nucl. Part. Phys. **34** (2007) R165–R242

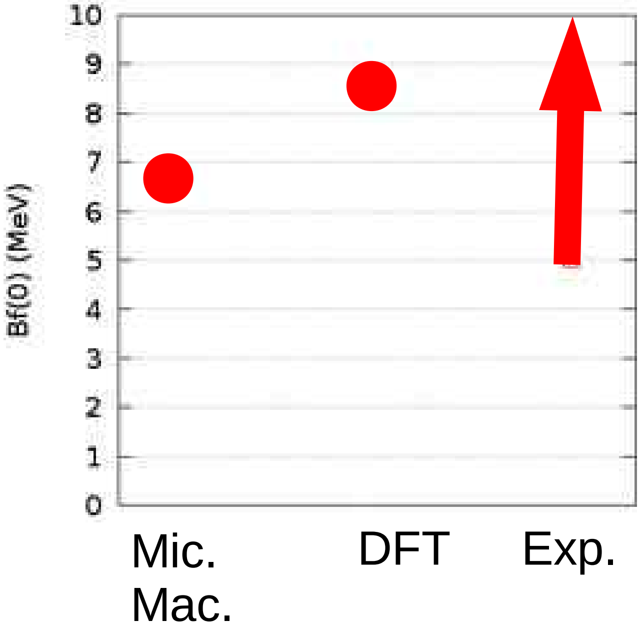
Study of ^{254}No

Why measure B_f in ^{254}No ?

- Production cross section *large* enough → ~1 µbarns
- Several prediction exist:
- Previously: exprimental lower bound limit

$$B_f > 5 \text{ MeV}$$

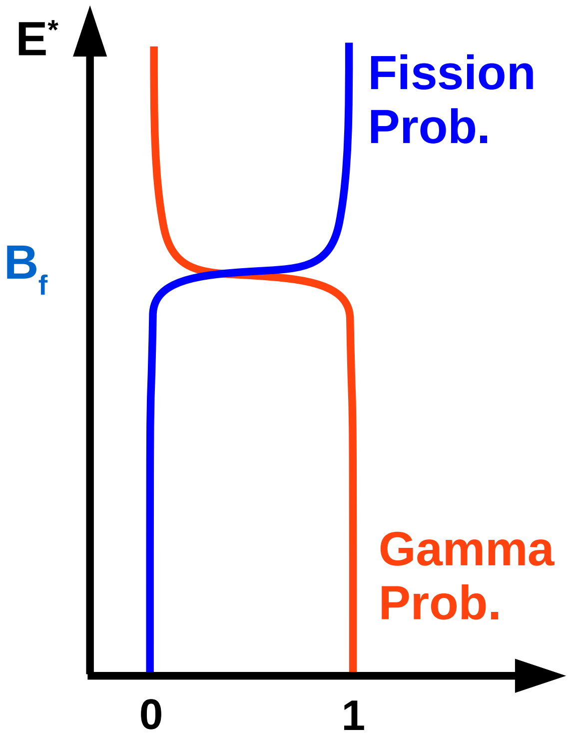
- Shell effect strength is large (B_f^{LD} = 0.9 MeV)



Method: competition Fission/Gamma

If $B_f < S_n$:

$$P_{fission} \approx \Gamma_{fission} / \Gamma_{fission} + \Gamma_{\gamma} \approx 1 - P_{\gamma}$$



Method: Gamma calorimetry

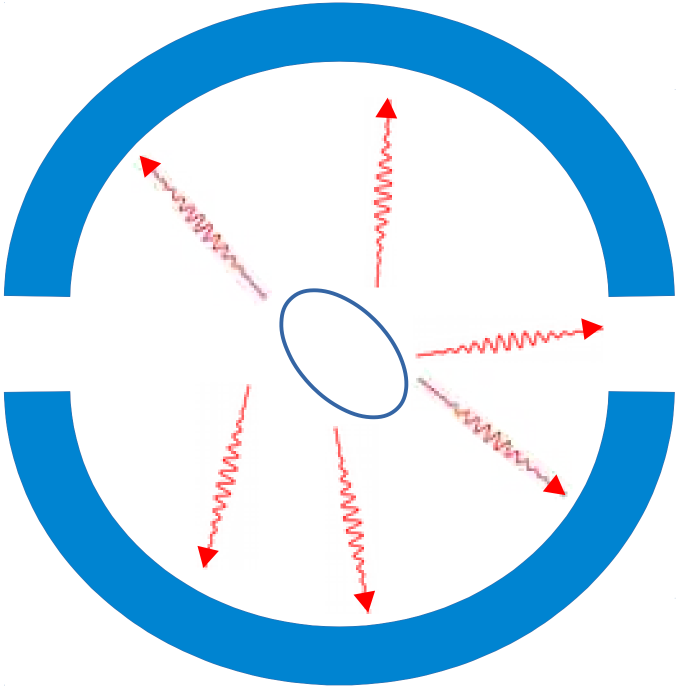
P_γ from calorimetric measurements :

- Detecting gamma emitted by the ER, vs. E*, I
- E* is the sum of the energies of particle evaporated by the nucleus, ending in its ground state.

$$E^* \approx \sum E_\gamma$$

- I is linked to the multiplicity of γ rays emitted

$$I = \sum \delta I_\gamma \approx \langle \delta I_\gamma \rangle \times M_\gamma$$



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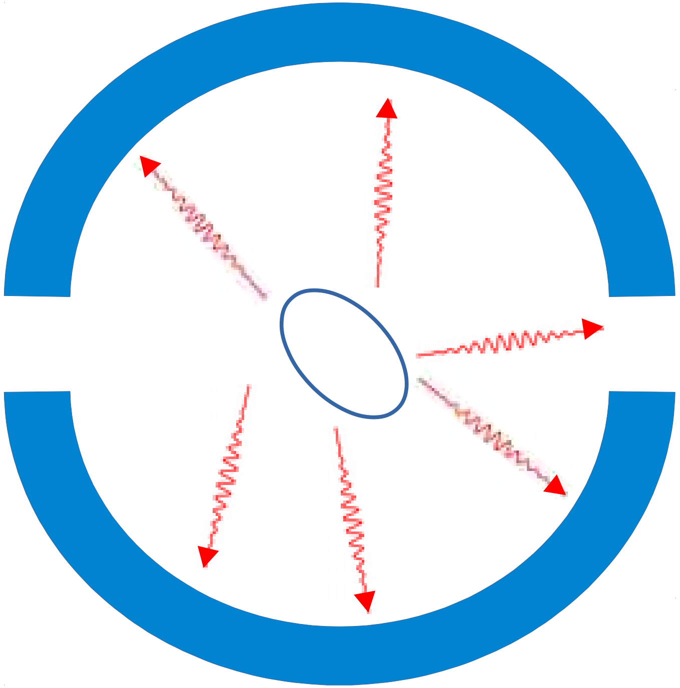
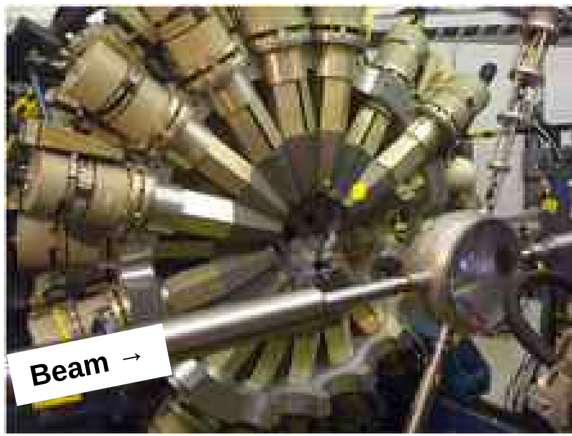
Some knowledge of the level structure needed.



Experimental setup

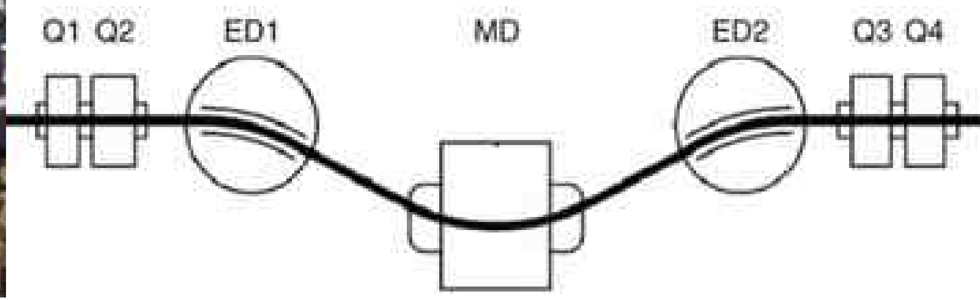
^{48}Ca @ 219, 223 MeV + ^{208}Pb → 2n + ^{254}No*

Gammasphere



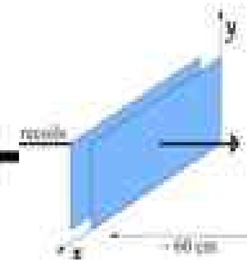
- ~ 100 modules (Ge+BGO)
- Detection efficiency:
  - Ge: 10%
  - Ge+BGO: 78%

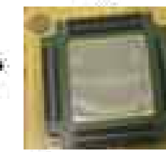
Fragment Mass Analyzer



- High selectivity in m/Q
- Poor transmission (7%)

Focal plane detectors





- Identify the evaporation residues

Data processing: unfolding

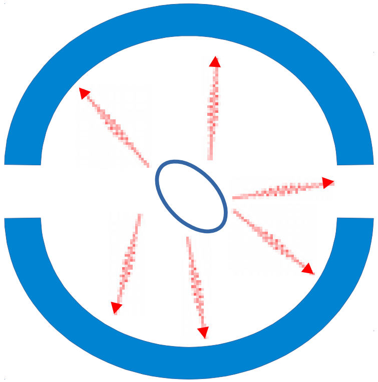
Collecting the total energy and multiplicity of emitted γ rays

Emitted

- ➔ M γ-rays
- ➔ Total energy E_{sum}

Measured

- ➔ Number of hits **k** (fold)
- ➔ Total energy **H**



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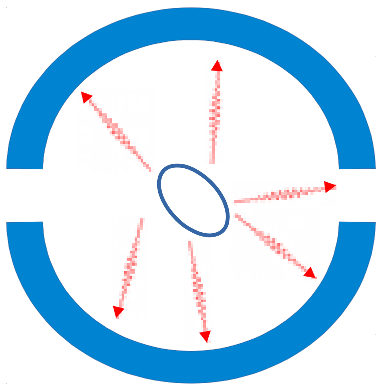
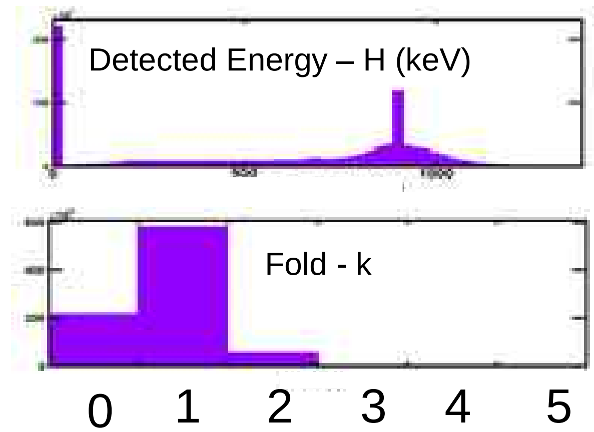


Calibrate the relation between k and M, H and E

^{88}Y: E_1 = 1836 kev
E_2 = 898 keV



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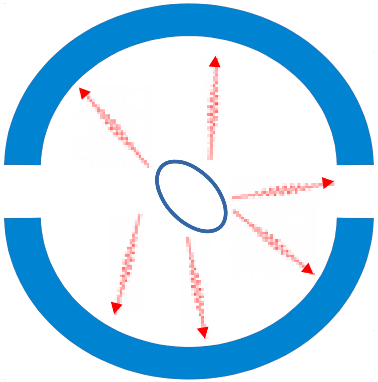

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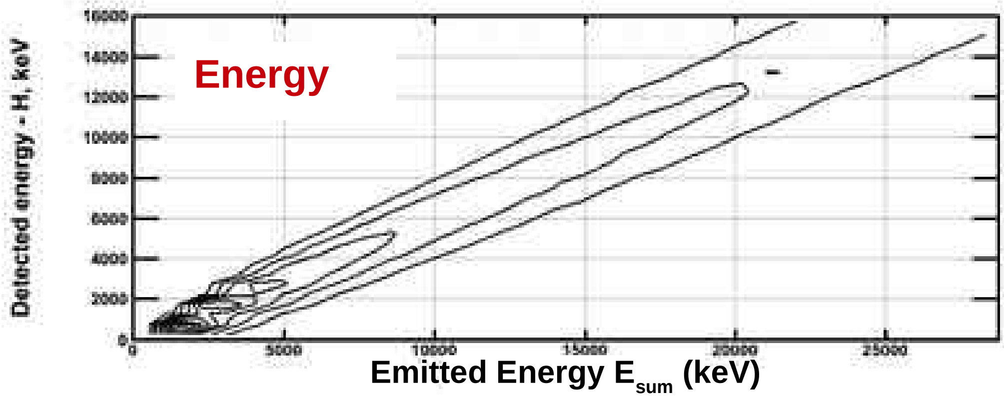
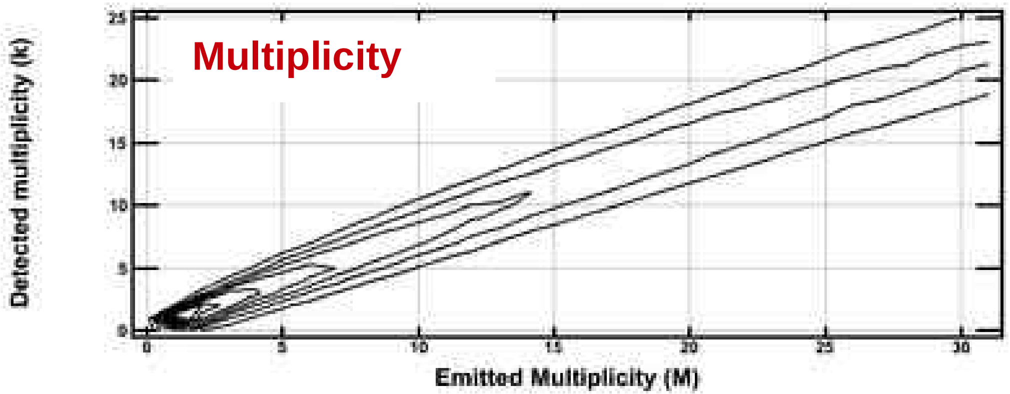


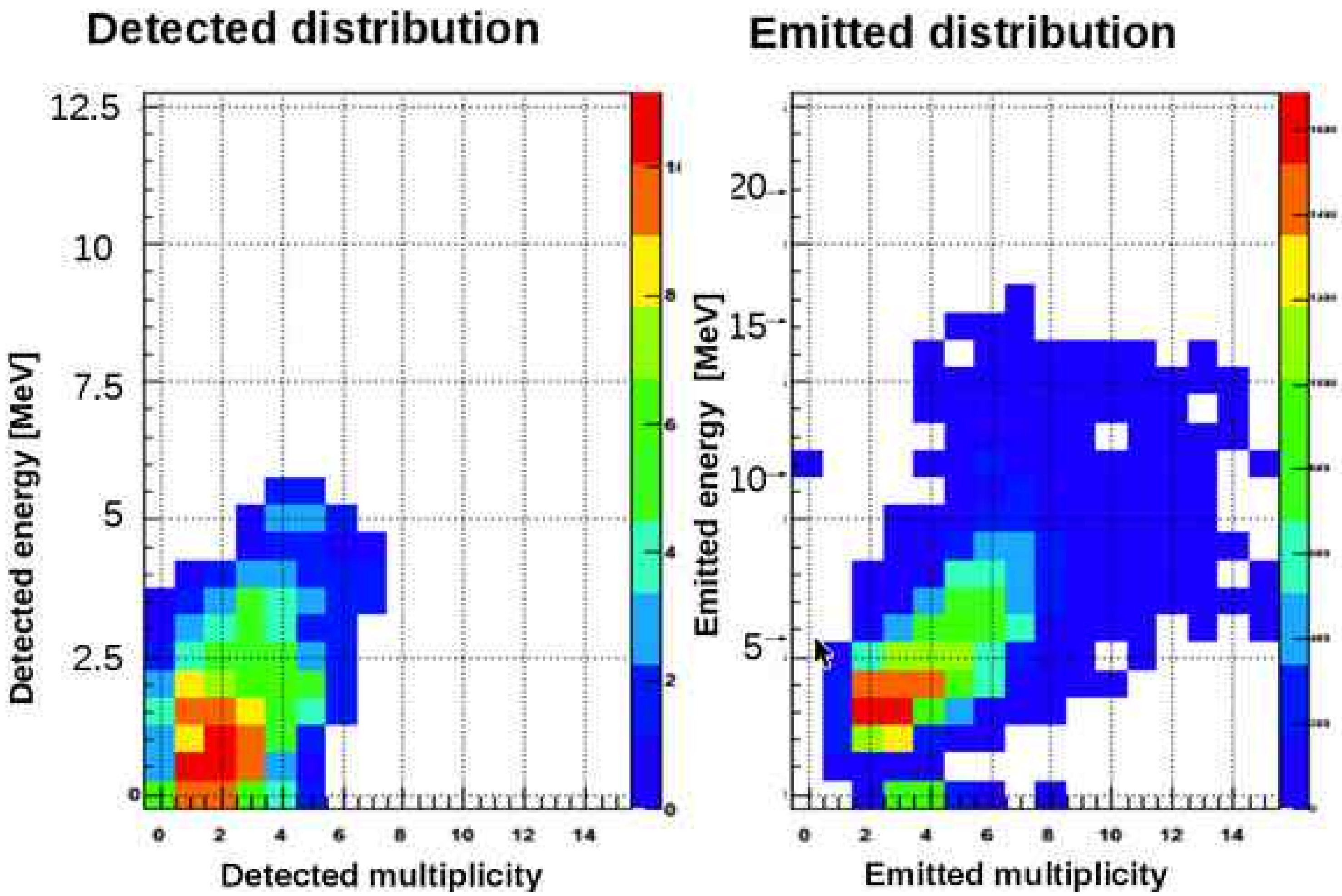


Calorimetric Efficiency: **H/E = 63 %**
Detection Efficiency**: k/M = 70 %**

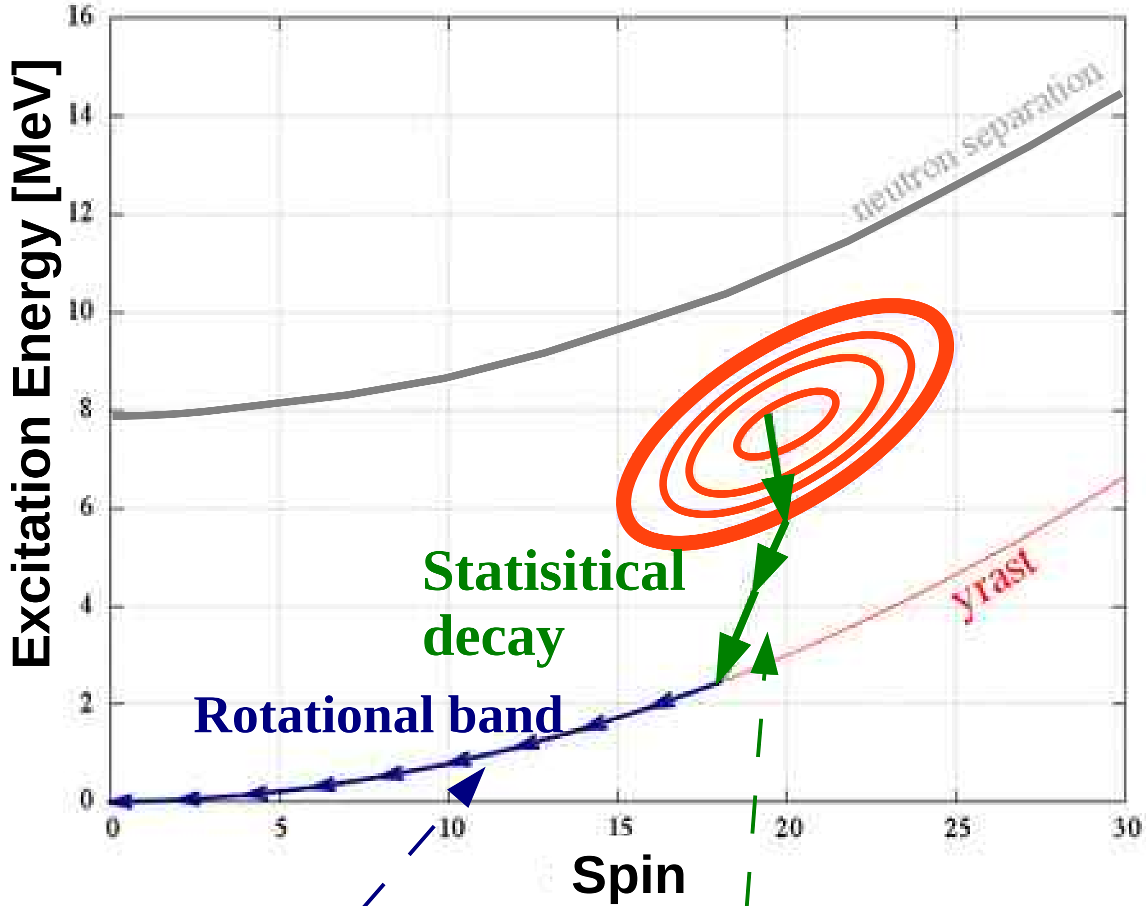
Reconstructing emitted distribution Mgamma, Egamma

Using a Statistical *unfolding* method

Reconstructing emitted distribution Mgamma, Egamma



Reconstructing Entry distribution



Conversion electrons

$$I = \Delta I\,(M - N_{stat}) + \Delta I_{stat}\,N_{stat} + I_{electrons}$$

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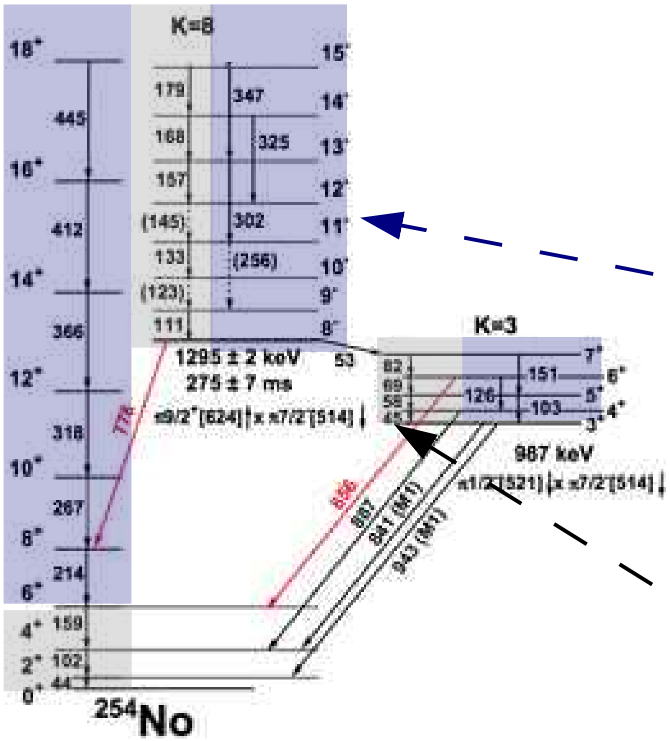


Statistical decay

$N_{stat} \sim 3$

$\Delta I_{stat} \sim 0.5\ \hbar/\gamma$

Rotational bands

$\Delta I = 2\ \hbar/\gamma$

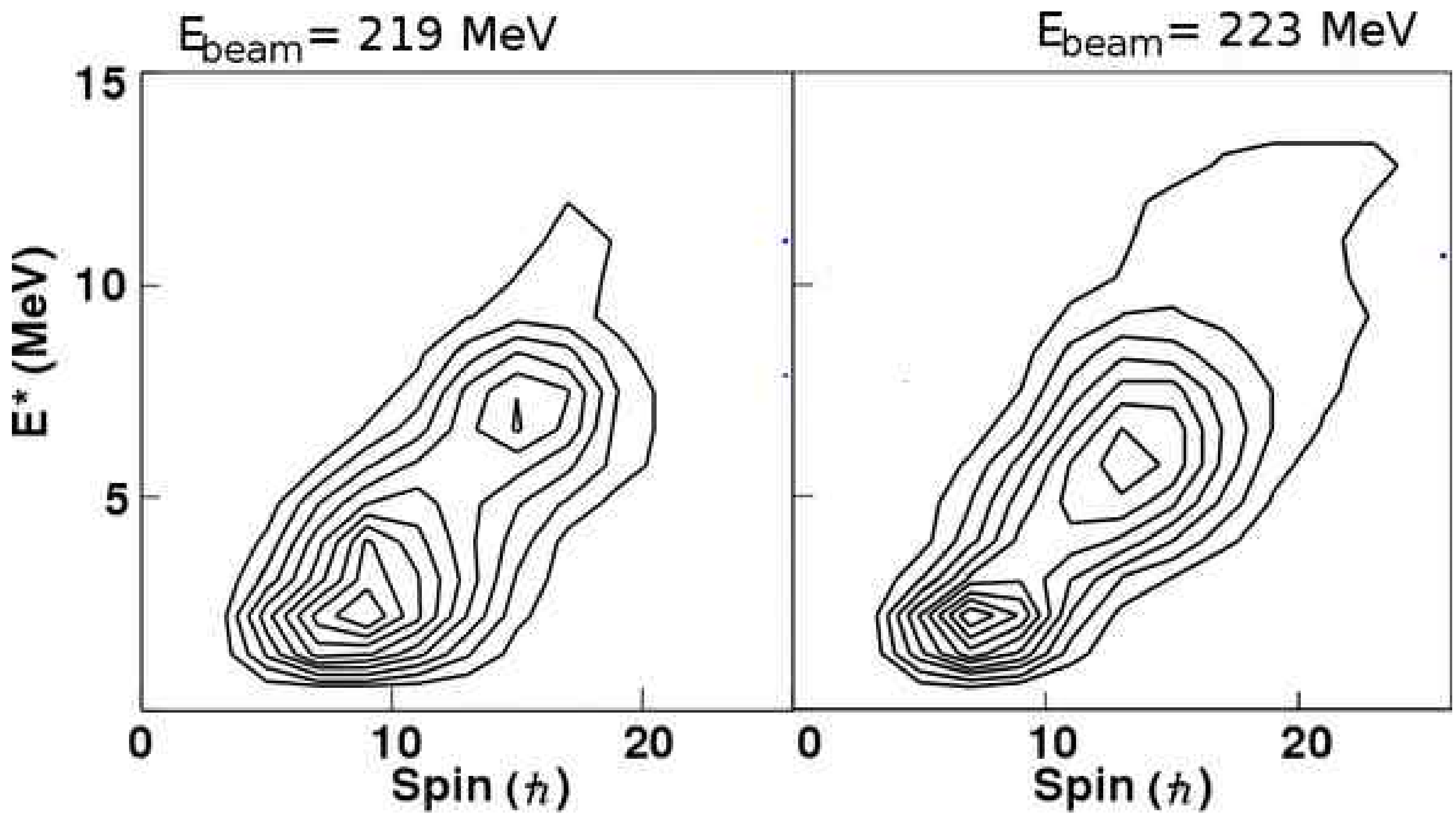
Conversion electrons

$I_{electrons} \sim 8\ \hbar$

$E_{electrons} = 900\ keV$

M. Leino et al., Eur. Phys. J. A 6, 63–69 (1999)
P. Reiter et al., Phys. Rev. Lett., vol 82 (1999) 509
S. K. Tandel et al., Phys. Rev. Lett. **97,** 082502 (2006)
F.P. Heßberger et al., Eur. Phys. J. A 43, 55–66 (2010)
R.M. Clark et al., Physics Letters B 690 (2010) 19–24
R.-D. Herzberg et al., Nature 442 (2006) 896

Entry distribution



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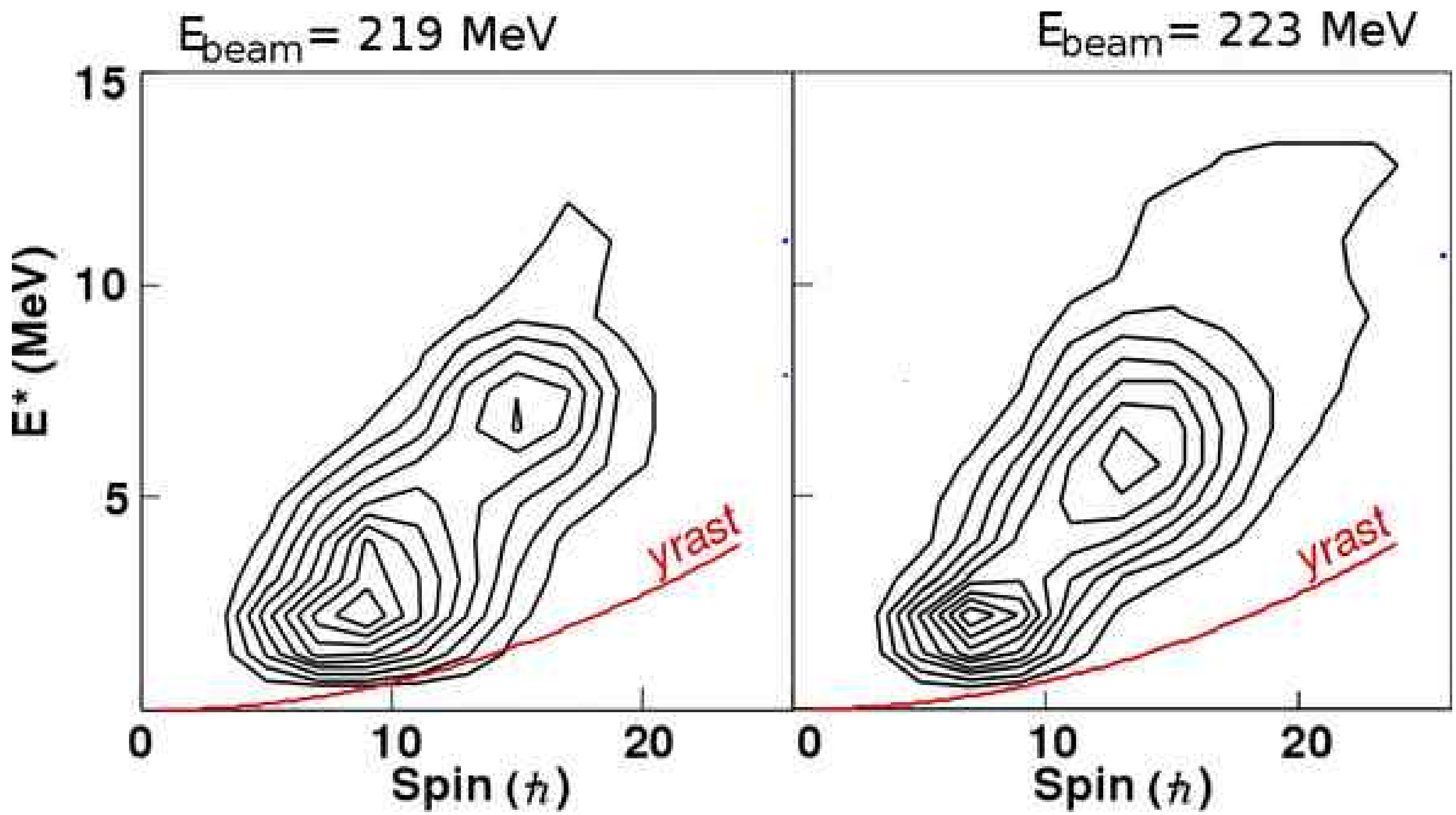

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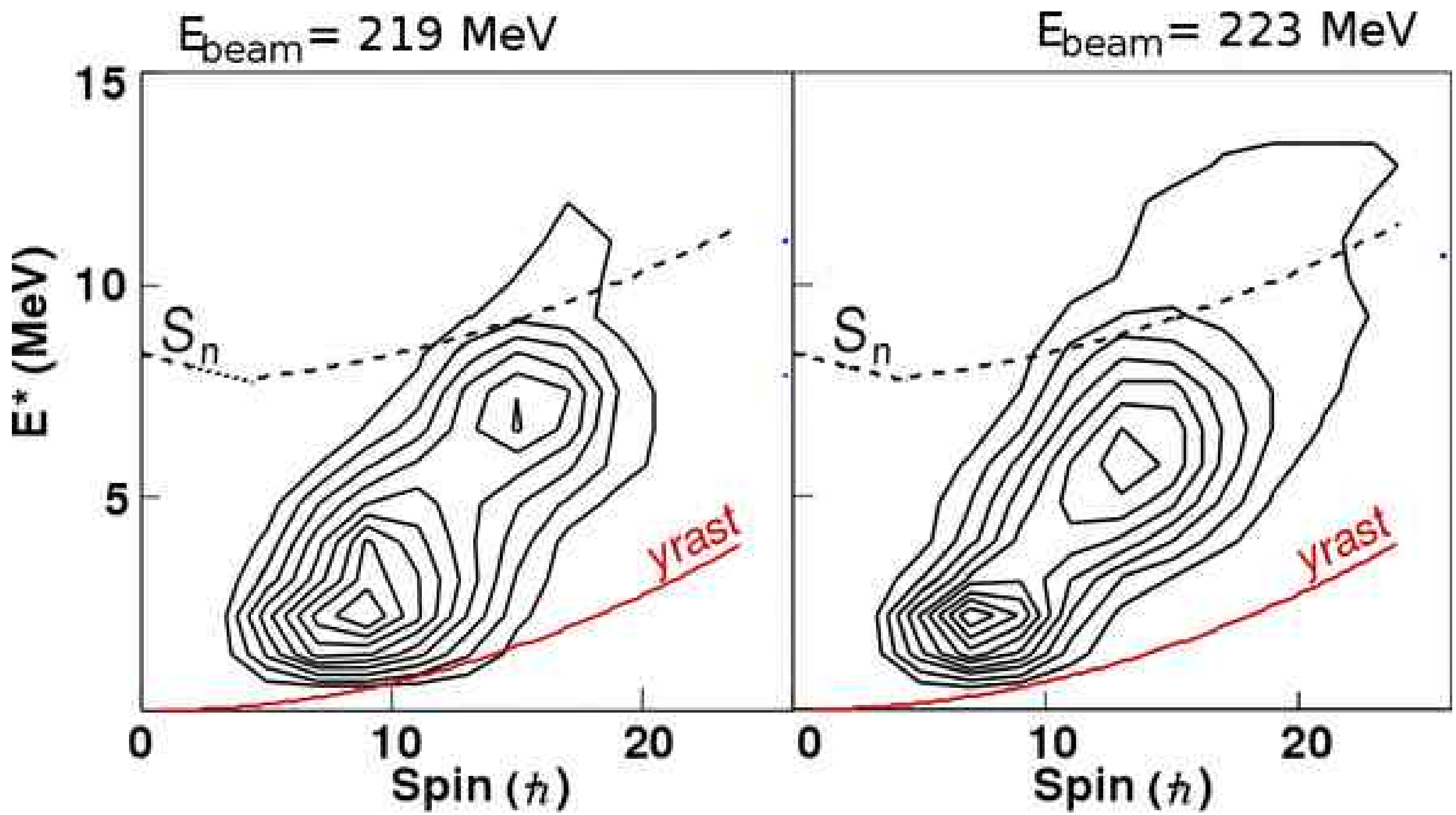

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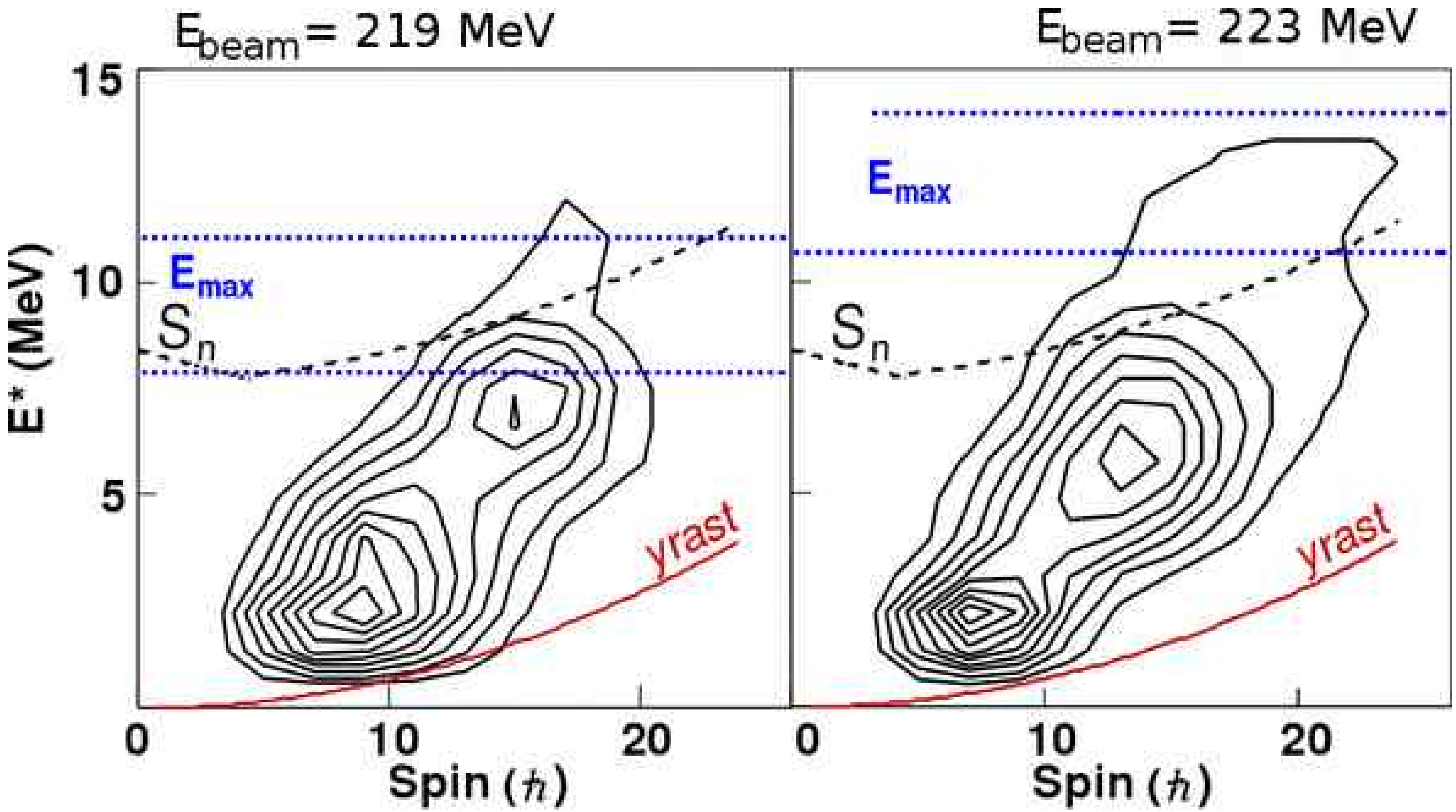

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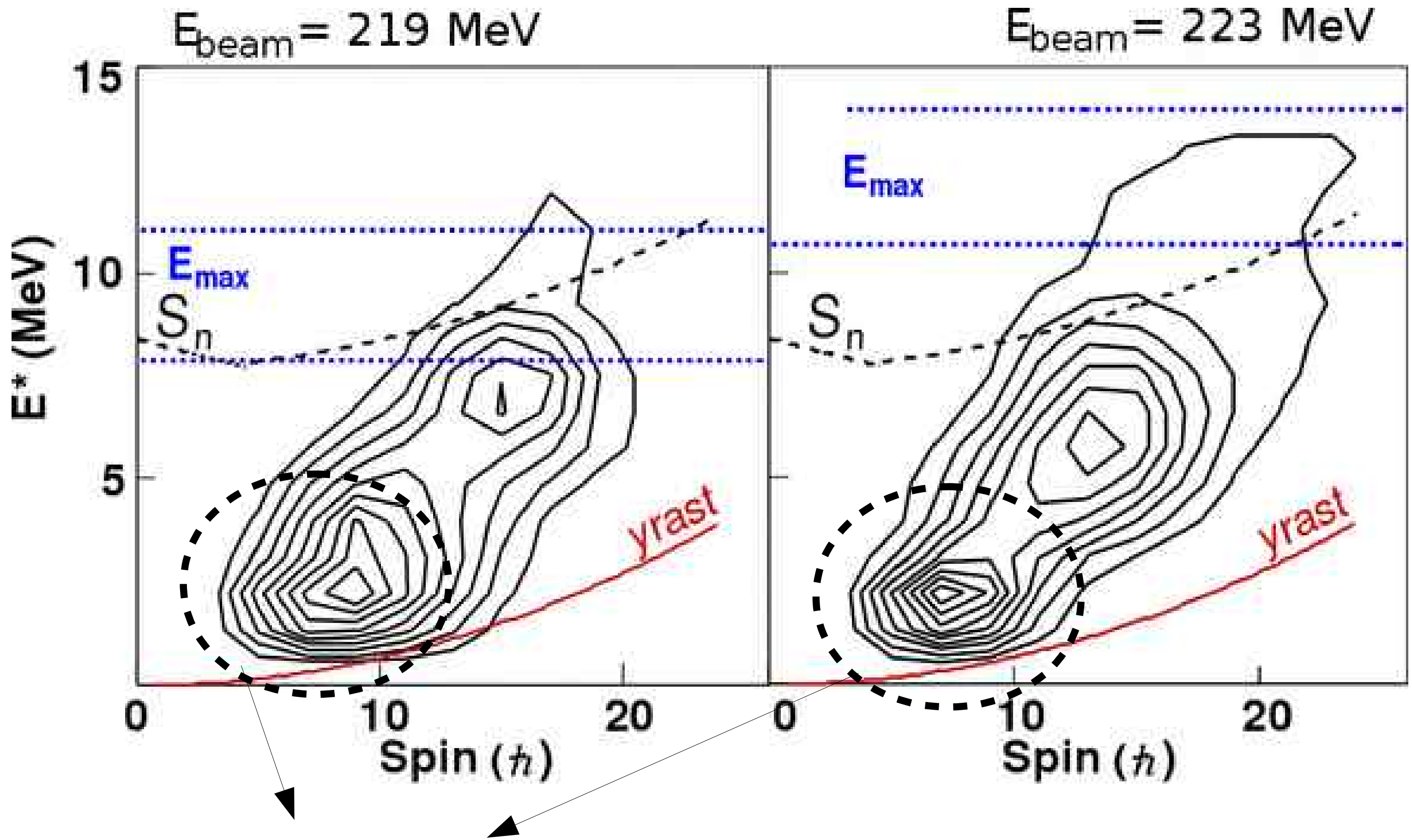
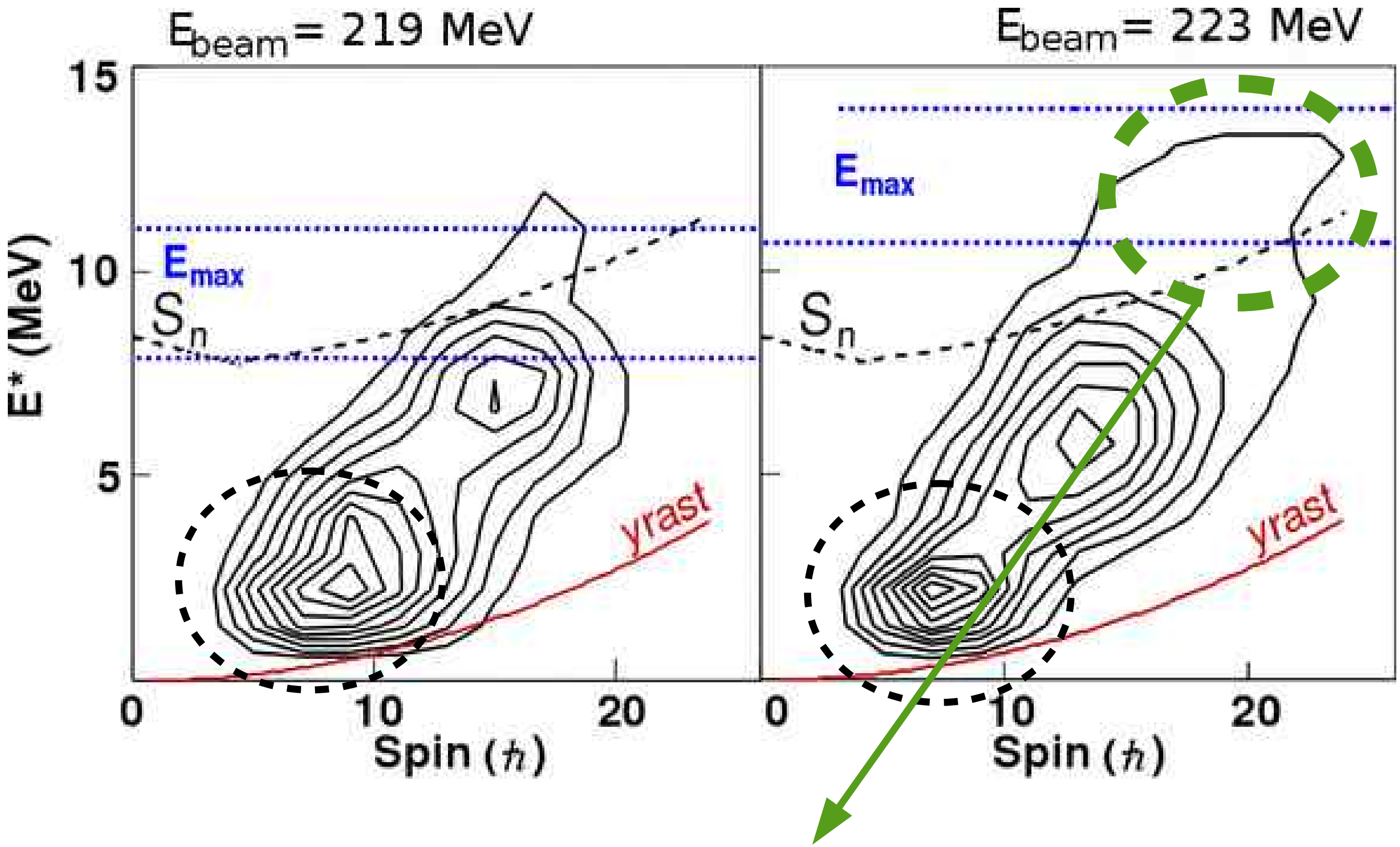


Isomer events: reconstructed at the wrong I, E*

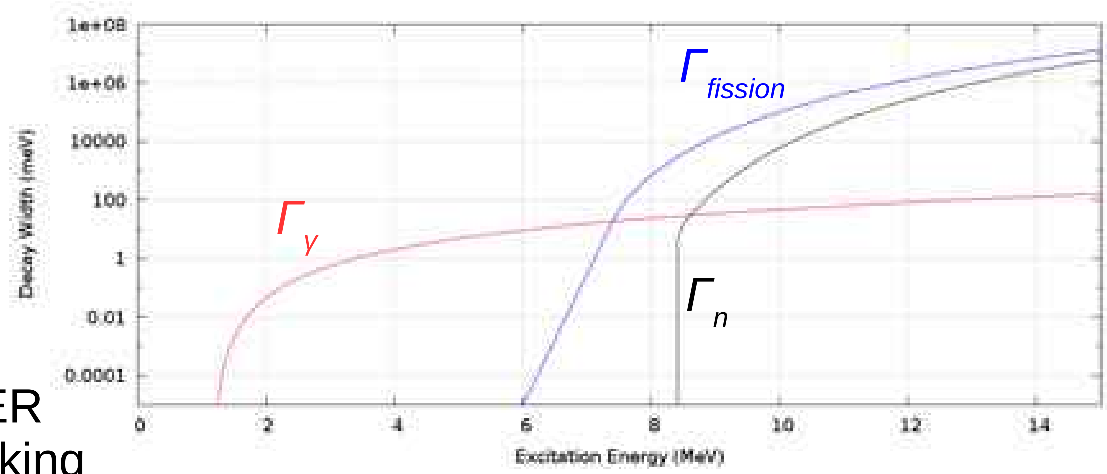
Entry distribution



Tail toward high E* from random summing with reaction background

Maximum E* at a given spin ?

$$N_\gamma(E^*) = \frac{\Gamma_\gamma(E^*)}{\Gamma_{total}(E^*)} \times D(E^*)$$



If we control for the population of the ER *D(E*)*, then the fall of N_γ reflects the taking over of gamma decay by fission.

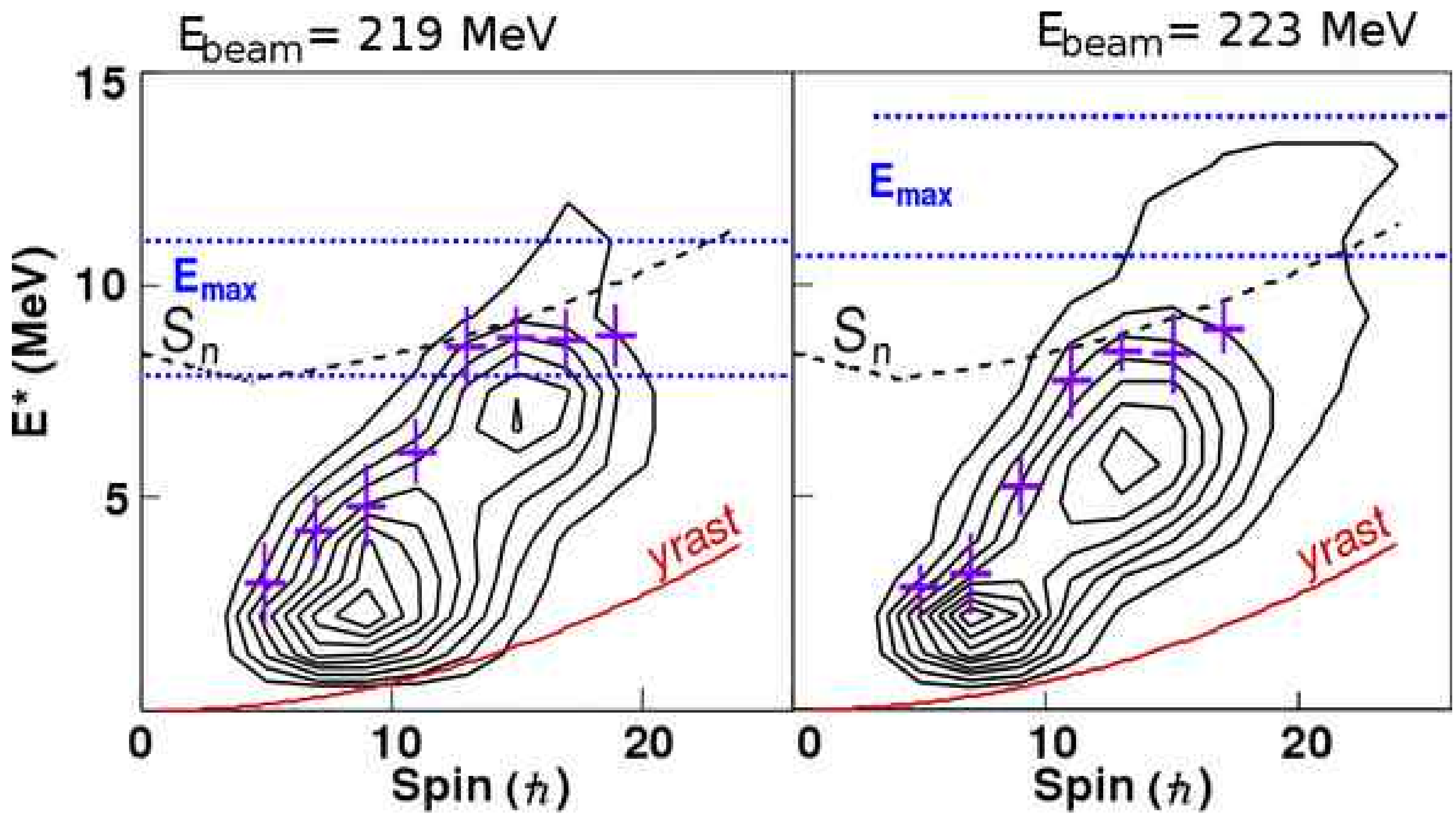
To account for the distribution of formed ER, study with calculation codes :

- NRV,
- KEWPIE2.

Extract relationship between the energy $E_{1/2}$ where N_γ(E*, I)=1/2 and E_{saddle}(I) : $\Delta(I)=E_{1/2}-E_{saddle}$

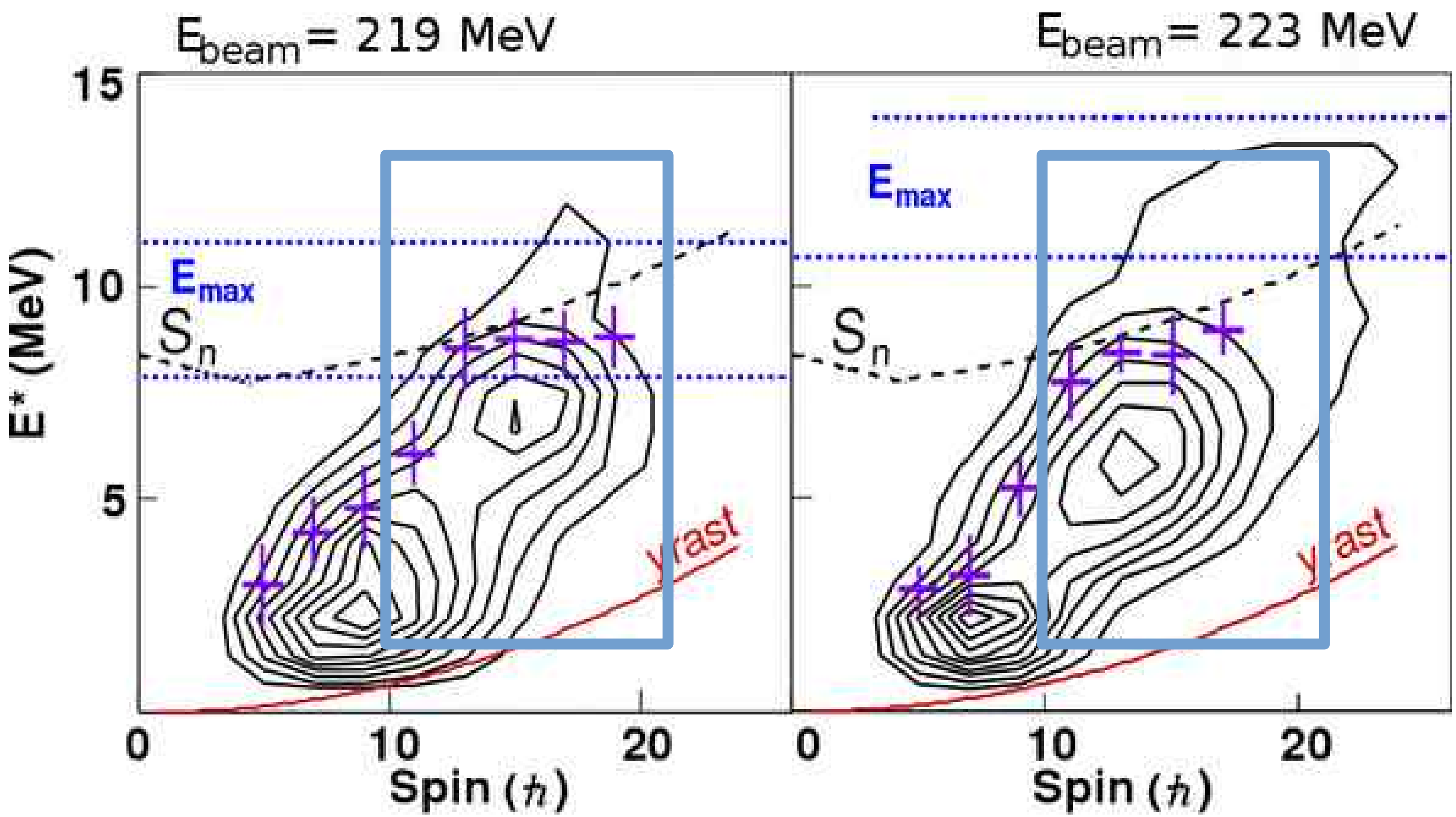
$$\Delta(0\hbar) \approx 1\,MeV \qquad \Delta(20\hbar) \approx 0\,MeV$$

$E_{1/2}$



E_beam = 219 MeV
E_beam = 223 MeV
15
10
5
E* (MeV)
E_max
E_max
S_n
S_n
yrast
yrast
0
10
20
0
10
20
Spin (ħ)
Spin (ħ)

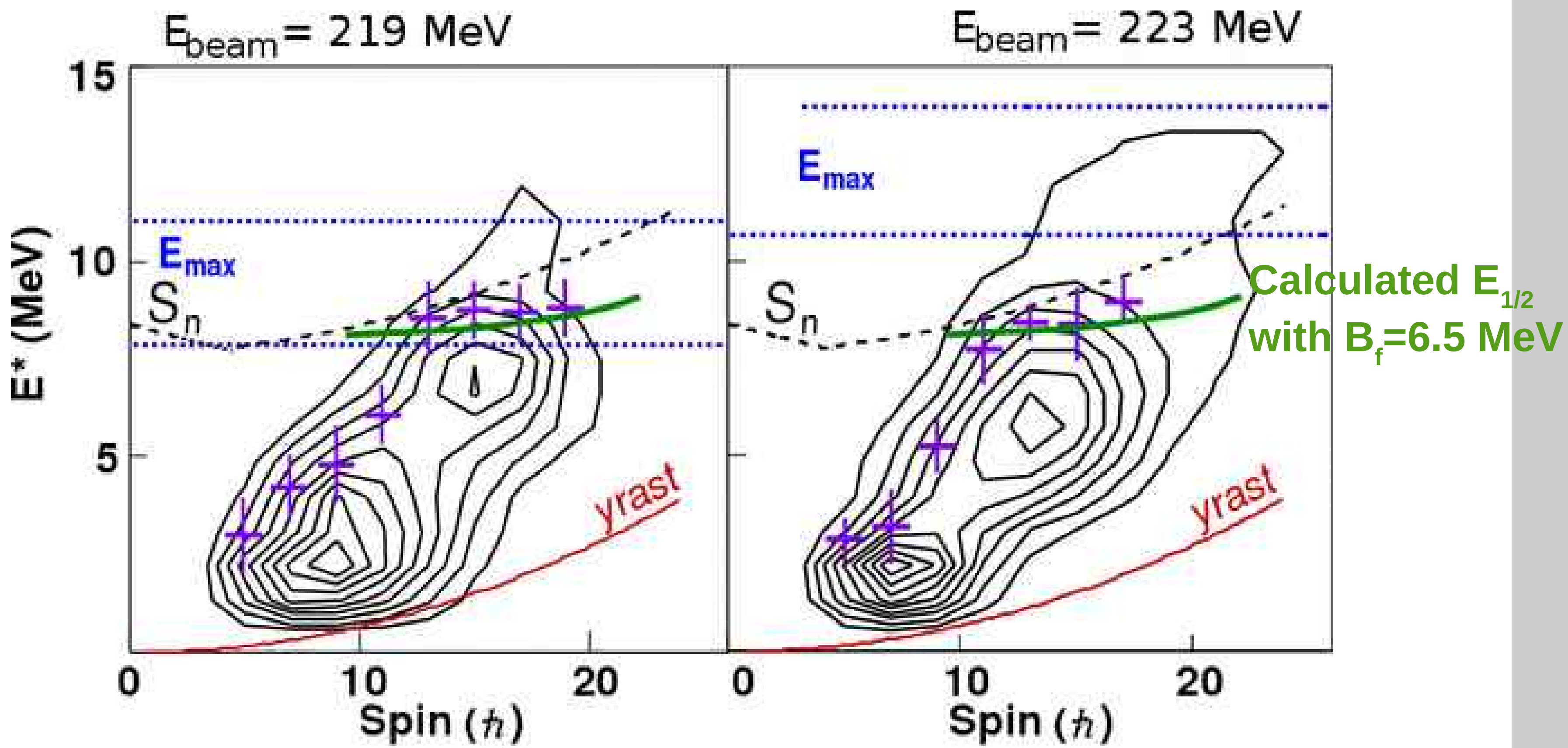
$E_{1/2}$



Range of interest for the Entry distribution

Where the fission has an impact on the entry distribution

$E_{1/2}$: experiment vs. calculation



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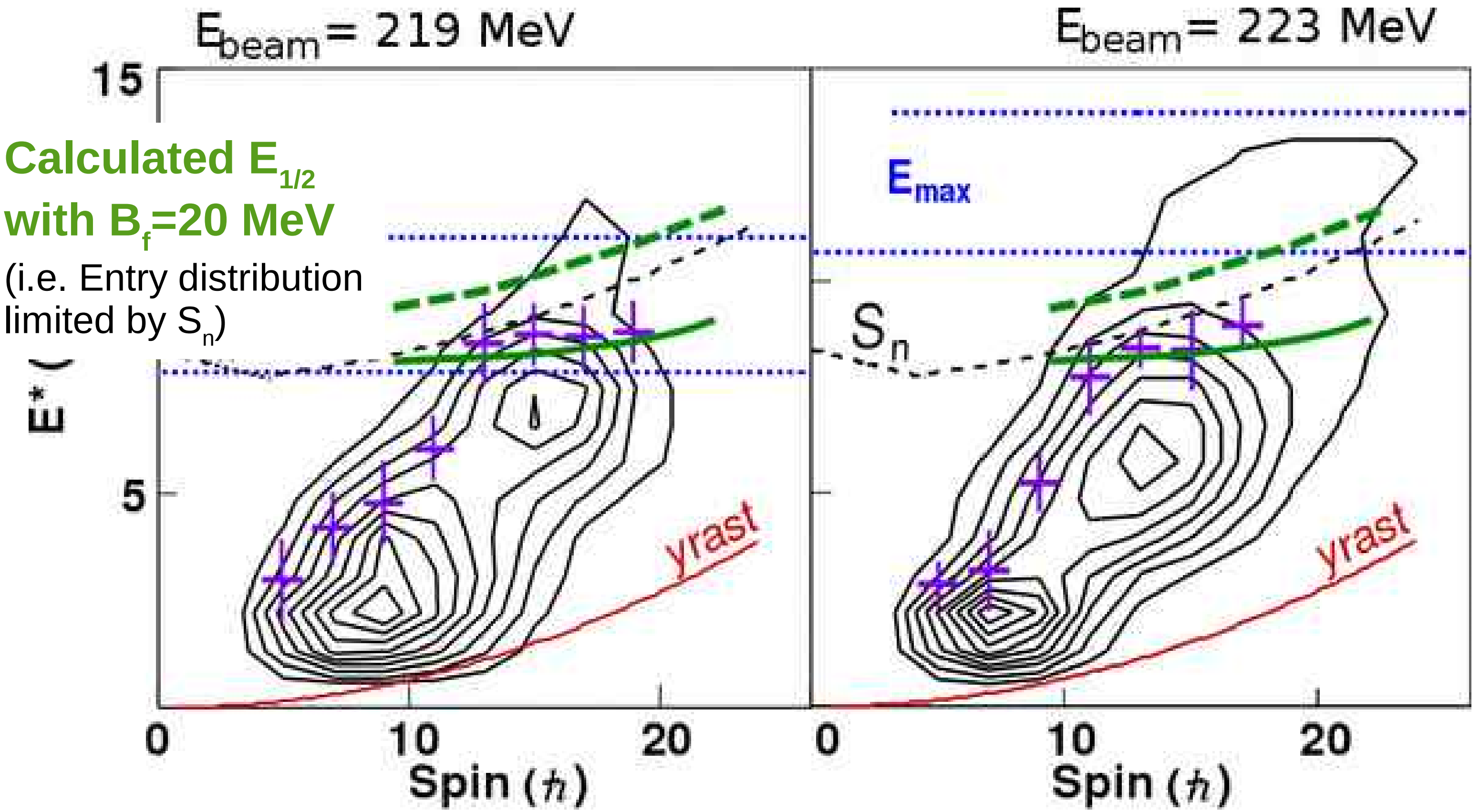
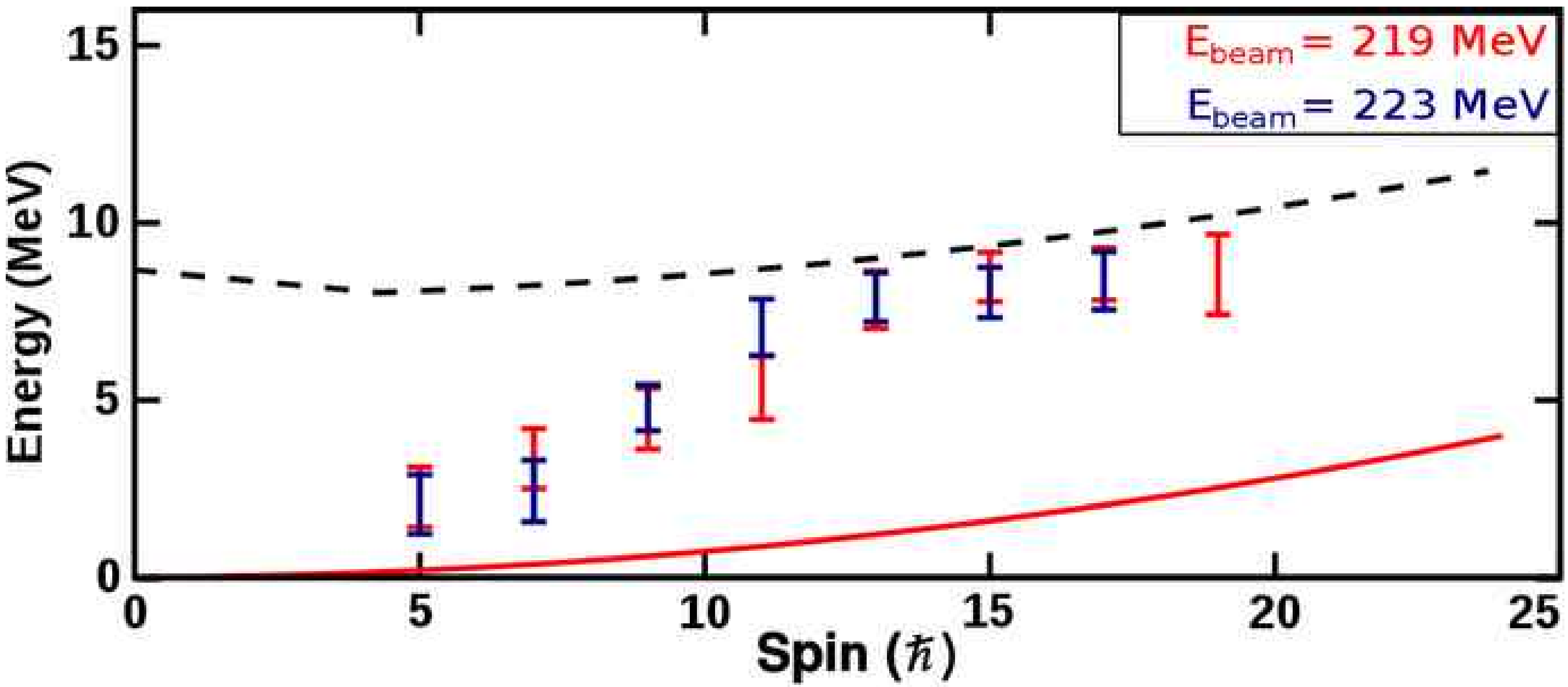


Calculated $E_{1/2}$ with B_f=20 MeV

(i.e. Entry distribution limited by S_n)

Extracting $E_{saddle}(I)$

- Multiple unfoldings to take care of statistical variation in the process,
- For each resulting entry distribution, extract $E_{1/2}$,



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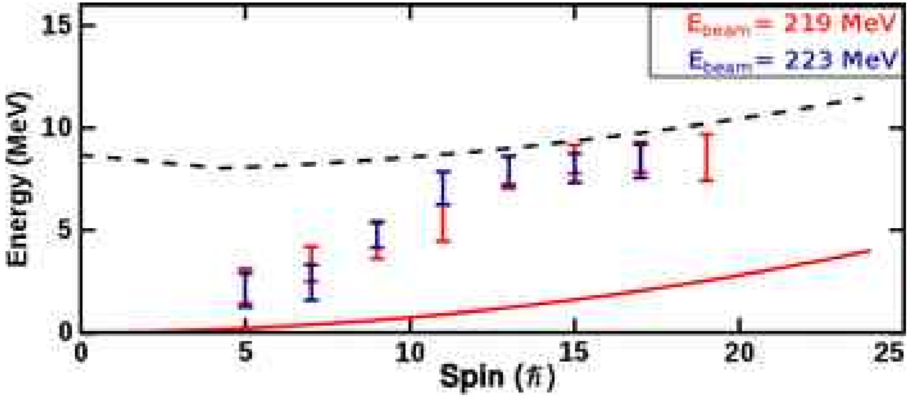

For I in [13, 19], fit on $$E_{saddle}(I)=B_f(0)+\frac{I(I+1)}{2J_{saddle}}$$

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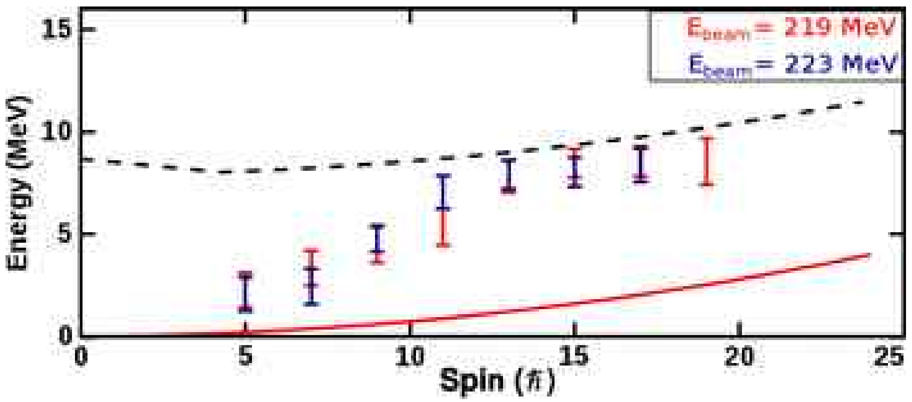
- Multiple unfolding to take care of statistical variation in the process,
- For each resulting entry distribution, extract $E_{1/2}$

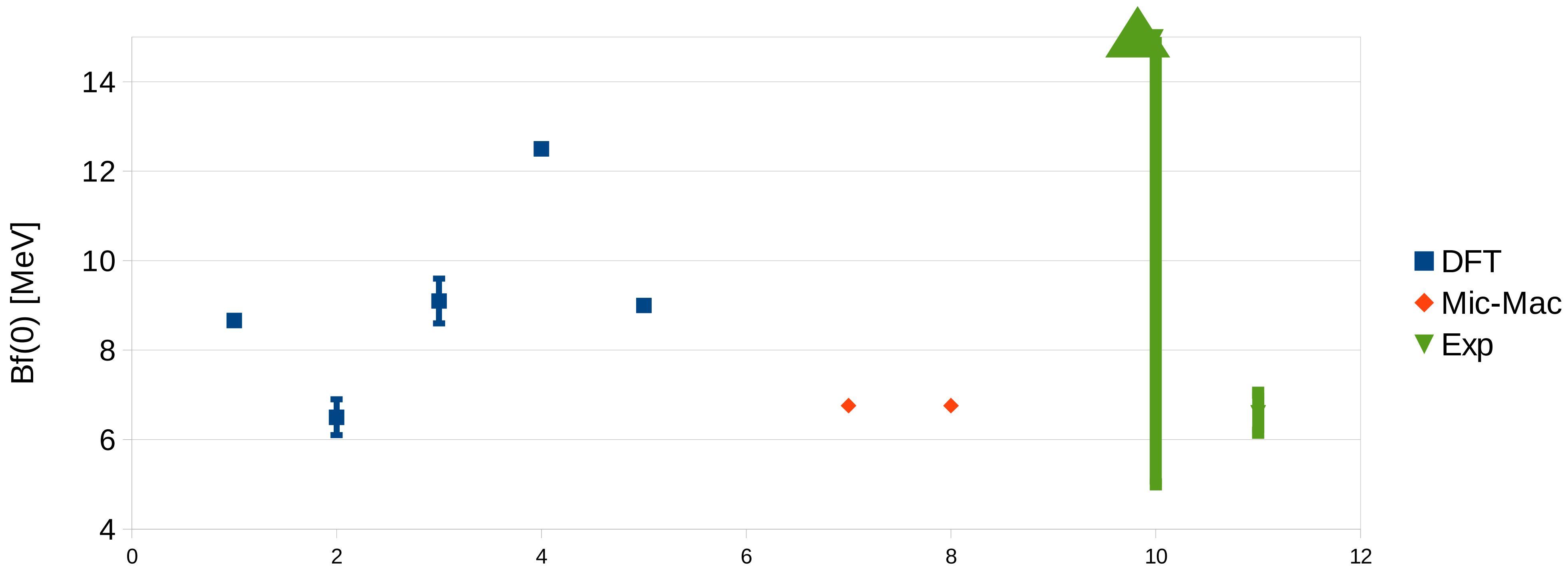


For I in [13, 19], fit on $E_{saddle}(I) = B_f(0) + \frac{I(I+1)}{2J_{saddle}}$

$B_f(0) = 6.6 \pm 0.9$ MeV

$J_{saddle} = 125 \pm 60$ $\hbar^2$/MeV (corr = 0,95)

Results compared to existing predictions



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2 J.P. Delaroche et al., Nuclear Physics A 771 (2006) 103.
3 L. Bonneau, et al., Eur. Phys. J. A 21, 391 (2004).
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10 P. Reiter, et al., Phys. Rev. Lett. 82, 509 (1999).
11 G. Henning et al., Phys. Rev. Lett. 113, 262505

Looking to the future

- Experimental improvements
- Data interpretation and theory

Coming soon...

Digital Gammasphere
- Make use of GRETINA digitizer
- Will allow higher count rate

→ resolve difficulties with calorimetry

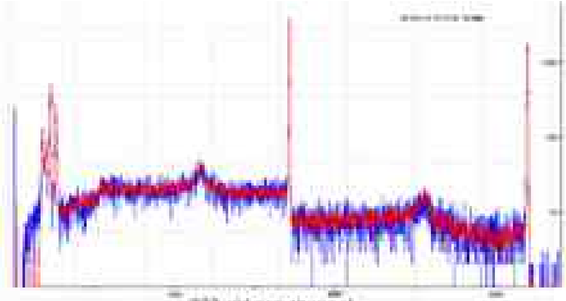
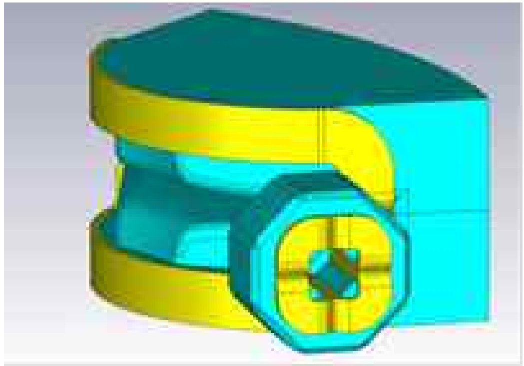


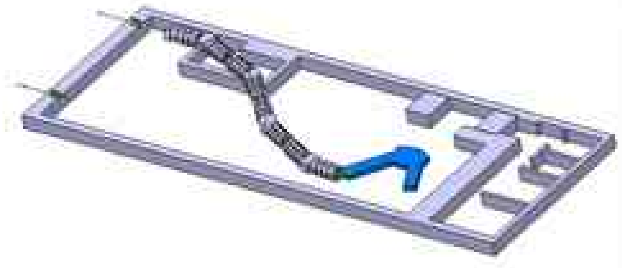
Fig. 9. Comparative spectra from old and new Gammasphere DAQ

AGFA
- Argonne Gas Filled Analyzer
- Quadrupole + Dipole
- Short length and large acceptance

→ improve recoil detection efficiency (70% foreseen for ^{254}No)



S^{3}



- Super Separator Spectrometer
- Good reaction product separation
- Diversity of focal plane instrumentation

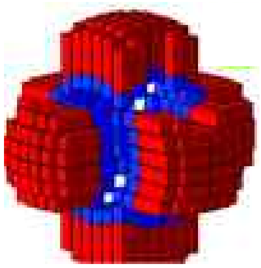
But... Calorimetry at the target position ?

AGATA or GRETA

- Arrays of Ge crystal with pulse shape analysis and tracking
- May be useful for calorimetry once reaching 4π

PARIS

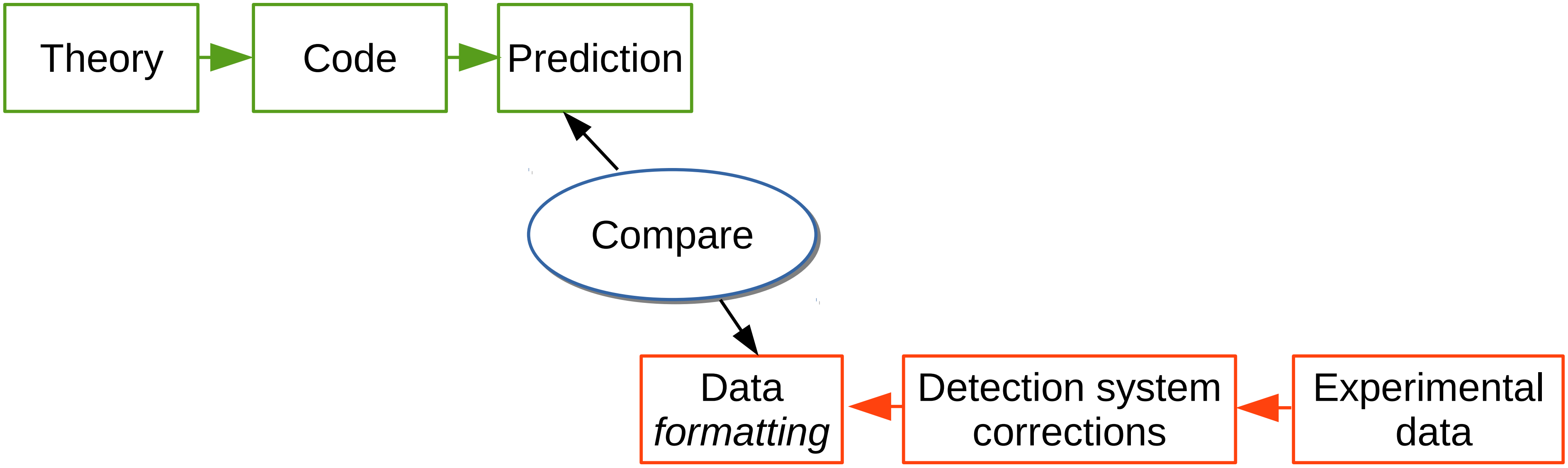
- Photon Array for studies with Radioactive Ion and Stable beams
- Medium resolution spectroscopy and calorimetry of γ-rays in large energy range
- Aimed at reaction mechanism studies



Your favorite Gamma array and separator ?

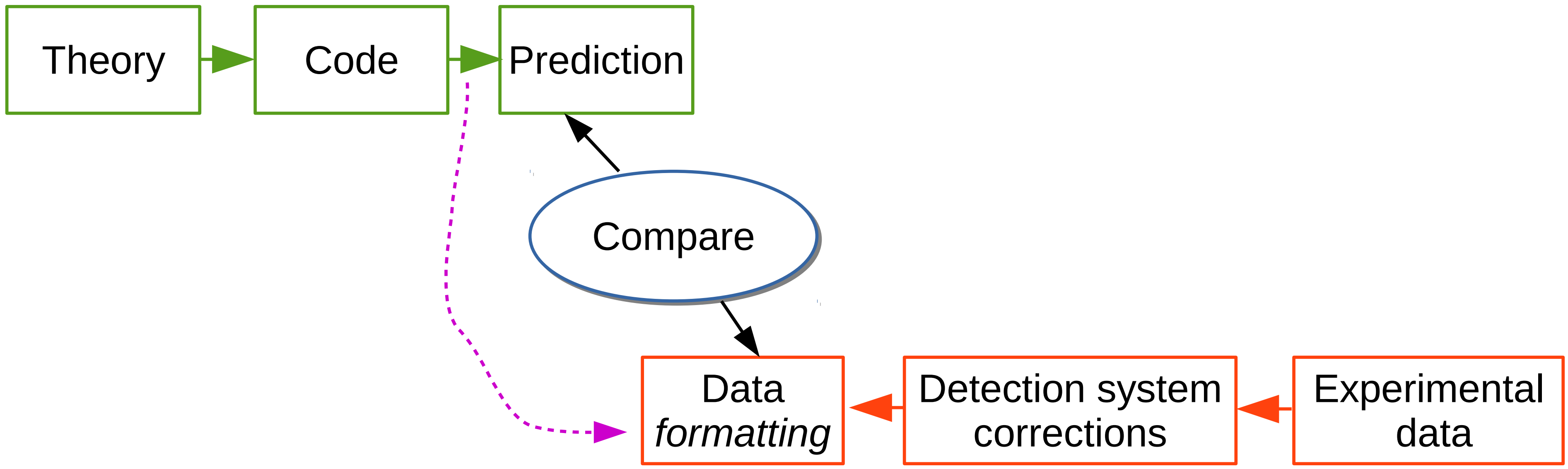
- Some energy resolution and detection efficiency required
- Try it!

Interpretation scheme followed in this work:



Data interpretation

Interpretation scheme followed in this work:



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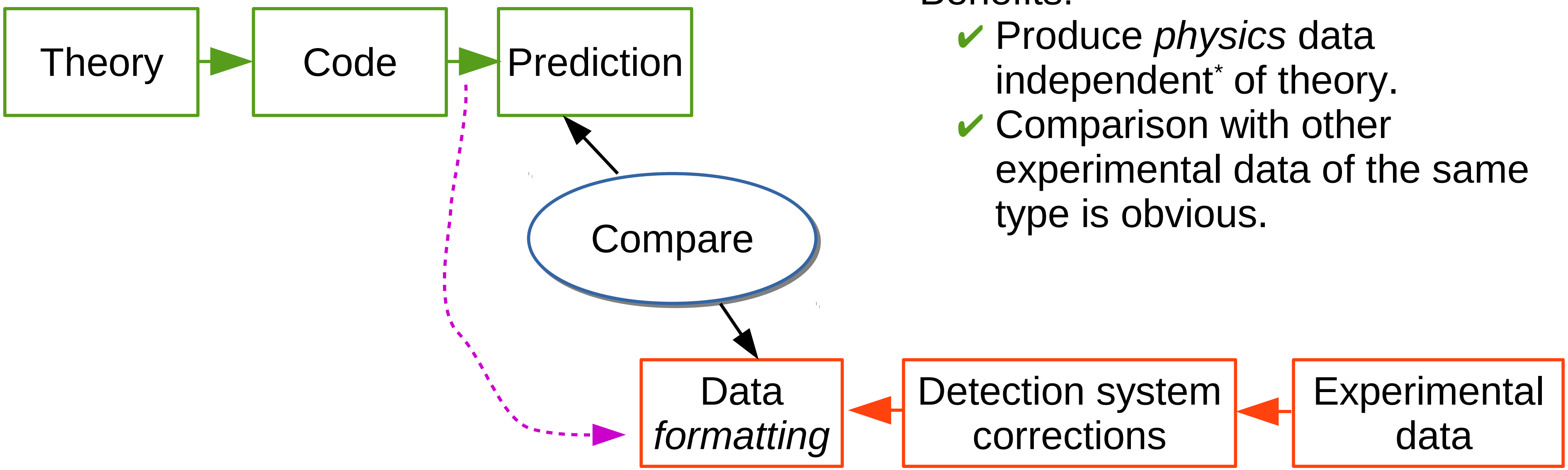


Benefits:

- ✔ Produce *physics* data independent* of theory.
- ✔ Comparison with other experimental data of the same type is obvious.

Limitations:

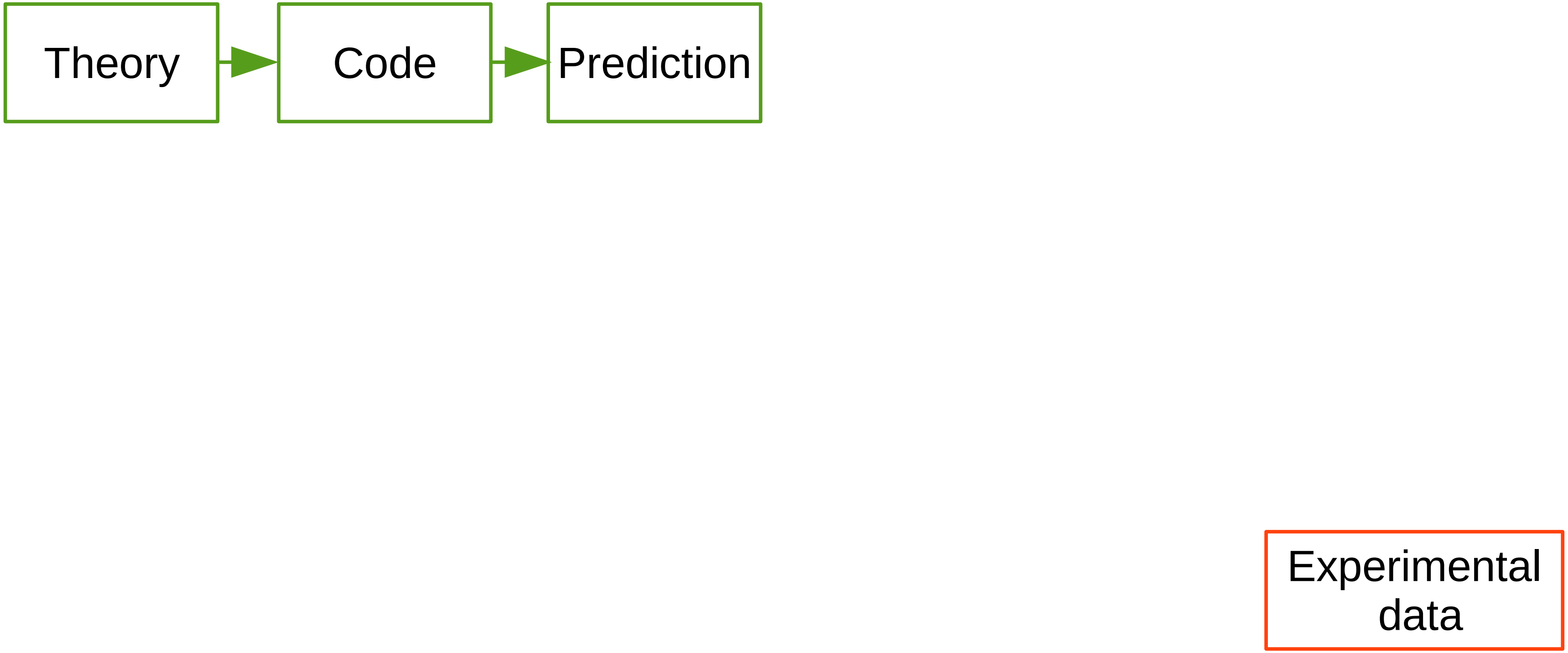
- ✗ Formatted data is not an observable (case of B_f).
- ✗ Some assumptions on physics used.

Interpretation scheme: Experimental data is a benchmark of theory

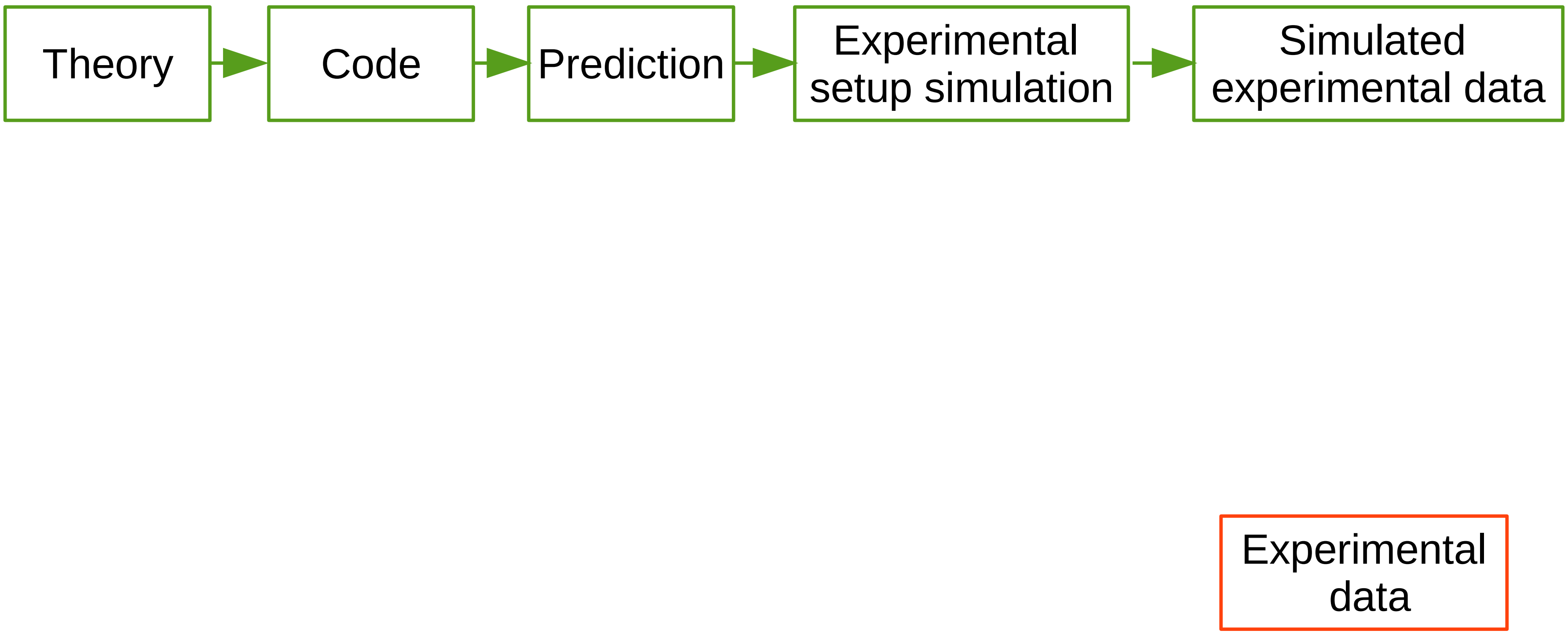
Theory

Experimental data

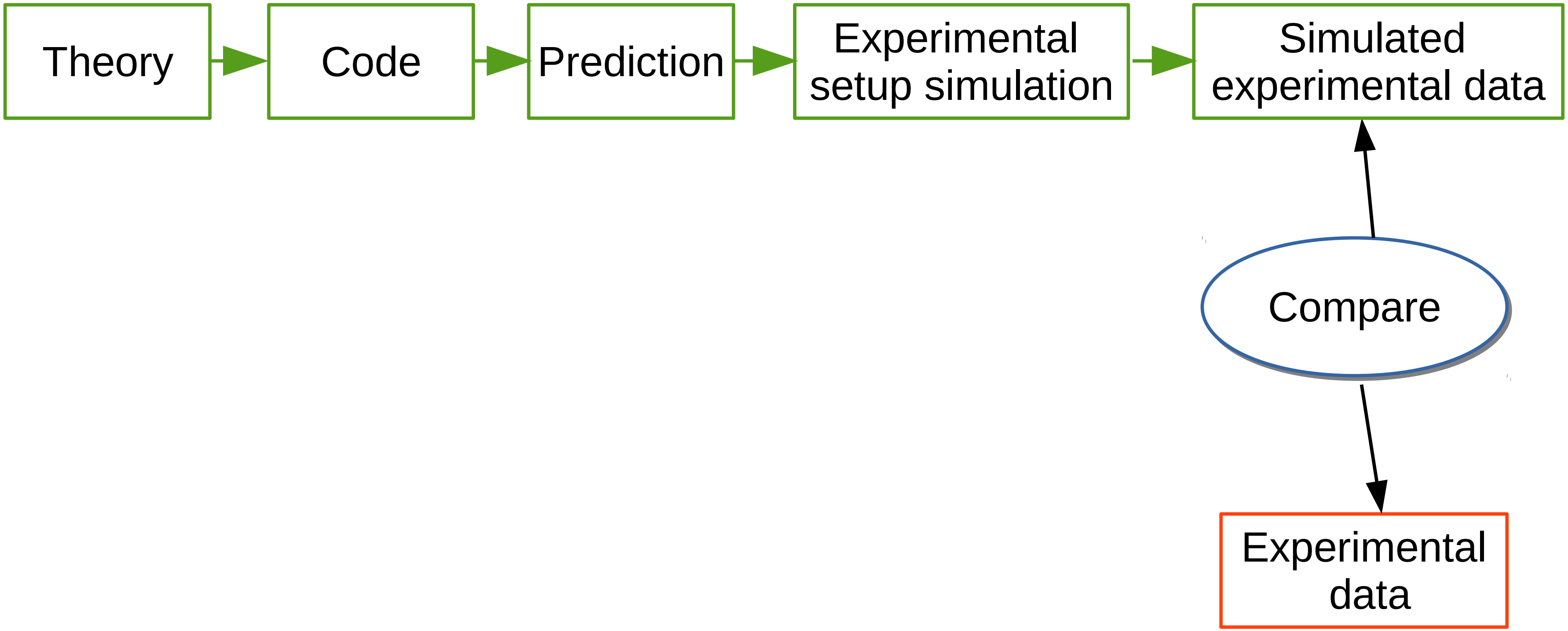
Interpretation scheme: Experimental data is a benchmark of theory



Interpretation scheme: Experimental data is a benchmark of theory



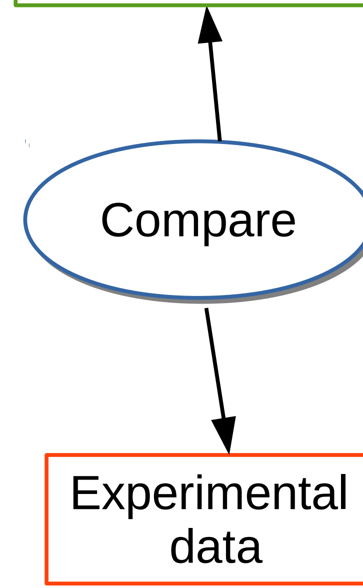
Interpretation scheme: Experimental data is a benchmark of theory



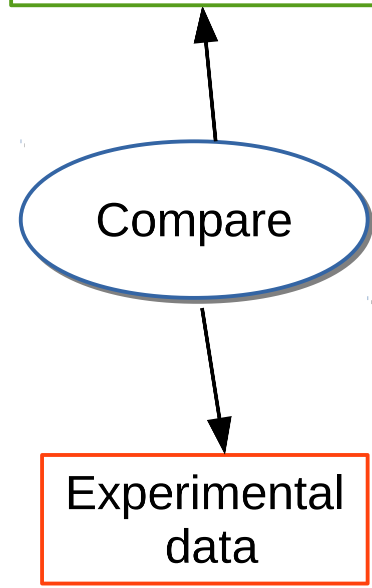
Interpretation scheme: Experimental data is a benchmark of theory

Limitations:

- ✗ Need precise characterization of setup, confidence in simulations.
- ✗ Need code producing events as input for simulations.
- ✗ Need computation power.
- ✗ **Need a quantitative measure of difference between experimental and simulated data.**
- ✗ Result dependent on the theory, code used.



Interpretation scheme: Experimental data is a benchmark of theory



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Benefits:

- ✔ Takes into account the full physics, event by event.
- ✔ Can test many codes, theories with one data set.
- ✔ **Allow exploration of model parameters, production of uncertainty, covariance data.**

Interpretation scheme: Experimental data is a benchmark of theory

Theory → Code → Prediction → Experimental setup simulation → Simulated experimental data

Compare

Experimental data

Limitations:

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- ✗ Result dependent on the theory, code used.

Benefits:

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- ✔ Can test many codes, theories with one data set.
- ✔ **Allow exploration of model parameters, production of uncertainty, covariance data.**

The two schemes are complementary and should yield converging results,
(otherwise, something's wrong)

Conclusion and perspective

- ✔ Calorimetry experiment allowed the successful extraction of ^{254}No's B_f
- ✔ $B_f(0)$= 6,6 ± 0,9 MeV, J_{saddle}= 125 ± 60 $\hbar^2$/MeV
- ✔ Experimental B_f in *better* agreement with mic-mac prediction than DFT

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Looking to the future for :

➔ Systematic measurement in other nuclei (^{255}Lr, ^{253}No ?)
➔ Benefit from experimental improvements
➔ Other facilities, setups to perform the measurement

➔ Improvement in theory, code, data interpretation

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? What other measurement can benchmark fission barrier (and other) properties ?
? How **accurately** can we measure, predict them ?

Read more:

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- A. Heinz, T. Khoo, P. Reiter, et al., Nucl. Phys. A682, 458 (2001).
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