# A Monte Carlo Simulation of Prompt Gamma Emission from Fission Fragments

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WONDER, 27/09/2012

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# Gamma heating problematic

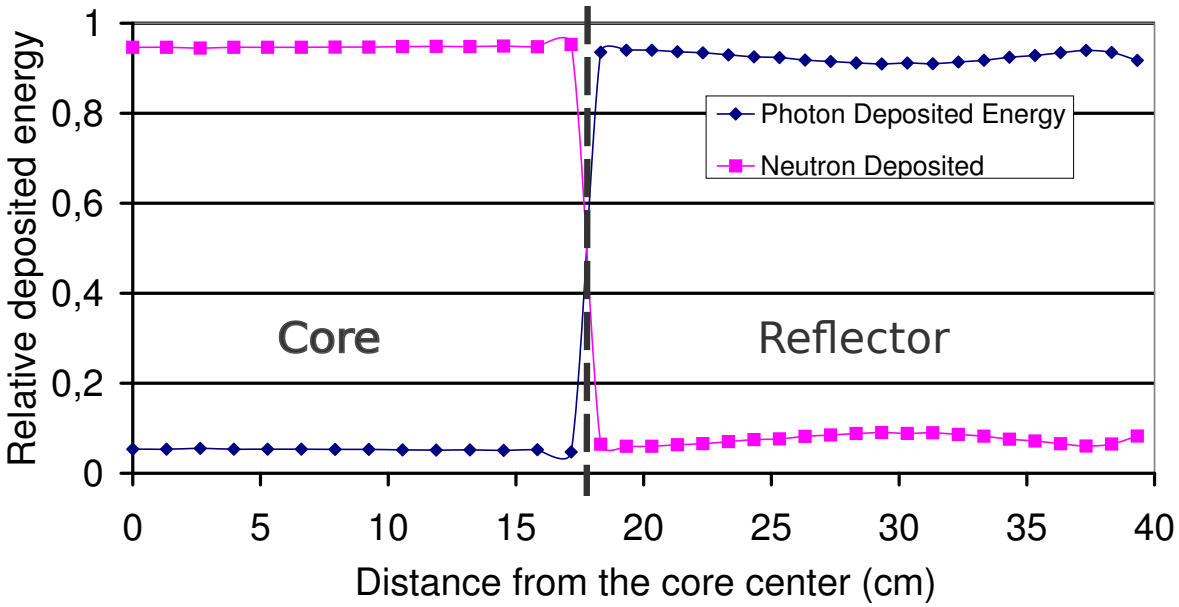


Figure 1: Relative neutron and photon heating in the Perle experiment (From Phd student S. Ravaux transport calculation with Tripoli-4.7)

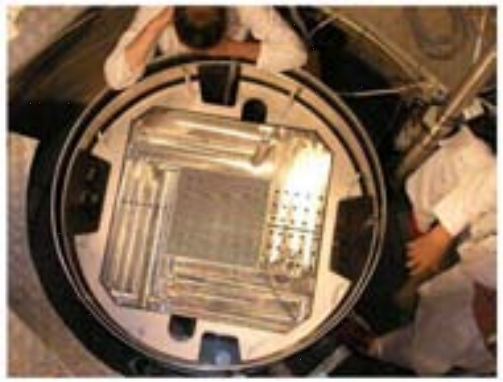

Figure 2: Perle experiment

# Prompt fission gamma data in evaluated files

## Two spectra used for all the main fissionning isotopes

- ($n$+$^{239}$Pu, f) : based[a] on Verbinski et al. measurement (1973)
- ($n$+$^{235}$U, f) : based[b] on Verbinski et al. measurement (1973)

[a] R. E. Hunter and L. Stewart, LA-4901 (1972)
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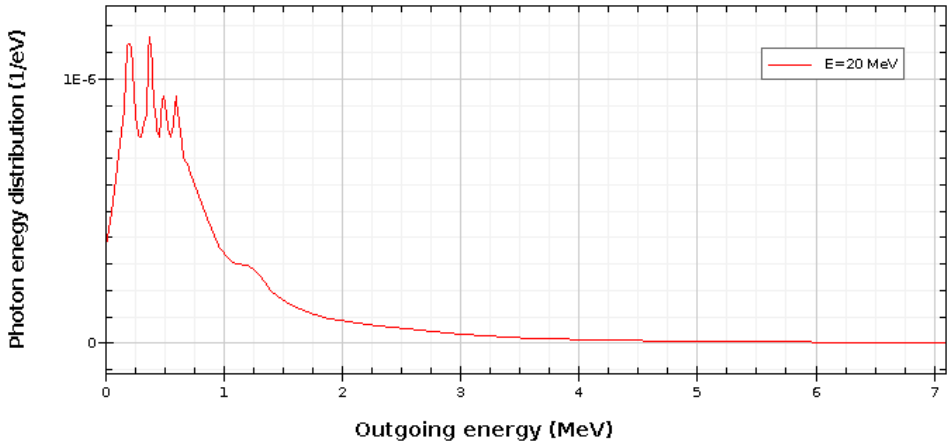


$M_\gamma$= 7.78 $\gamma$/f

Figure 3: JEFF-3.1.2 fission gamma spectrum for ($n$+$^{239}$Pu, f)

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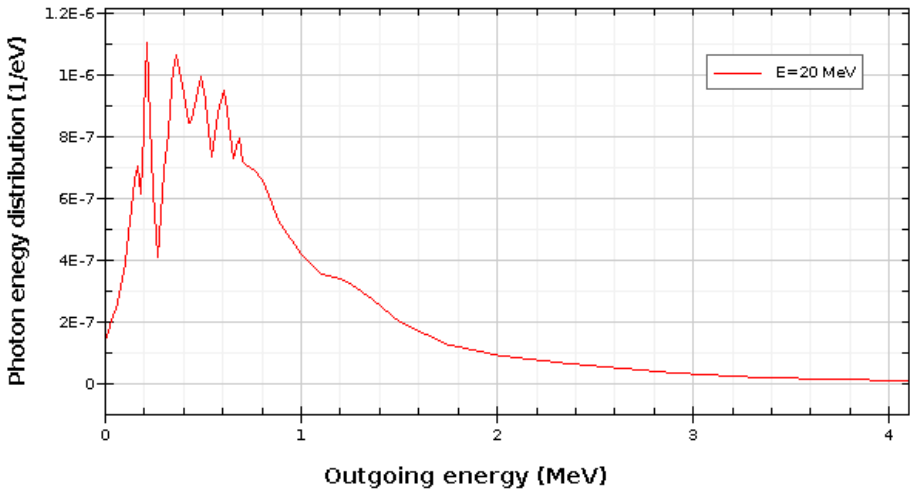


$M_\gamma$ = 7.17 $\gamma$/f

Figure 3: JEFF-3.1.2 fission gamma spectrum for ($n$+$^{235}$U, f)

# FIFRELIN: A Monte Carlo simulation of fission fragments evaporation

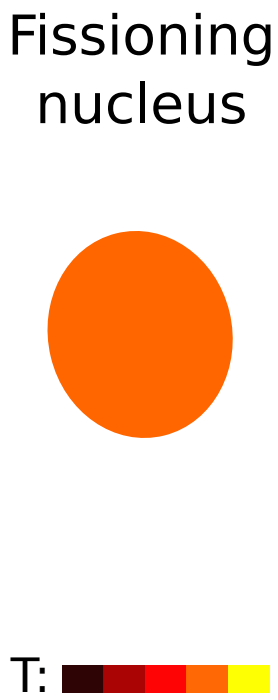


Figure 4:
Compound nucleus

(T= nuclear temperature)

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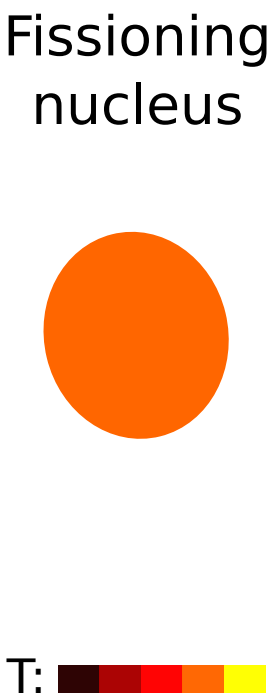


Figure 4: Compound nucleus

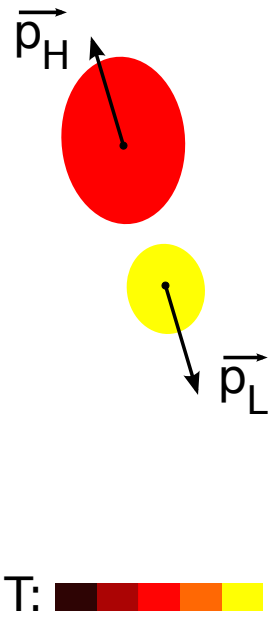


Figure 5: Fully accelerated fragments

(T= nuclear temperature)

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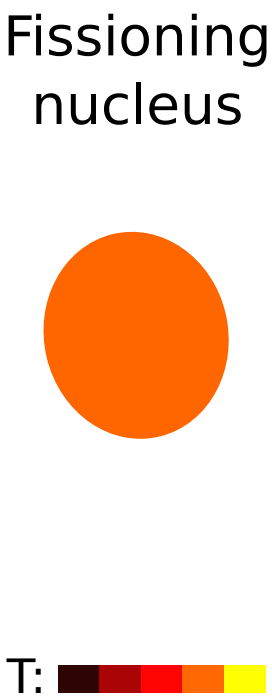


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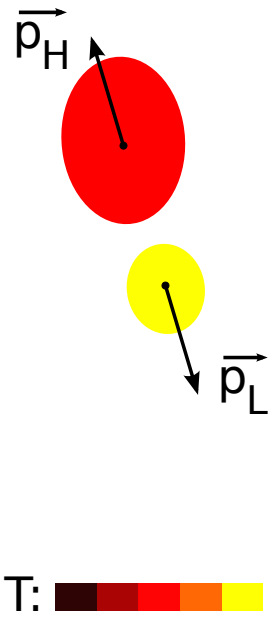


Figure 5: Fully accelerated fragments

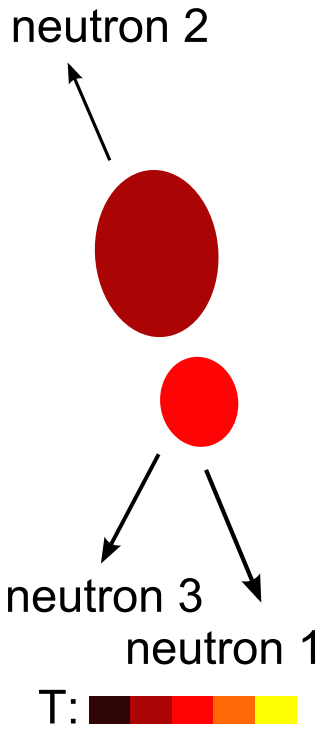


Figure 6: Prompt neutron emission

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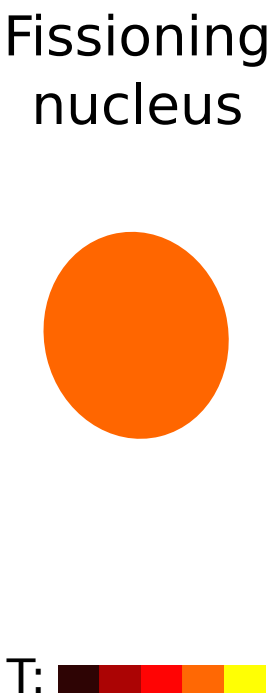


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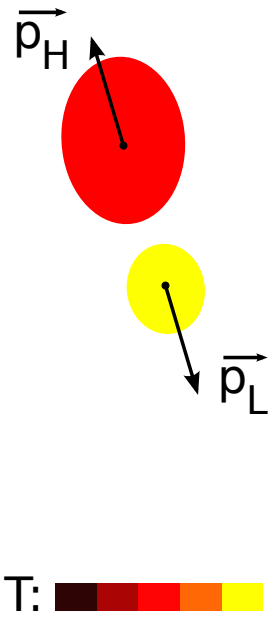


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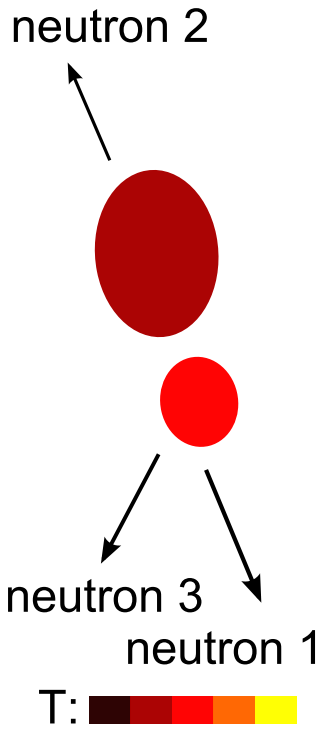


Figure 6: Prompt neutron emission

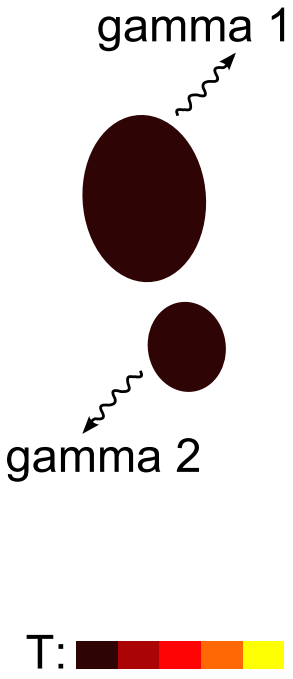


Figure 7: Prompt gamma emission

(T= nuclear temperature)

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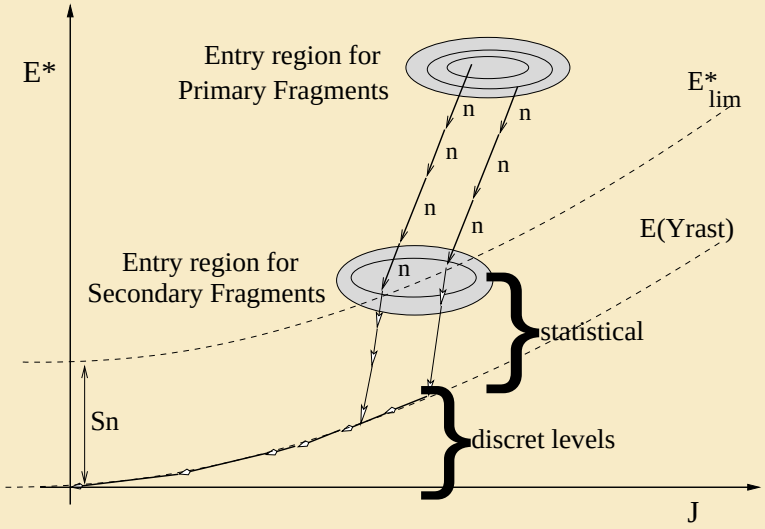
# Model 1

## Approximation on neutron/gamma competition

1. Emit neutrons until a limit energy is reached, $E_{limit} = Sn + E_{rot}(J)$
2. Decay by gamma and/or conversion electron emissions.




## Neutron emission

- Energy sampled in a Weisskopf spectrum:

$$\chi(\epsilon_n) \propto \sigma_{inv}(\epsilon_n)\ \epsilon_n\ e^{-\epsilon_n/T}$$

- Total angular momentum:

$$J_{A-1} = J_A - 1/2\hbar$$

# Model 1

## Gamma emission

For one fission fragment

1. Departure from a known excited level $(E_i^*, J_i, \pi_i)$
2. Decay probabilities calculation:

$$I_\gamma(i \to j) = \frac{\Gamma_\gamma(i \to j)}{\Gamma_{\gamma,tot}} \quad (1)$$

$$\Gamma_\gamma(i \to j) = \frac{f_{XL}(\epsilon_\gamma)\epsilon^{2L+1} y_{fluctuation}}{\rho(E_f, J_f, \pi_f)} \quad (2)$$

3. Sample one transition
4. Gamma decay until a stable level is reached

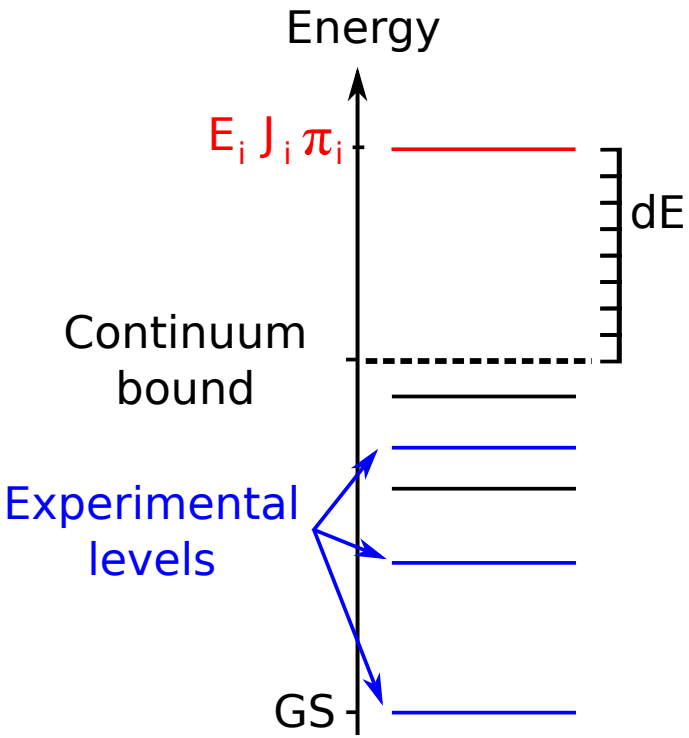



Figure 8: Level scheme of the fission fragment

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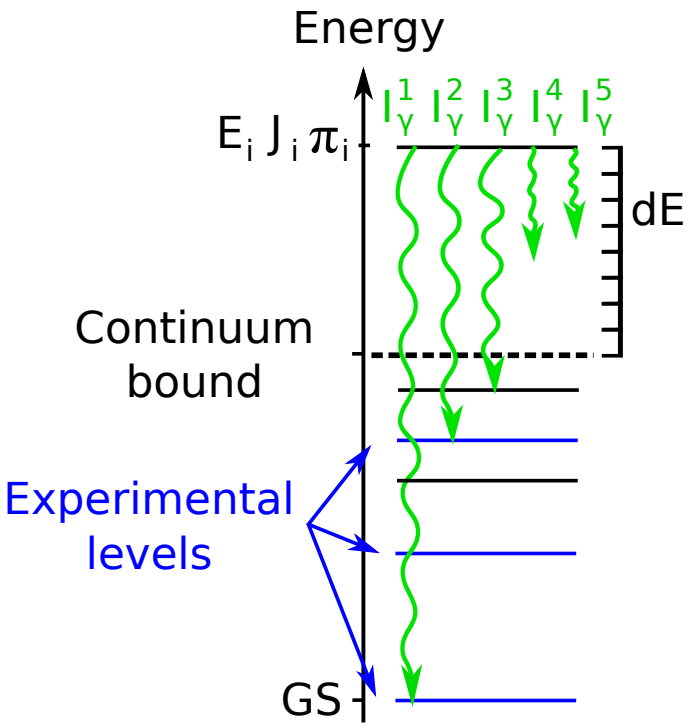


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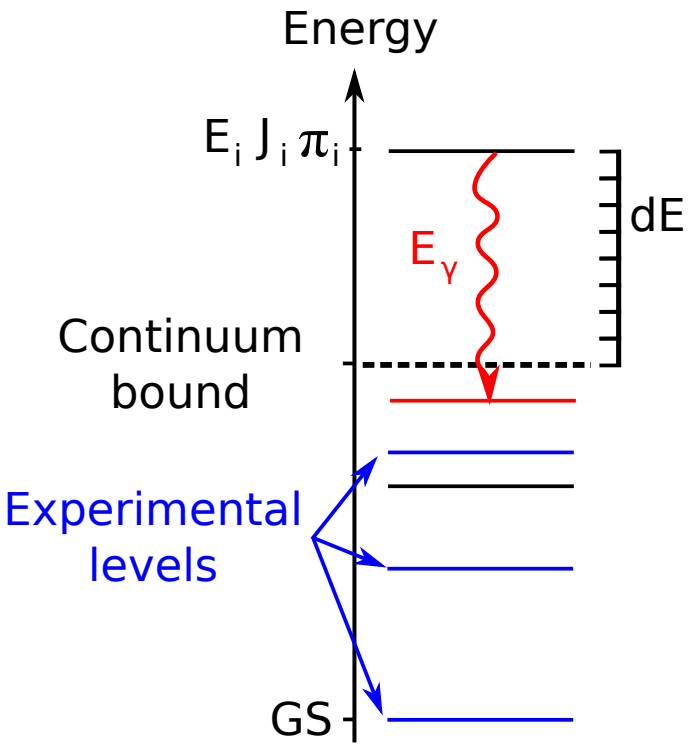


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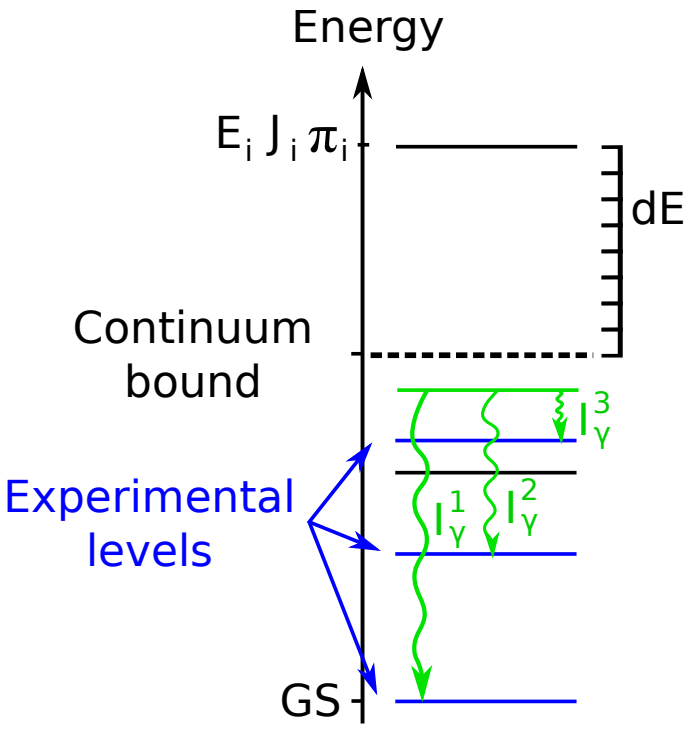


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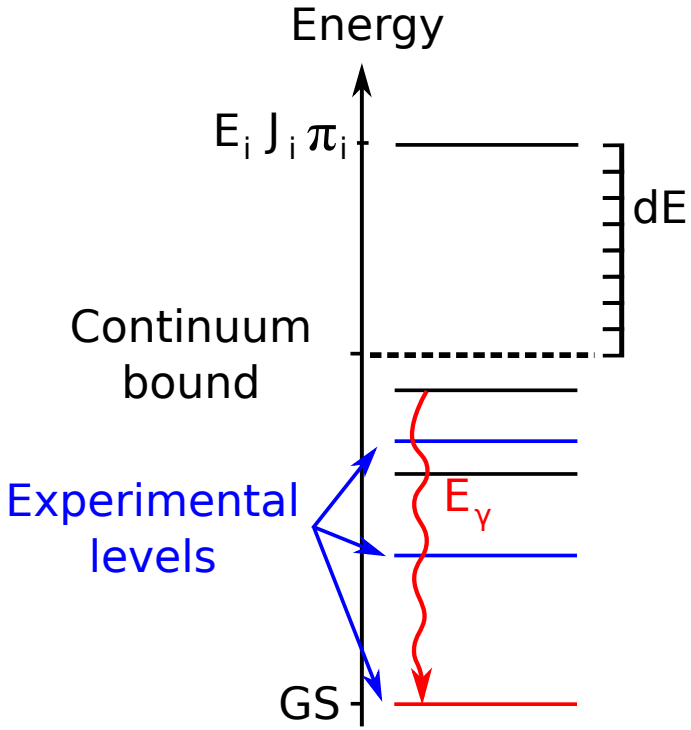



Figure 8: Level scheme of the fission fragment

# Model 1: Results for the $^{252}$Cf spontaneous fission

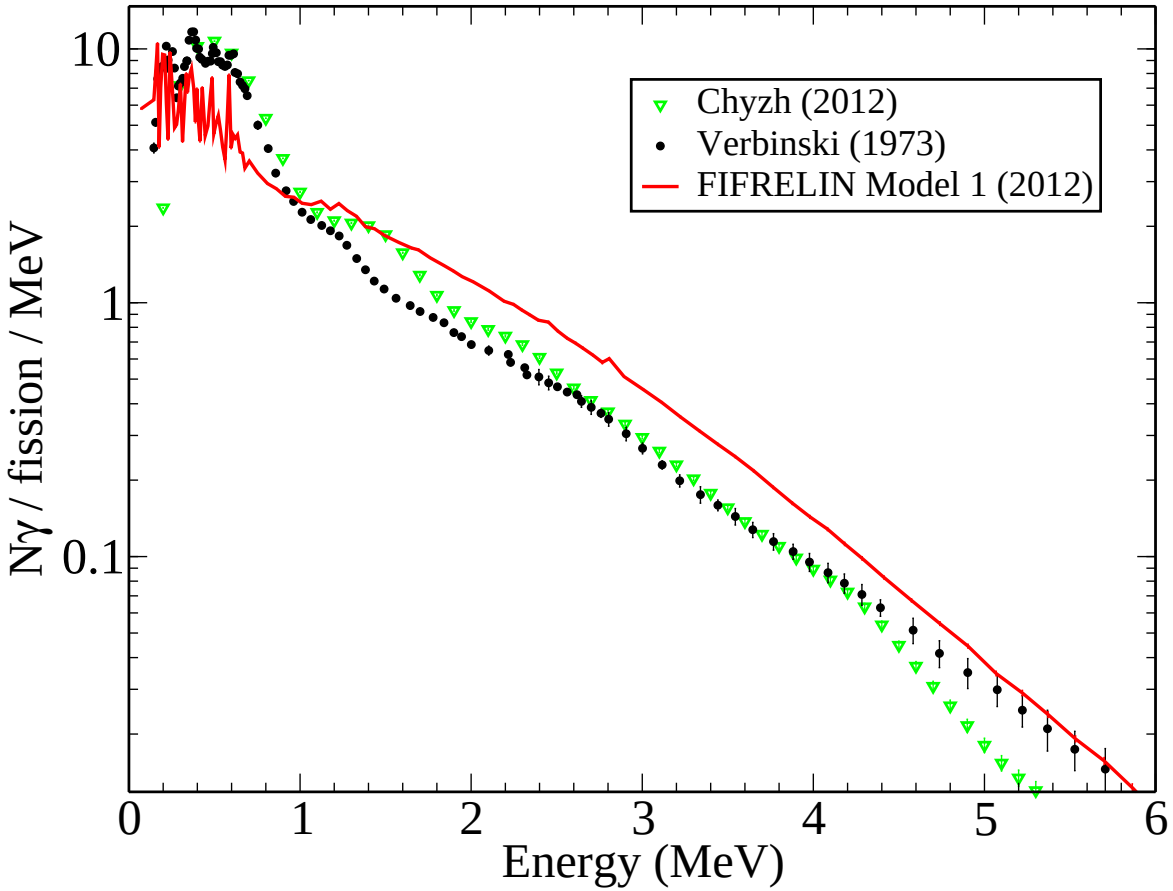



Figure 9: Total prompt gamma spectrum

FIFRELIN:

- $\nu = 3.78\ n/f$
- $M_\gamma = 8.0\ \gamma/f$
- $E_\gamma^{tot} = 8.1$ MeV
- $E_{elec}^{tot} = 39$ keV

($\sigma_{stat} < 0.1\%$)

Experiments:

- $\nu = 3.76 \pm 0.03\ n/f$
- $M_\gamma \simeq 8 \pm 0.4\ \gamma/f$
- $E_{\gamma,tot} \simeq 7 \pm 0.4$ MeV

# Model 1: Results for the $^{252}$Cf spontaneous fission

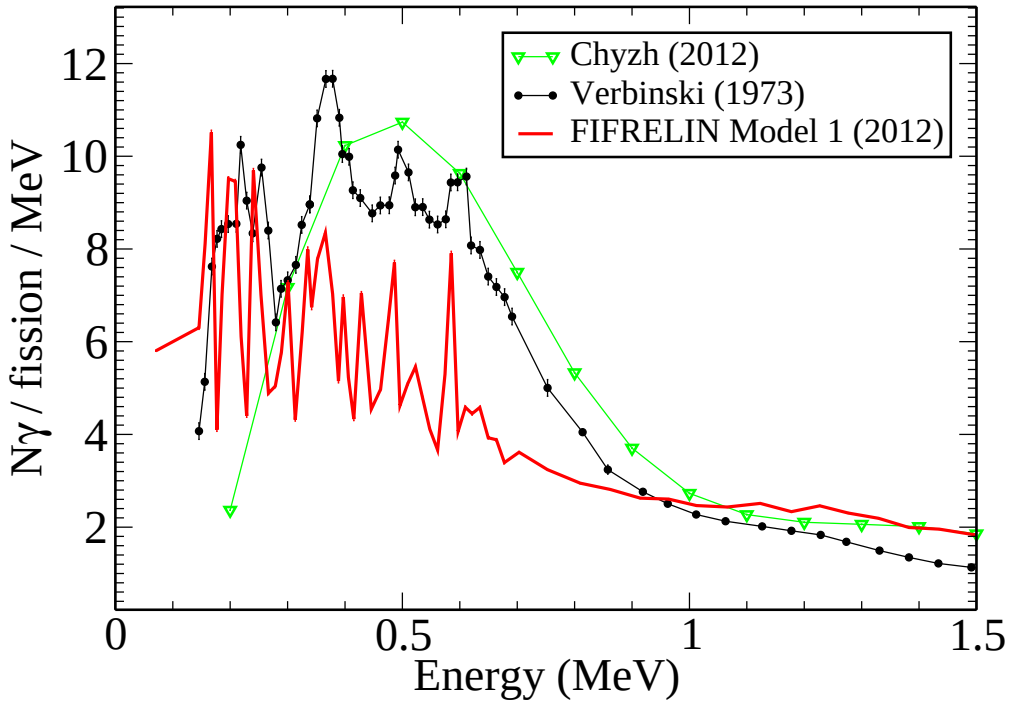



Figure 10: Fifrelin prompt gamma spectrum in the fragment frame (same resolution as Verbinski measurements)

**Verbinski et al. experimental setup**

- Detection threshold: 140 keV
- Thin sample : $\simeq 200 \mu g.cm^{-2}$ $\rightrightarrows$ Doppler effect

# Model 1: Results for the $^{252}$Cf spontaneous fission

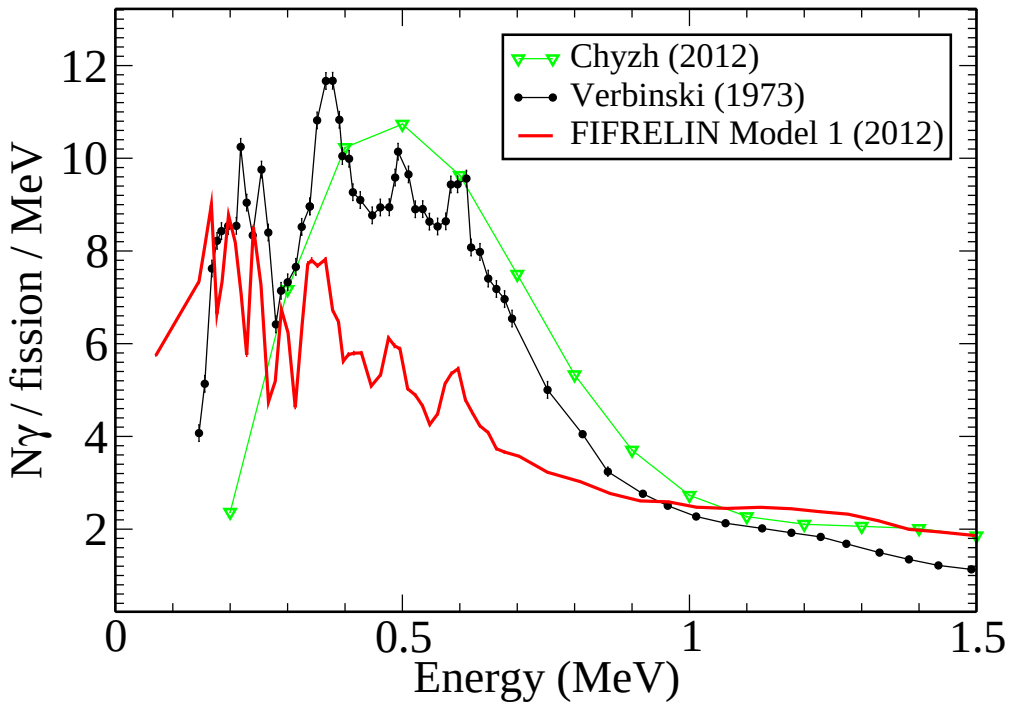


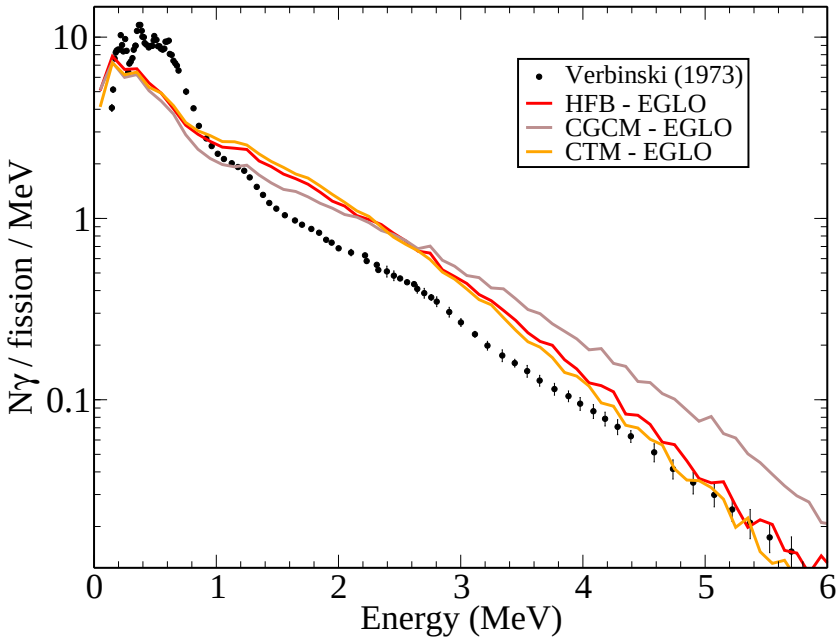

Figure 11: Fifrelin prompt gamma spectrum in the laboratory frame (same resolution as Verbinski measurements)

Assumptions:

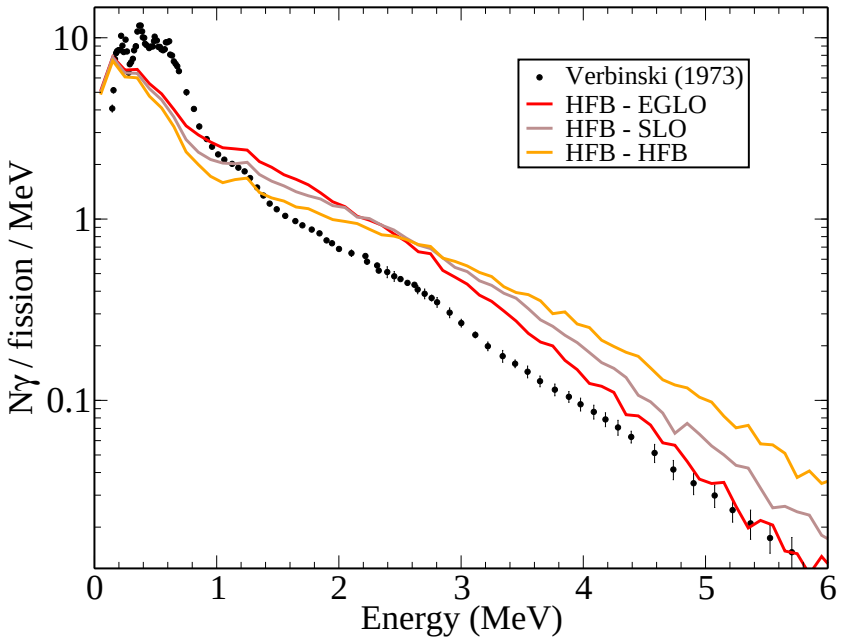
- $4\pi$ detection of gamma emitted.
- Isotropic emission of gamma rays in the fragment frame.
- No kinetic energy loss in target.
- Lorentzian transformation.

# Model 1: Level density and strength function influence

Level density models:



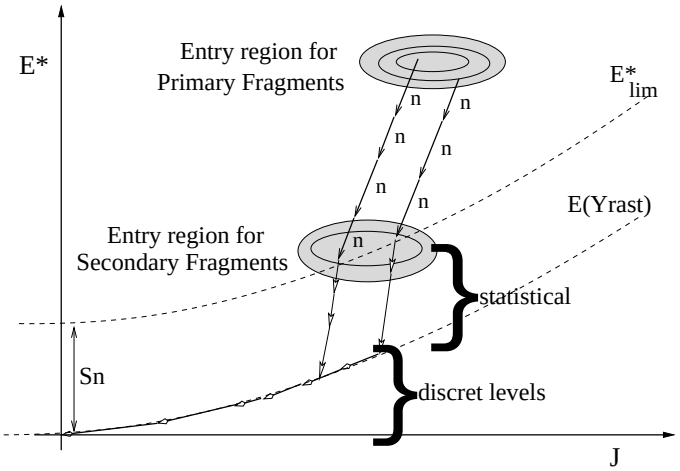

Strength function models:




- CTM: Constant temperature
- CGCM: Composite Gilbert-Cameron
- HFB: Microscopic calculation

- SLO: Standart Lorentzian
- EGLO: Enhanced Generalized Lorentzian
- HFB: Microscopic calculation

# Model 1: Angular momentum of the fragments




$\Longrightarrow$ Low energy part of the spectrum highly sensitive to $J_{init}$

## In FIFRELIN

- Before neutron emission:

$$P(J) = \frac{(J+1/2)}{\sigma^2(T)} e^{\frac{(J+1/2)^2}{2\sigma^2(T)}}$$

$$\bar{J}_H = 6.6\hbar, \qquad \bar{J}_L = 5.9\hbar$$

- During neutron emission:

$$J_{A-1} = J_A - 1/2\hbar$$

| Ref | Wilhelmy[1,2](1972) | Skarsvag[1,2](1980) | Mukhopadhyay[1,2](2012 ) |
|---|---|---|---|
| $\bar{J}_L$ | $7\hbar$ | $6\hbar$ | $\simeq 5\hbar$ |
| $\bar{J}_H$ | $8.4\hbar$ | $5.3\hbar$ | $\simeq 12\hbar$ |

Table 1: Average angular momentum of primary fragments from $^{252}$Cf SF

1: Only even-even post-neutron fragments are considered.
2: Estimation of the uncertainty: $\pm 2\hbar$.

# Effect of an increase of post-neutron fragment J

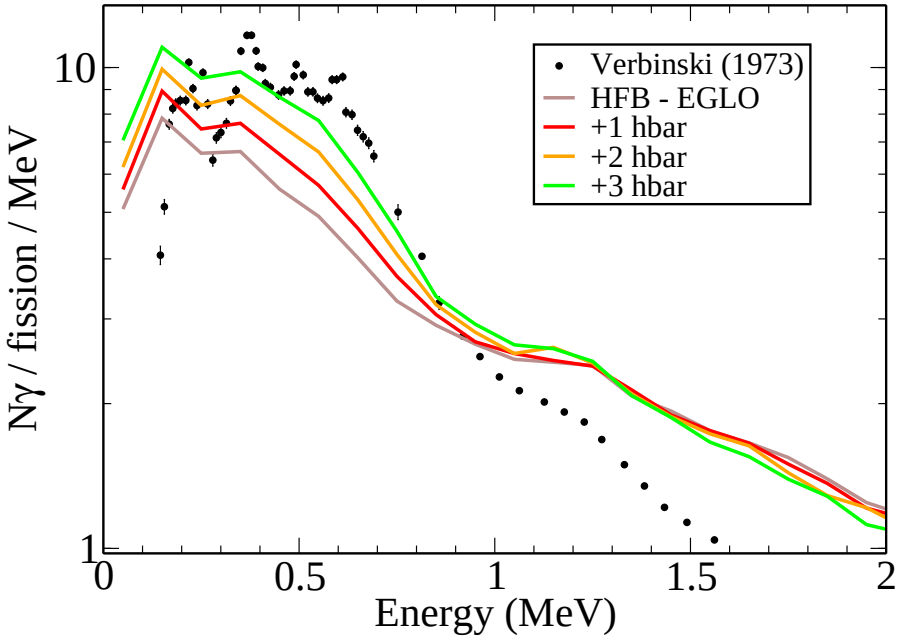



Figure 12: Prompt gamma spectrum for the spontaneous fission of $^{252}$Cf

For a good agreement of low energy part of the gamma spectrum post-neutron angular momentum are found to be:

$$J_L \simeq 8\hbar, \qquad J_H \simeq 9\hbar$$

# From model 1 to model 2 ...

Model 1 results:

- Good agreement of neutron observables with experiments.
- First prediction of a prompt gamma fission spectrum.
- Overestimation of total gamma energy ($E_{\gamma,tot}$) ?
- Prompt gamma spectrum too hard.

Remaining questions:

- Neutron emission before gamma emission ?
- Average $\Delta J = 1/2\hbar$ during a neutron emission ?
- Initial total angular momentum of the fission fragments ?
- Validity of a Weisskopf spectrum at low excitation energy ?

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# Model 2

## Transition probability

$$p(i \rightarrow j) = \frac{\Gamma(i \rightarrow j)}{\Gamma_{\gamma}^{tot} + \Gamma_{neutron}^{tot}} \quad (3)$$

$\rightrightarrows$ Neutron and gamma emission competition

## Neutron width calculation

$$\Gamma_n(i \rightarrow j) = \frac{T_{l,j}(\epsilon_n) y_{fluctuation}}{2\pi\rho(E_f, J_f, \pi_f)} \quad (4)$$

$T_{l,j}(\epsilon_n)$ are provided by a Talys-1.4 optical model calculation using a Koning-Delaroche spherical potential

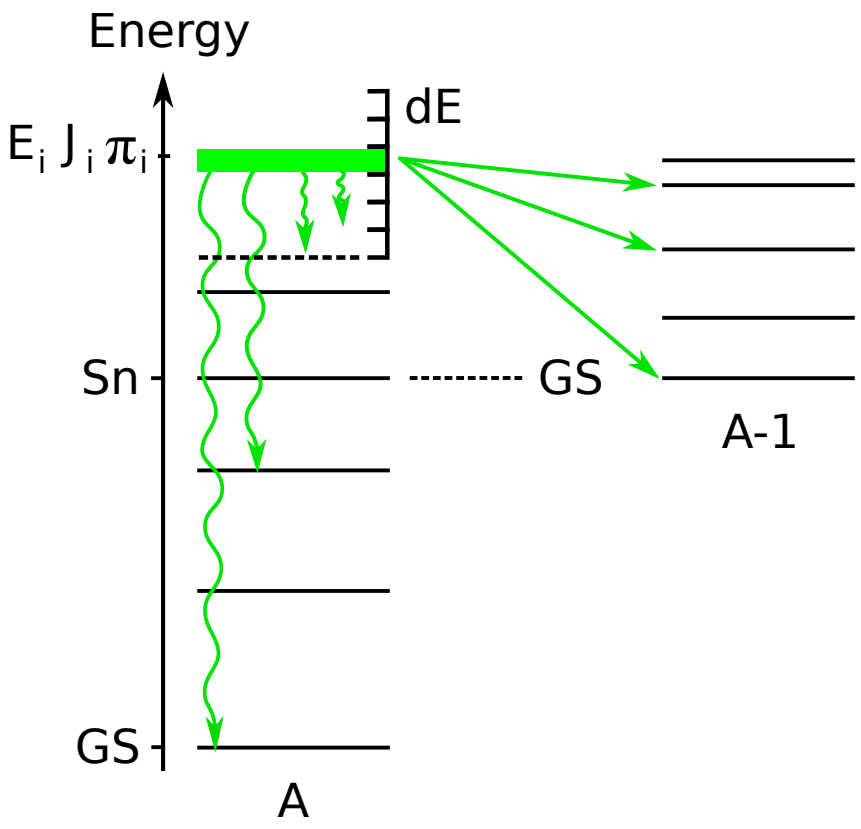


Figure 13: Possible decay

# Model 2: Preliminary results for the $^{252}$Cf SF

| | $< \epsilon_n >$ in FF frame (MeV) | $\nu$ | E* for neutron (MeV) |
|---|---|---|---|
| Vorobyev (2005) | | $3.76 \pm 0.03$ | |
| Model 1 | 1.34 | 3.78 | 25.7 |
| Model 2 | 1.23 | 4.0 | 27.4 |

Table 2: Neutron results

| | $< \epsilon_\gamma >$(MeV) | $M_\gamma$ | $E_{\gamma,tot}$ (MeV) |
|---|---|---|---|
| Chyzh (2012) | 0.94 | 8.16 | 7.8 |
| Model 1 | 1.0 | 8.0 | 8.1 |
| Model 2 | 0.86 | 7.5 | 6.4 |

Table 3: Gamma results

## New observables provided by the model 2

1. $\Delta J_n$= 0.1 $\hbar$/n
2. Average number of gamma emitted before the last prompt neutron: $\simeq 4.10^{-3}\gamma$/f (1$\gamma$ every 250 fissions)

# Model 1 vs Model 2 for the $^{252}$Cf spontaneous fission

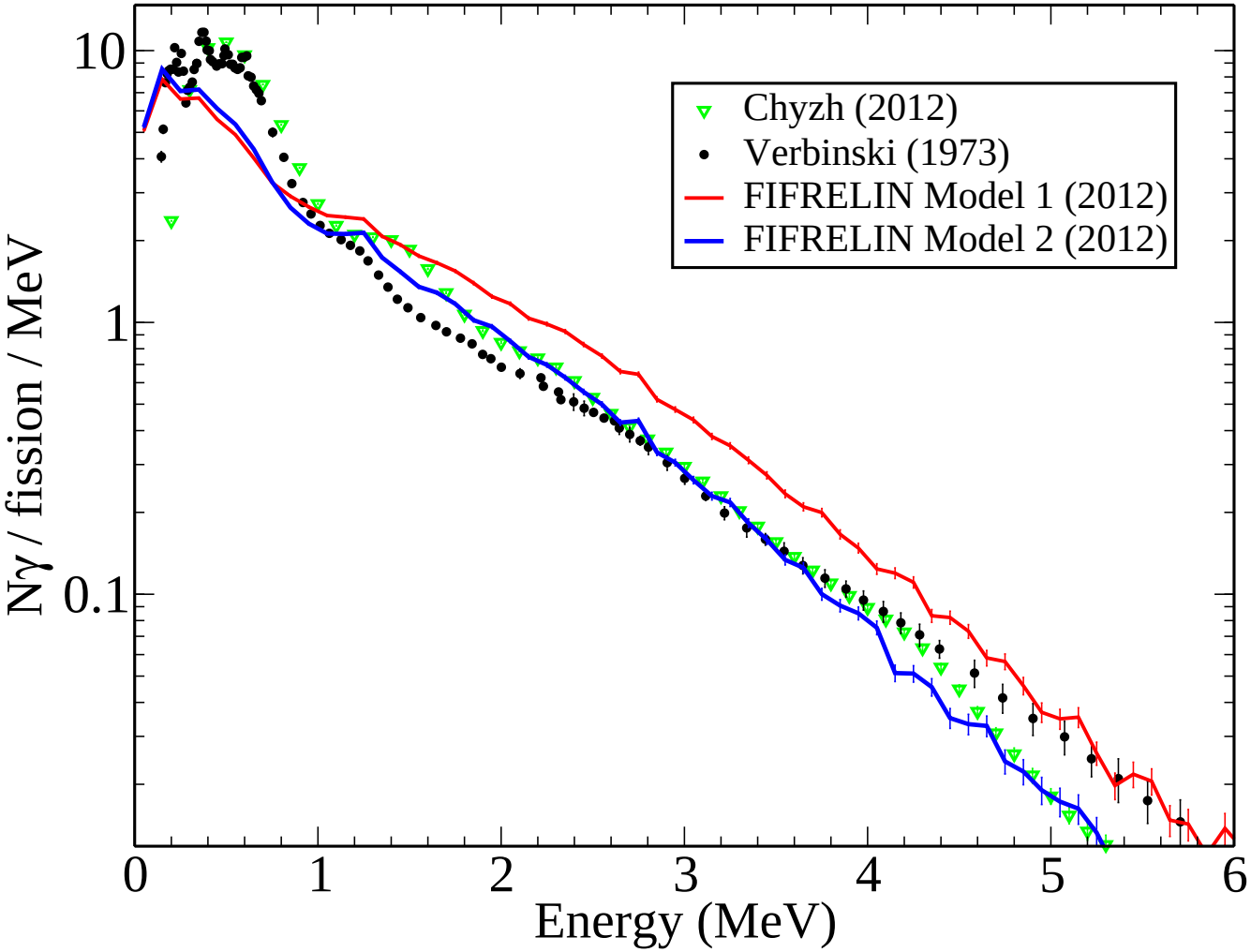


Figure 14: Total prompt gamma spectrum

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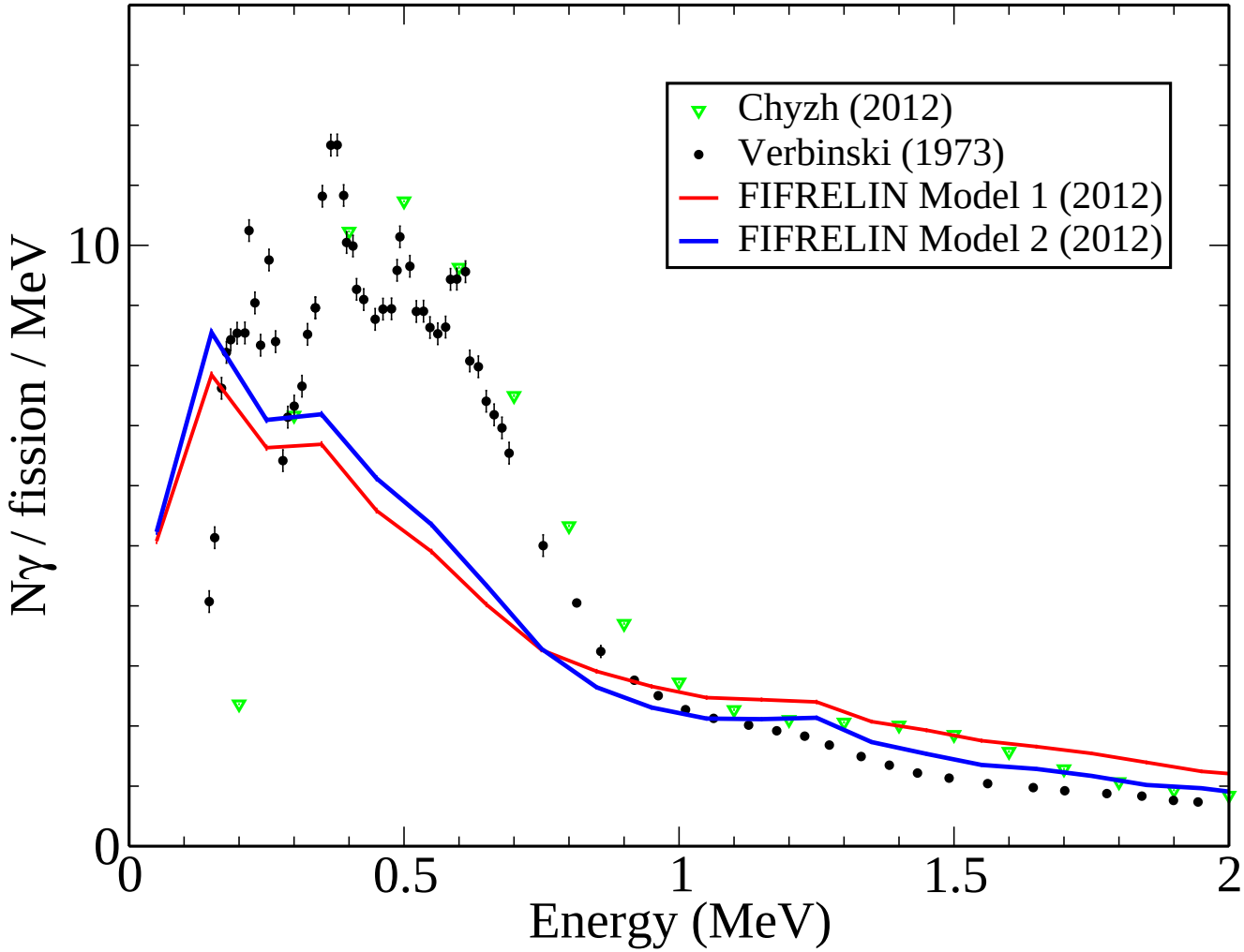


Figure 14: Total prompt gamma spectrum

# Influence of parameters and models

## Strength function $\gamma$

- $\Delta\nu < 1\%$
- $\Delta\epsilon_\gamma \simeq 12\%$
- $\Delta E_{\gamma,tot} \simeq 1\%$
- Shape of the gamma spectrum impacted

## Level density

- $\Delta\nu \simeq 3\%$
- $\Delta\epsilon_\gamma \simeq 6\%$
- $\Delta E_{\gamma,tot} \simeq 4\%$
- Shape of the gamma spectrum impacted

## Angular momentum of primary FF

High sensitivity of main observables, $+2\hbar$ leads to:

- $\nu$: $-1\%$
- $\epsilon_n$: $-2$ %
- $E_{\gamma,tot}$: +0.7 MeV
- $\epsilon_\gamma$: $-7$ %
- $M_\gamma$: $+20\%$

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# Realized for the moment:

- Implementation of two main cascade models, work on neutron/gamma competition.
- Implementation and comparison of several models of level density and strength function.
- Optimization in speed and memory of the code, parallelization.
- Calculation of several observables of the fission process ( post-neutron fragments data, multiplicity for a given fragmentation ...).

# Perspectives:

- Impact of the optical model used for neutron transmission calculation.
- Investigation on the energy balance between neutron and gamma emission.
- Calculation of observables with high sensitivity to angular momentum: anisotropy gamma.
- Measurements at ILL before end of 2012.
- ...

Other application scope:

- Neutron capture calculation: spectrum, multiplicity, branching ratio...

**Thank you for your attention !**