DE LA RECHERCHE À L'INDUSTRIE

Theory of Neutrons and Gammas Emission in Fission

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Introduction

- Time scale in fission
- Energy components in fission
- Some definitions

Part I: Prompt neutron Emission

- *Mechanism of Prompt neutron emission*
- *Prompt Neutron Multiplicities*
- *Angular Distribution of Prompt neutrons*
- *Prompt Fission Neutron Spectrum (PFNS)*

Part II: Prompt gamma Emission

- *Time scale for prompt and 'late' gamma emission*
- *Available Energy for Prompt gamma Emission*
- *Prompt Fission Gamma spectrum (PFGS)*
- *Prompt Fission Gamma-ray Multiplicity*

Part III: Delayed neutron and Gamma Emission

- *Origin of the delayed neutron and gamma emission*
- *The main precursors*
- *Examples of delayed neutron and gamma spectra*
- *Influence of incident neutron energy on DN multiplicity*

Introduction

- Time scale in fission
- Energy components in fission
- Some definitions

In 1937, Hans Halban was invited to join the team of Jean Frédéric Joliot and Marie Curie at the Collège de France in Paris. The team also included Francis Perrin and Lew Kowarski.

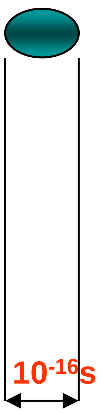
In 1939 the group measured the mean number of neutrons emitted during nuclear fission, and established the possibility of nuclear chain reactions and nuclear energy production.

Two main ingredients govern the prompt neutrons and/or gamma emission:

- The time needed for their emission
- The energy required for their emission

Time scale in fission

The fission process takes place in 5 main phases

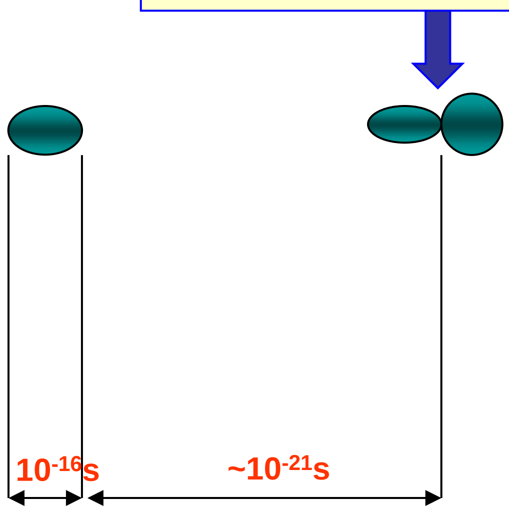


Phase I: Formation of the compound nucleus

Time scale in fission

The fission process takes place in 5 main phases

Primary Fission Fragments or Fission Fragments (FF)



Phase I: Formation of the compound nucleus

Phase II: Deformation of the nucleus from the saddle point to the scission point

Time scale in fission

The fission process takes place in 5 main phases

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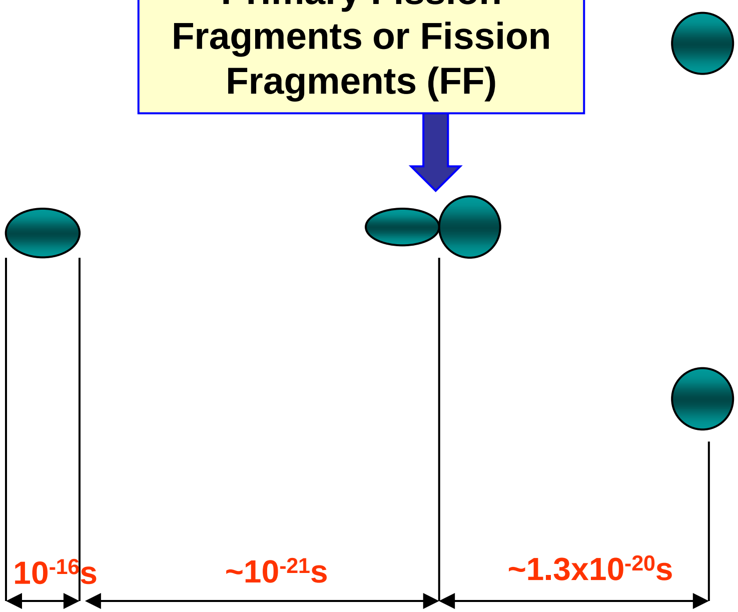
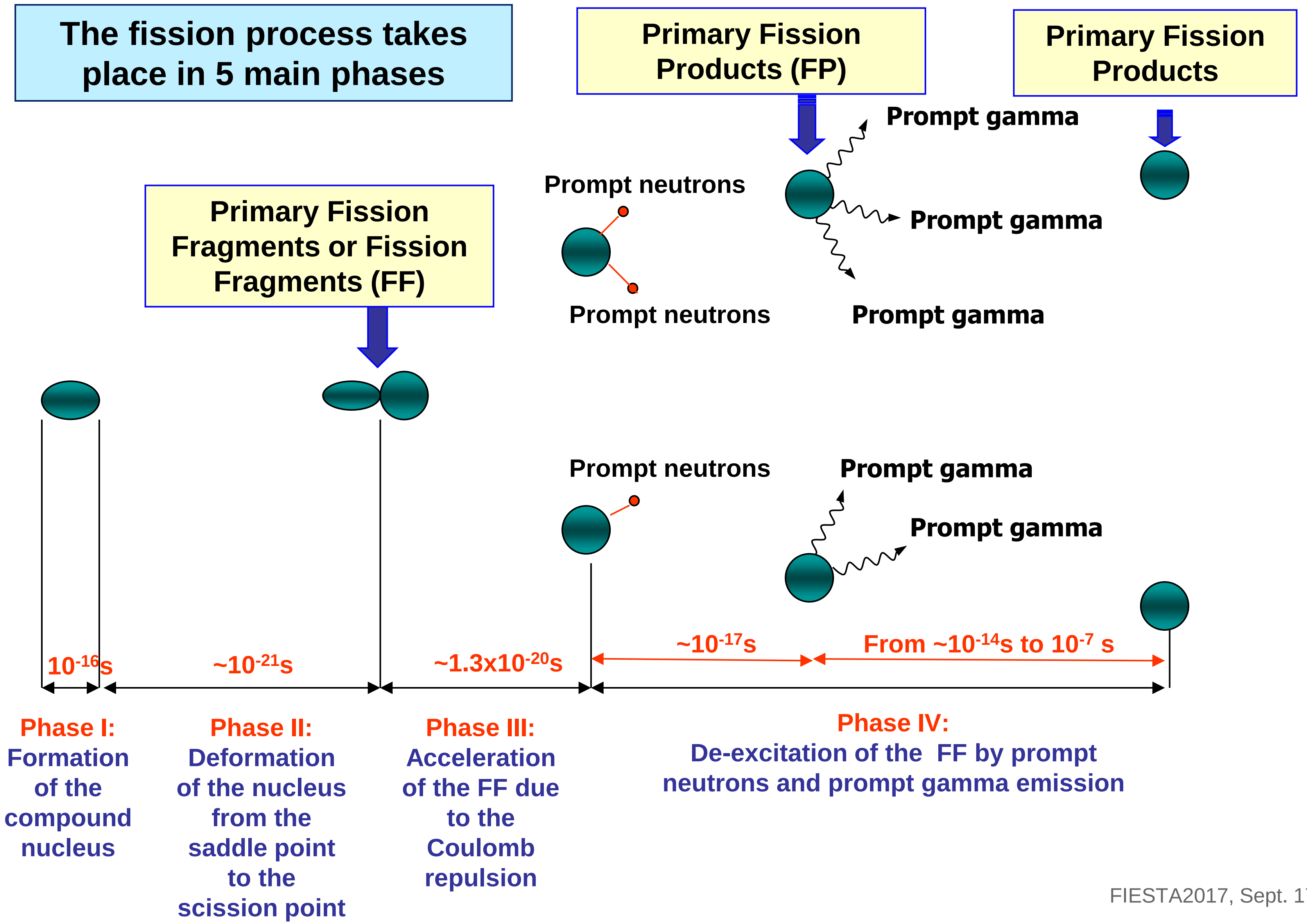


Phase I: **Formation of the compound nucleus**

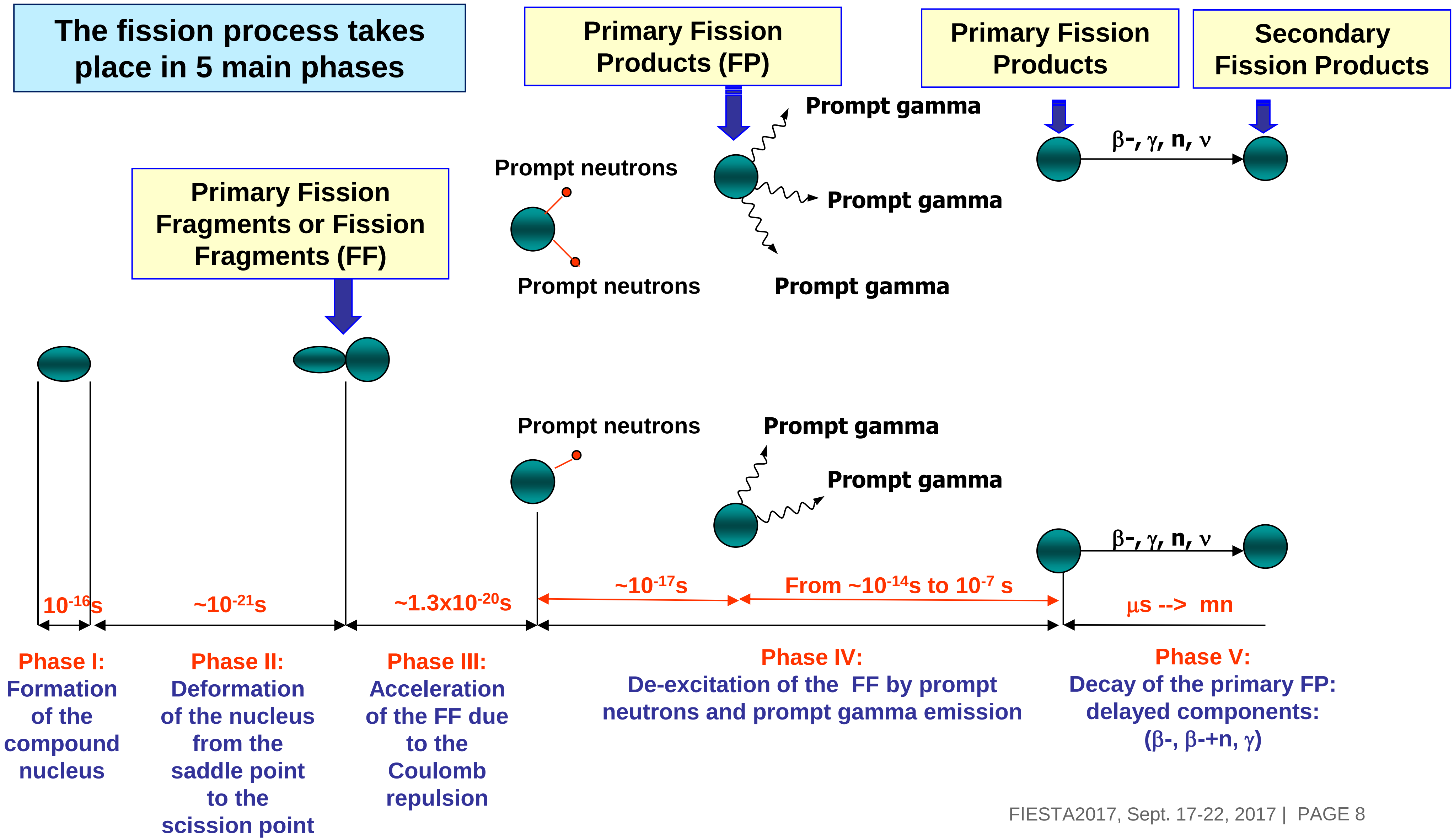
Phase II: **Deformation of the nucleus from the saddle point to the scission point**

Phase III: **Acceleration of the FF due to the Coulomb repulsion**

Time scale in fission



Time scale in fission



Energy Components

- The total energy release Q in binary fission $$\boxed{Q/c^2 = M_{CN} - M_{Light} - M_{Heavy}}$$

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TKE: Total Kinetic Energy; TXE: Total eXcitation Energy
B_n: neutron binding energy=M_n+M_{Target}-M_{CN}
E_n: incident neutron energy
In case of spontaneous fission: B_n=0 and E_n=0

$$E_n + B_n + Q = TKE + TXE$$

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KE_{pre}: is the pre-scission Kinetic Energy
E_{coul}: is the Coulomb potential energy at scission

$$TKE = KE_{pre} + E_{coul}$$

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- **At scission**, the Total Excitation Energy (TXE) is given by:

- ❑ Intrinsic excitation energy (noted '*')
- ❑ Deformation energy (noted 'Def')
- ❑ Collective excitation mode

$$TXE = E^{Def,SC}_{Light} + E^{Def,SC}_{Heavy} + E^{*,SC}_{Light} + E^{*,SC}_{Heavy} + E^{Rot,SC}$$

Energy Components

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$$TXE = E_{Light}^{Def,SC} + E_{Heavy}^{Def,SC} + E_{Light}^{*,SC} + E_{Heavy}^{*,SC} + E^{Rot,SC}$$

- **After the full acceleration of the FF**, the Total Excitation Energy (TXE) is given by:

$$TXE = E^*_{Light} + E^*_{Heavy} + E^{Rot}_{Light} + E^{Rot}_{Heavy}$$

Energy Components

Energy needed to emit prompt neutrons and prompt gammas is taken from TXE

Two possible ways for the experimental determination of <TXE> at scission:

- Via Q (example: $^{235}U(n_{th},f)$):

$$\boxed{\begin{aligned} <TXE> &= <Q> + B_n + E_n - <TKE> \\ &= 186.6 + 6.545 + 0.0253\times10^{-6} - 169.4 = 23.2\ \text{MeV} \end{aligned}}$$

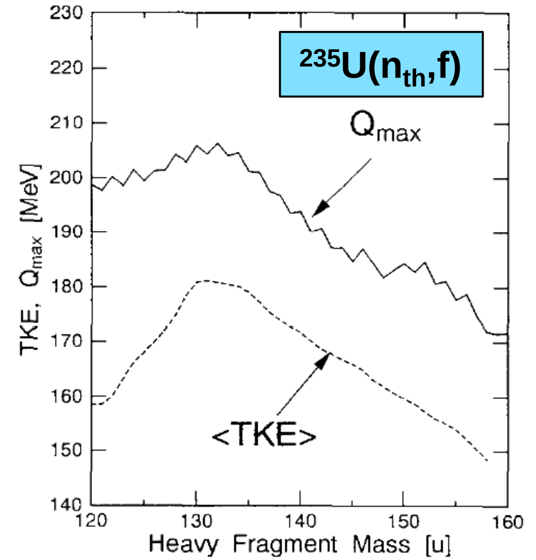
- Via neutron and gamma emissions (example: $^{235}U(n_{th},f)$):

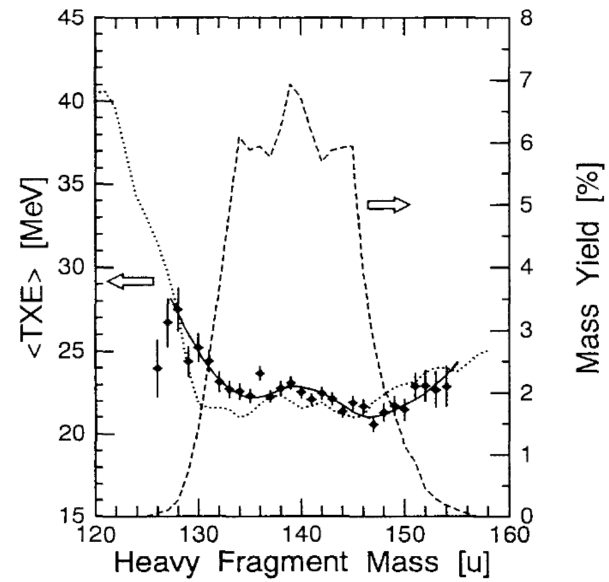
$$\boxed{\begin{aligned} <TXE> &= <\nu_P>\left(<S_n> + <\varepsilon_n>\right) + <E_\gamma> \\ &= 2.42\,(5.1+1.3) + 7.7 = 23.2\ \text{MeV} \end{aligned}}$$

$<\nu_P>$: average prompt neutron multiplicity
$<S_n>$: average neutron separation energy
$<\varepsilon_n>$: average KE of the emitted neutron in the center of mass
$<E_\gamma>$: average total energy released by γ-emission

$<\nu_P>\left(<S_n> + <\varepsilon_n>\right)$: average energy used to emit prompt neutrons
$<E_\gamma>$: average energy used to emit prompt gammas.

From Nishio et al., Nucl. Phys. A632 (1998) 540



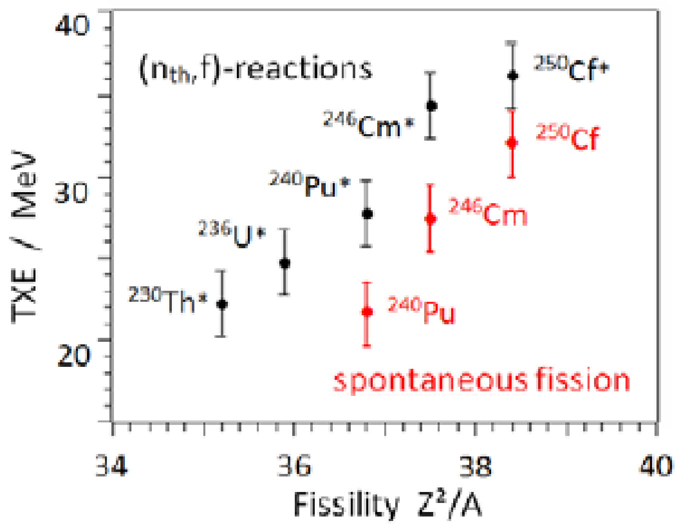


Energy Components

Excitation Energy

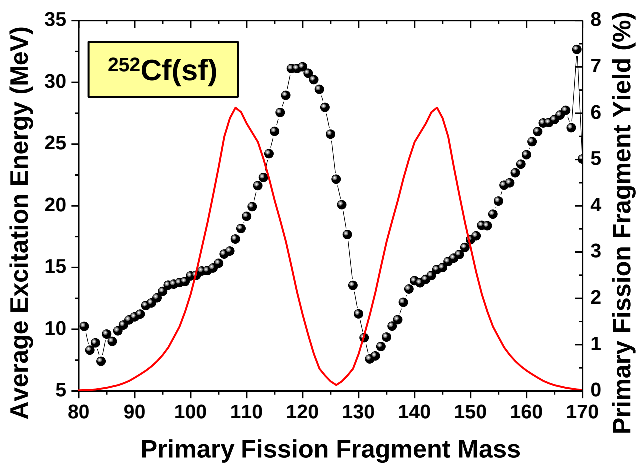
Average Total Excitation Energy <TXE>

for thermal neutron induced fission reactions and spontaneous fission of actinides (From Gonnenwein, lecture Ecole Joliot-Curie, 2014)



Average excitation energy <E*> as a function of mass

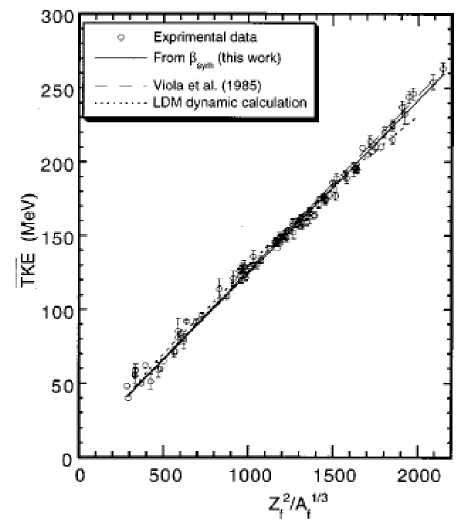
Pre-neutron mass yield plotted on the right scale (red curve).



Kinetic Energy

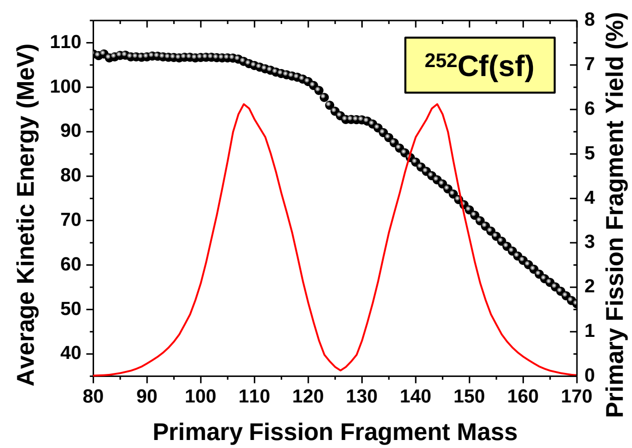
Average Total Kinetic Energy <TKE>

(from Zhoa et al. PRC 62, 014612 (2000))



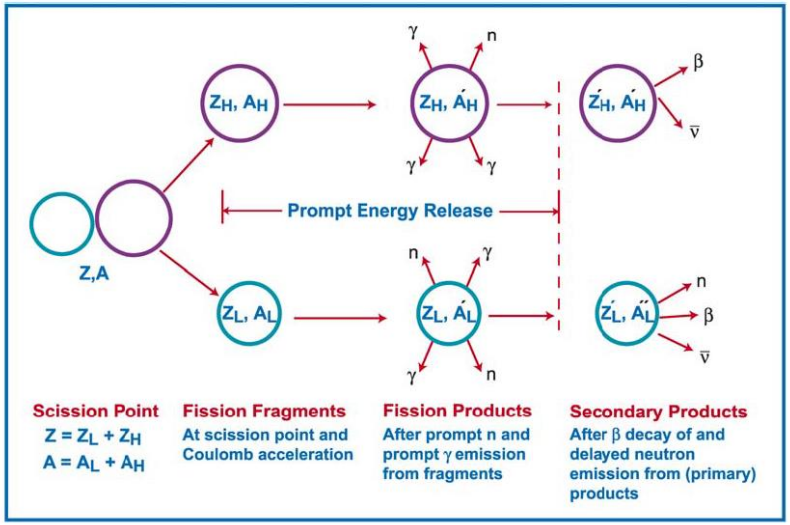
Average kinetic energy <KE> as a function of mass

Pre-neutron mass yield plotted on the right scale (red curve).



Some definitions

Following the discussion proposed by D. Madland, 2006



- ❑ Primary fission fragment
- ❑ Secondary fission fragment
- ❑ Fission products

- ❑ Prompt neutrons
- ❑ Prompts gamma
- ❑ Late gamma
- ❑ Delayed neutrons
- ❑ Delayed Gamma

- ***Primary Fission fragment*** *(or Fission Fragment)*: Nuclear species existing at the scission point and just beyond, but prior to the emission of prompt neutrons and prompt gamma rays.

- ***Primary Fission product*** (or *Fission product*): Nuclear species existing following prompt neutron emission and prompt gamma emission from a fragment, but before any β decay has occurred.

- ***Secondary fission product***: Nuclear species existing following at least one β decay of a primary fission product.

Part I: Prompt neutron Emission

- *Mechanism of Prompt neutron emission*
  - Pre-fission neutrons
  - Neutron emission from ternary fission
  - Scission neutrons
  - Emission during the acceleration of the FF
  - Evaporation from the fully accelerated FF
- *Prompt Neutron Multiplicities*
  - Average total prompt neutron multiplicity $<\nu_{tot}>$ versus the available total excitation energy of the fissioning nucleus
  - Influence of the incident neutron energy on the total prompt neutron multiplicity : $<\nu>$(En)
  - Distribution of Neutron Multiplicity : P(ν)
  - Prompt neutron multiplicity as a function of the FF Total Kinetic Energy : $<\nu>$(TKE)
  - Prompt neutron multiplicity as a function of pre-neutron mass (saw-tooth) : $<\nu>$(A)
  - Influence of the incident neutron energy on the ‘saw-tooth’ curve
- *Angular Distribution of Prompt neutrons*
- *Prompt Fission Neutron Spectrum (PFNS)*
  - Maxwellian
  - Watt
  - Los Alamos Model (LAM)
  - Stochastic approaches

Part I: Prompt neutron Emission

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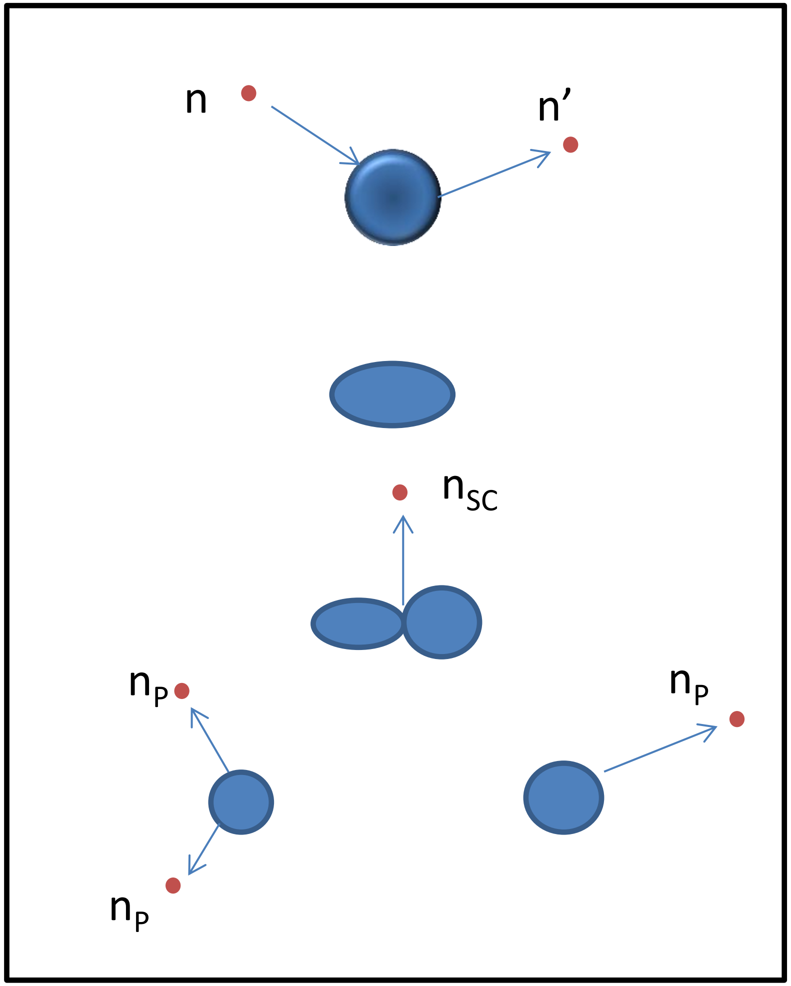
Mechanism of Prompt neutron emission

"Prompt" neutrons refer to neutrons emitted prior to the onset of fission-fragment β-decay processes. It includes several components:

- Pre-fission neutrons **(n'):** neutrons emitted prior to the fission in multiple-chance fission
- Neutron emission from ternary fission: negligible contribution
- Scission neutrons **(n_{sc}):** their existence is still controversy
- Emission during the acceleration of the FF (negligible due to time emission limitations)
- Evaporation from the fully accelerated FF **(n_P):** by far the main contribution



Mechanism of Prompt neutron emission

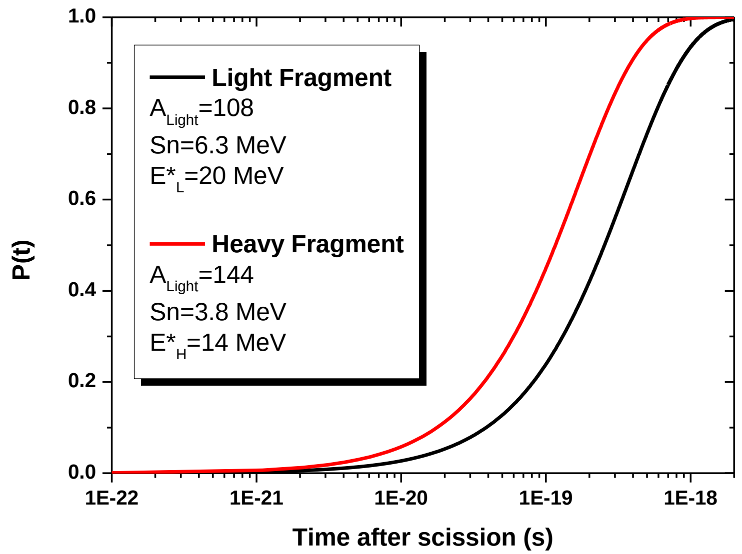
Time needed for neutron emission by an evaporation process

According to Ericson, the probability to decay by neutron emission is a time-dependent function given by:

$$\boxed{P(t) = 1 - P_0 \exp(-t/\tau)}$$

Where the decay time τ is obtained from:

$$\boxed{\tau\,(s) = 1\times10^{-21}\frac{2A^{1/3}}{(E^*\text{-}S_n)}\exp\left(\frac{S_n}{T}\right)}$$

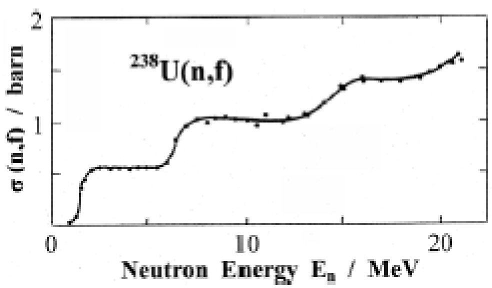


These probabilities are plotted for typical Light and Heavy Fragment pair appearing during the spontaneous fission of ^{252}Cf:

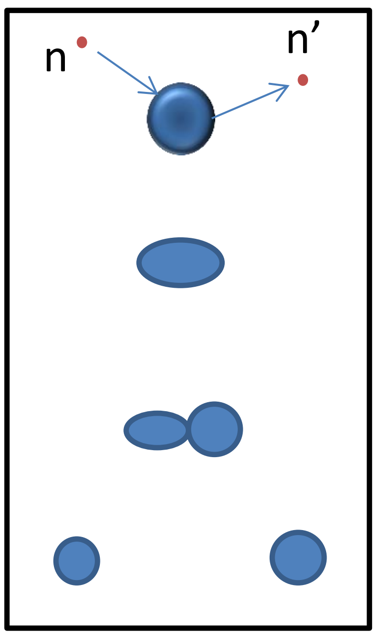
$$\boxed{\begin{aligned}\tau_{\text{Light}} &= 3.7\times10^{-19}\,s\\ \tau_{\text{Heavy}} &= 1.7\times10^{-19}\,s\end{aligned}}$$

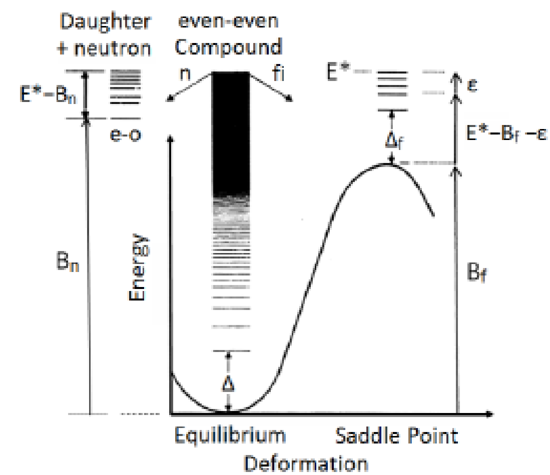
Mechanism of Prompt neutron emission

❑ **Pre-fission neutrons (n'): neutrons emitted prior to the fission in multiple-chance fission**



- Pre-fission neutrons start to be emitted above the second-chance threshold (E_n~6–7 MeV for ^{238}U(n,f)).
- At this energy range: after capture of a neutron, the compound nucleus can decay either by re-emission of a neutron (pre-fission neutron) or by fission
- There are thus several processes contributing to pre-fission neutron emission:
  - "second chance fission": (n,n´f)
  - "third chance fission" : (n,2n'f), …





The relative probabilities of decay are quantified by the decay widths Γ_f and Γ_n for fission and neutron emission, respectively.

R. Vandenbosch and J.R. Huizenga : "Nuclear Fission" , Academic Press, 1973

Generally produced by equilibrium (evaporation), preequilibrium, direct, or knockout reaction mechanisms

Mechanism of Prompt neutron emission

❑ Neutron emission from ternary fission: negligible contribution

- Fission process leads usually to two main fission fragments (binary fission). Nevertheless, sometimes (about 0.2% of fission events in the case of $^{235}U(n_{th},f)$), the two main FF can be accompanied by the emission of a light charged particles (ternary fission).

- The main emitted ternary particles are ^4He-particles (about 90% of ternary fission events).

- According to Halpern: 'average energy cost' needed to emit a ternary alpha particle is about 20 MeV in the case of $^{235}U(n_{th},f)$ reaction. Prompt neutron emission becomes strongly inhibited in case of ternary fission.

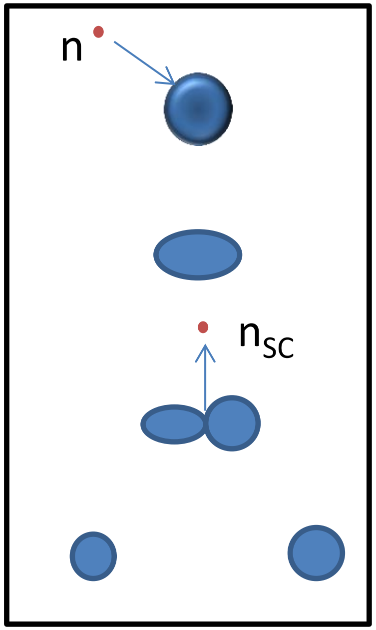
- Possible emission of ^5He ternary particle (estimated to 0.001%) which decays into ^4He+n ($T_{1/2}$=7.03E-22 s): **completely negligible neutron contribution**

Mechanism of Prompt neutron emission

❑ **Scission neutrons (n_{sc}): their existence is still controversy**

- **Poor and contradictory experimental data:** difficulty to distinguish experimentally neutrons from fully accelerated FF (evaporated neutrons) and neutrons emitted at the scission point (scission neutrons).

Author	Contribution	
Franklyn, 1978	20%	$^{235}U(n_{th},f)$
Vorobyev, 2009	5%	$^{235}U(n_{th},f)$
Bowman, 1962	10%	$^{252}Cf(sf)$
Marten, 1989	<1%	$^{252}Cf(sf)$
Budtz-Jorgensen, 1989	<1%	$^{252}Cf(sf)$
Kornilov, 2001	10%	$^{252}Cf(sf)$
Gagarski, 2012	8%	$^{252}Cf(sf)$
Chietera, 2014	8%	$^{252}Cf(sf)$



- **Argument in favor of scission neutrons:**
  - ❑ Ternary light charged particles can be emitted at the scission point. 'Ternary neutrons' (or scission neutrons) should therefore also exist
  - ❑ Could be even the most produced ternary particles because no Coulomb barrier has to be overcame for their emission (require less energy to be emitted)

Mechanism of Prompt neutron emission

❑ Scission neutrons (n_{sc}): their existence is still controversy

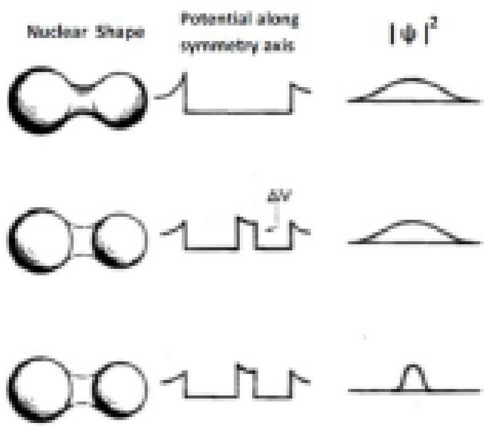
Possible mechanism of scission neutron emission

- ❑ Evaporation of neutrons from the neck near scission: highly improbable
- ❑ 'sudden approximation' model (Fuller, 1962): convincing description of the ternary particle emission process, including scission neutrons

Just Before Scission

Immediately After Scission

Immediately After Scission

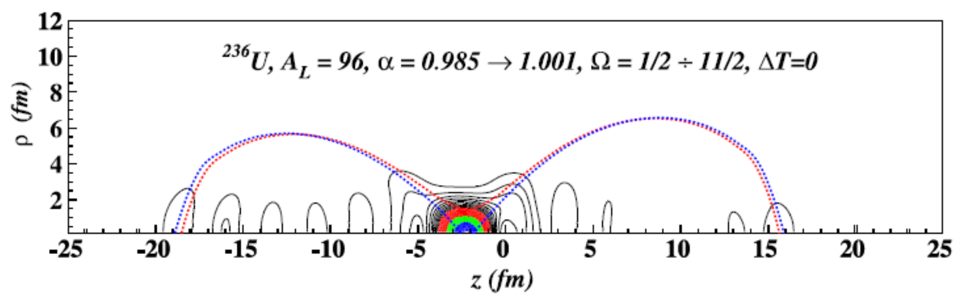


From I. Halpern, 1965

- The neck rupture is assumed to be very fast (< 10^{-22} s).
  ➡ very fast transition between 'Just Before Scission' and 'Immediately After Scission'
- Neutron: assumes to be in an eigenstate at 'JBS' time
  ➡ becomes a wave packet with components in the continuum at 'IAS' time.
- Probability to populate such states (continuum) gives the emission probability of neutrons at scission

❑ Emission of the scission neutrons: mainly perpendicular to the fission axis

Spatial distribution from the unbound neutrons:
From N. Carjan, NPA909 (2013) 50



Mechanism of Prompt neutron emission

❑ Emission during the acceleration of the FF

Part of the prompt neutrons can be emitted during the acceleration phase of the primary fission fragments ? To answer, we need to know:

- ***t*** Characteristic time of the acceleration phase (Coulomb repulsion)
- τ Characteristic time associated to neutron evaporation.

Estimation of *t*

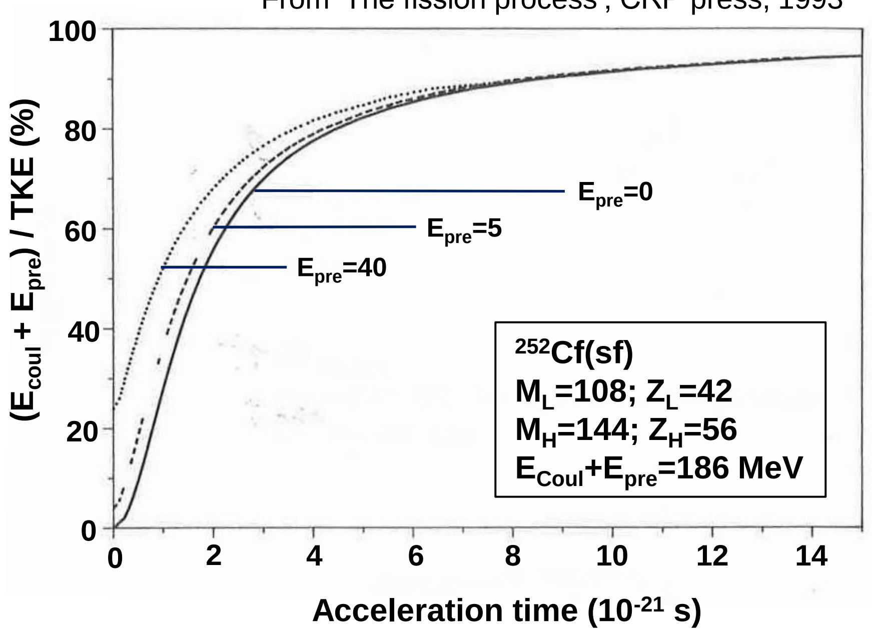
$$\frac{\mu}{0.5}\left(\frac{dr}{dt}\right)^2 + \frac{Z_L.Z_H e^2}{r} = E_{Coul} + E_{pre}$$

μ: reduced mass of the two FF
r: distance between the two charge centers
Z_L, Z_H: nuclear charges
E_{pre}: pre-Kinetic energy
E_{Coul}: Coulomb repulsion

when: $r \rightarrow \infty$, $E_{Coul}+E_{pre}$=TKE

Example: adopting E_{pre}=0,
90% of the TKE is reached after **8.6×10^{-21} s**

From ‘The fission process’, CRP press, 1993

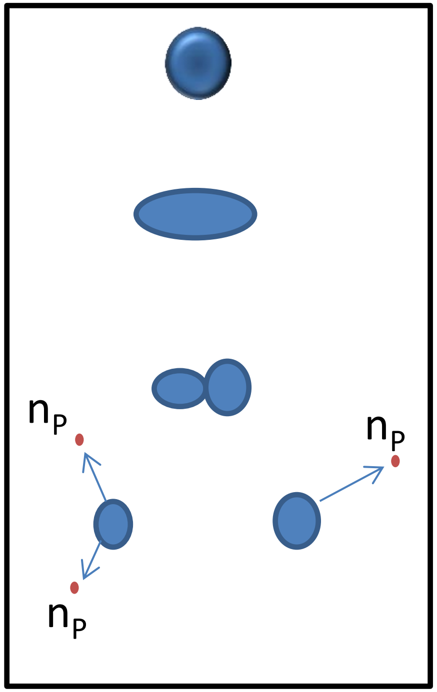


Since the decay time associated to the neutron emission seems to be longer than the acceleration phase time (τ > ***t***): **neutron emission during this phase is probably negligible**.

Mechanism of Prompt neutron emission

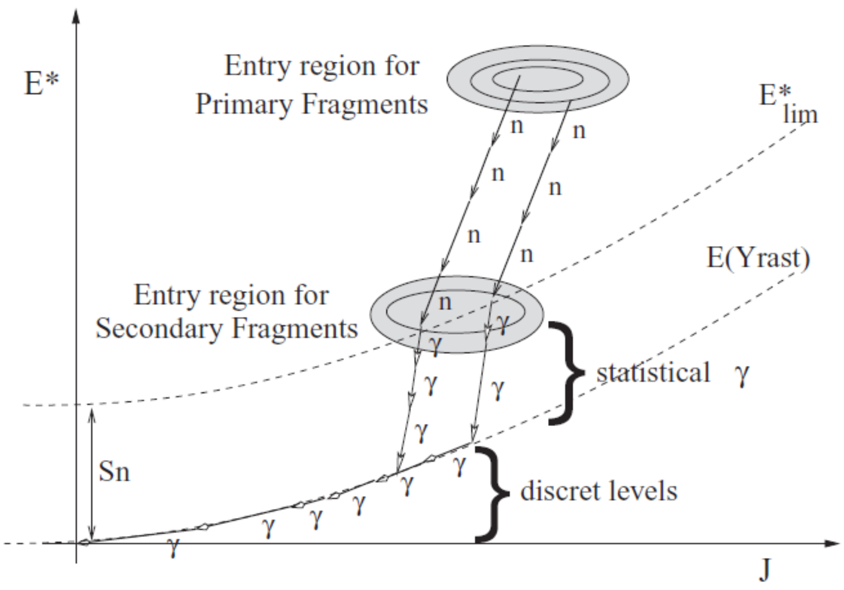
❑ **Evaporation from the fully accelerated FF (n_P): by far the main contribution**

In low-energy nuclear fission: the main source of neutrons comes from the evaporation of the excited primary fission fragments



- After full acceleration: primary FF are characterized by their excitation energy and their spin (rotating fragments)

- These excitation energy and spin are removed by evaporation of prompt neutrons and then, in competition with the last emitted neutrons, the nucleus emits γ-rays.



From O. Litaize, Phys. Rev. C82, 054616 (2010)

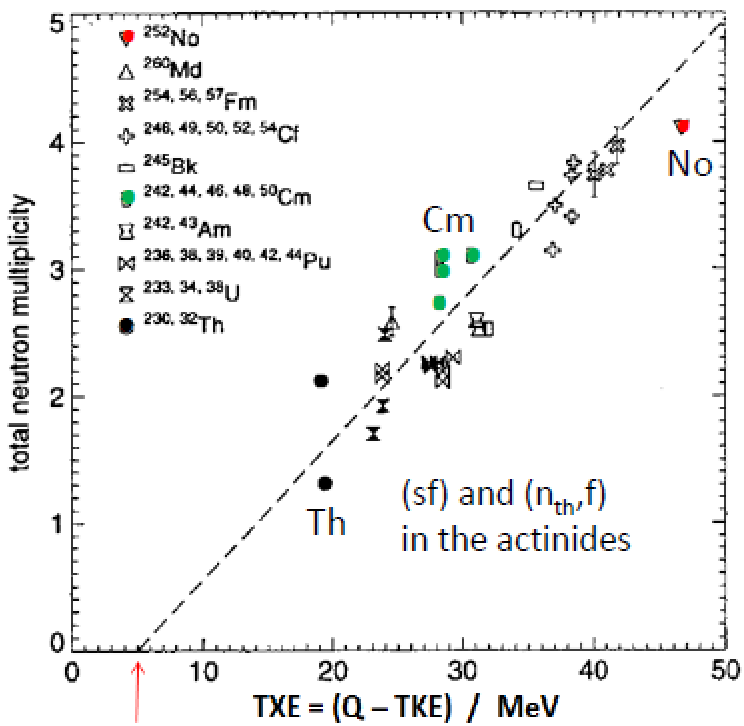
Part I: Prompt neutron Emission

- *Prompt Neutron Multiplicities*

  - Average total prompt neutron multiplicity $<\nu_{tot}>$ versus the available total excitation energy of the fissioning nucleus
  - Influence of the incident neutron energy on the total prompt neutron multiplicity : $<\nu>$(En)
  - Distribution of Neutron Multiplicity : P(ν)
  - Prompt neutron multiplicity as a function of the FF Total Kinetic Energy : $<\nu>$(TKE)
  - Prompt neutron multiplicity as a function of pre-neutron mass (saw-tooth) : $<\nu>$(A)
  - Influence of the incident neutron energy on the 'saw-tooth' curve

Prompt Neutron Multiplicities

- **Average total prompt neutron multiplicity $<\nu_{tot}>$ versus the available total excitation energy of the fissioning nucleus**



From F. Gonnenwein, lecture FIESTA-2014, extracted from D. Hilscher and H. Rossner: Ann. Phys.(Paris), 17 (1992) 471

- As expected: a clear increase of $<\nu_{tot}>$ observed with increasing <TXE>

In the figure: <TXE> calculated from:
$<TXE> = <Q> + B_n + E_n - <TKE>$
(B_n and E_n are zero in case of spontaneous fission).

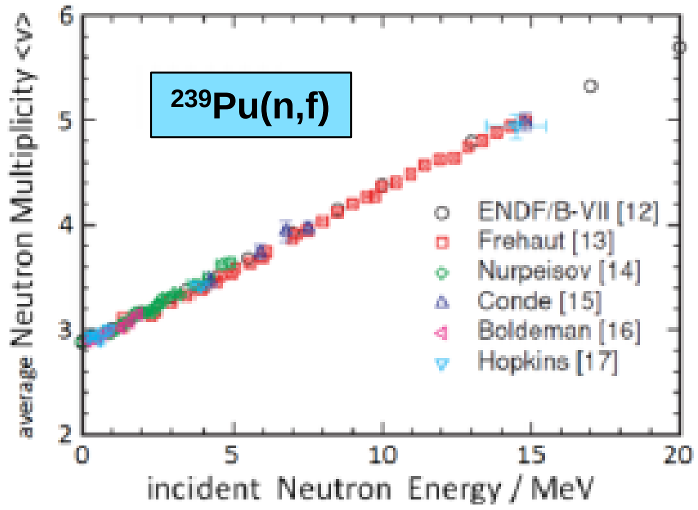
- Offset observed at about 5 MeV (red arrow): when <TXE> is lower than the neutron binding energy, prompt neutron emission becomes energetically not possible. Only prompt gamma rays will be emitted to cold the nucleus.

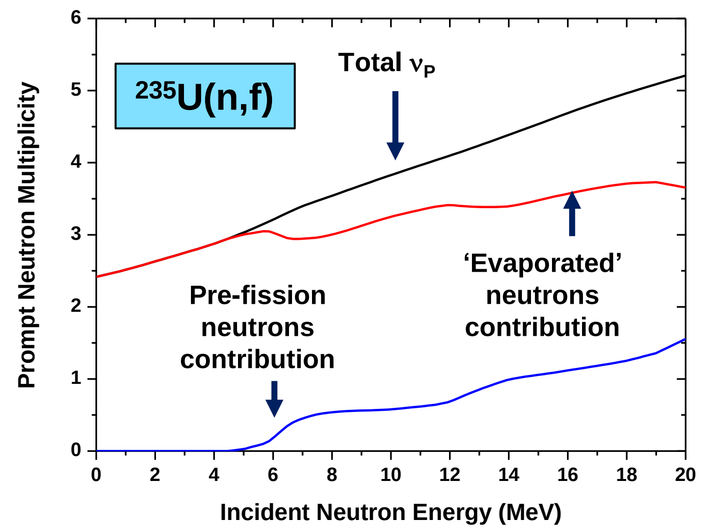
- Slope of the linear fit : 0.112 n/MeV

Prompt Neutron Multiplicities

❑ Influence of the incident neutron energy on the total prompt neutron multiplicity : <ν>(En)

- Increase of the prompt neutron multiplicity with incident neutron energy: ^{239}Pu(n,f) (top) and ^{235}U(n,f) (bottom)
- When 2nd and higher chance fissions are setting in (En higher than about 5 MeV for ^{235}U(n,f)), two components:
  - ❑ **Component 1** (red curve): neutrons evaporated by the fragments
  - ❑ **Component 2** (blue curve): neutrons re-emitted by the compound nucleus before fission ("pre-scission neutrons")
- Note: After first fission chance, 'evaporated' neutron multiplicity component is decreasing around 6 MeV (red curve) : after emission of a pre-fission neutron, the residual compound nucleus (A-1) has less available excitation energy.





❑ Distribution of Neutron Multiplicity : P(ν)

- Examples of measured P(ν) (normalized to one) for three fissioning systems

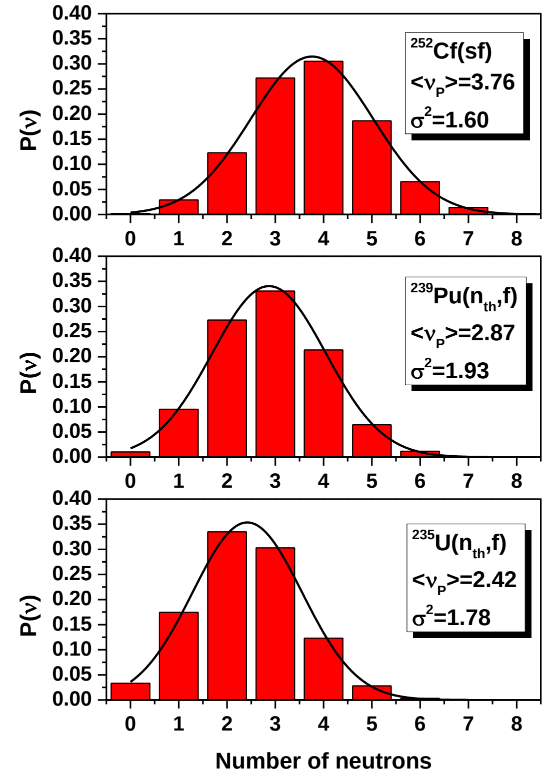
- P(ν) well reproduced by a Gaussian curve characterized by:
  - ❑ The average value: <ν>
  - ❑ The variance: σ^2

- For actinides (from Pu to Cm): variances rather constant,
  For Cf to No: variances rise significantly.

Nucleus	238U	238Pu	240Pu	242Pu	242Cm	244Cm	246Cm	248Cm	246Cf	250Cf	252Cf	254Cf	256Fm	257Fm	252No
σ^2	0.902	1.278	1.303	1.340	1.220	1.263	1.285	1.304	1.680	1.534	1.596	1.529	2.219	2.493	4.284

Variance data from spontaneous fissioning systems

- P(ν=0): neutron-less fission (also called 'cold fission'). May be very different from one fissioning nucleus to another.
  Examples ^{235}U(n_{th},f) (<ν> = 2.42) ➡ P(ν=0)=3.2%
  ^{252}Cf(sf) (<ν> = 3.76) ➡ P(ν=0)= 0.23%



Measured distribution of the neutron multiplicity P(ν) for 3 fissioning nuclei: ^{252}Cf(sf) (from Vorobyev, 2004); ^{235}U(n_{th},f) (from J.W. Boldeman ,1985); ^{239}Pu(nt_h,f) (from Gwin, 1984)

❑ Prompt neutron multiplicity as a function of Total Kinetic Energy: <ν>(TKE)

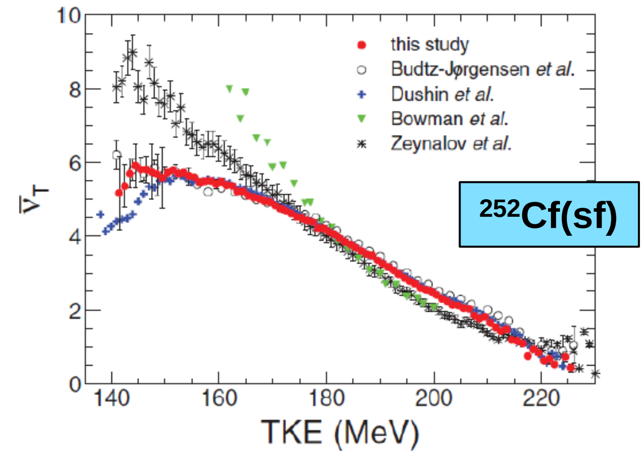
- Examples of the prompt neutron multiplicity dependence with TKE: <ν>(TKE)

- For increasing kinetic energy TKE, the excitation energy and hence the neutron multiplicity <ν> is expected to decrease, as observed experimentally.

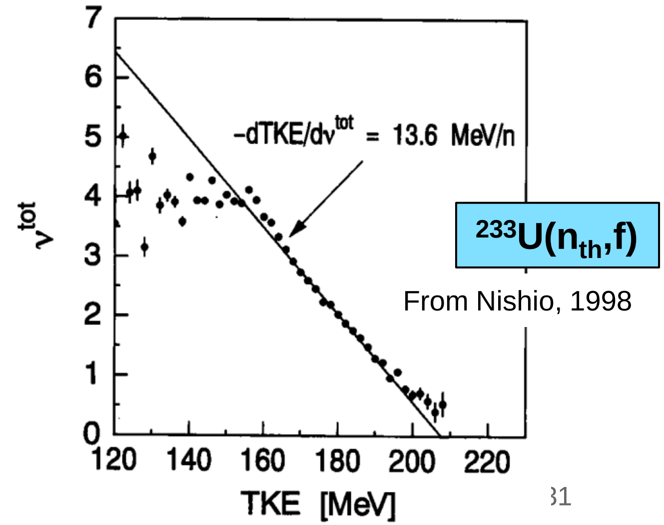
- Except at low TKE, this dependence is nearly linear. From least-squares fit:

^{252}Cf(sf): -dTKE/d<ν>= (12.6 ± 0.2) MeV/n (Gook)
^{235}U(n_{th},f): -dTKE/d<ν>= 12.0 MeV/n (Hambsch)
^{235}U(n_{th},f): -dTKE/d<ν>= 13.6 MeV/n (Nishio)

Note: This slope is difficult to measure. In particular, experimental results are reliable, only if a good TKE energy resolution is achieved (see Lecture given by F.-J. Hambsch, FIESTA 2017).



The red points correspond to the measurement performed by Gook (A. Gook, 2014)



From Nishio, 1998

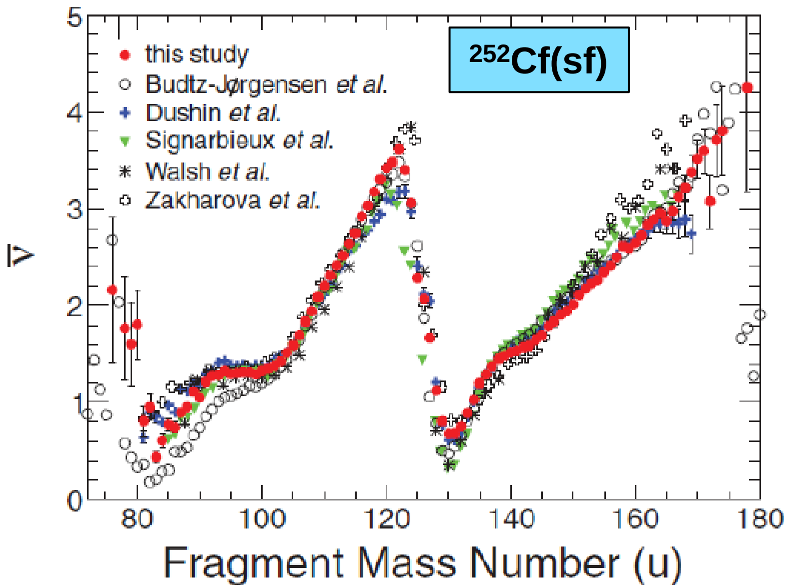
Prompt Neutron Multiplicities

❑ Prompt neutron multiplicity as a function of pre-neutron mass: <ν>(A)

- Plotted as a function of primary fragment mass, the average multiplicity <ν>(A) has a saw-tooth like appearance.
- Observed for all fissioning systems, but more pronounced at low fission energy
- In heavy mass region: a clear minimum is observed around the mass 130
- On average, light fragment group emits generally more neutrons than the heavy fragment group (at least for thermal neutron-induced fission and spontaneous fission): $\boxed{<\nu_{Light}> \geq <\nu_{Heavy}>}$

$$<\nu_{Light}> = \sum_{A_{pre} \in Light} Y(A_{pre}) <\nu_{Light}>(A_{pre})$$

$$<\nu_{Heavy}> = \sum_{A_{pre} \in Heavy} Y(A_{pre}) <\nu_{Heavy}>(A_{pre})$$



The red points correspond to the measurement performed by Gook (A. Gook, 2014)

Some examples

Reaction	$^{233}U(n_{th},f)$	$^{235}U(n_{th},f)$	$^{252}Cf(sf)$
ν_L / ν_H	1.395/1.100	1.390/1.047	2.056/1.710
Ratio	1.27	1.33	1.20

Prompt Neutron Multiplicities

❑ Prompt neutron multiplicity as a function of pre-neutron mass : <ν>(A)

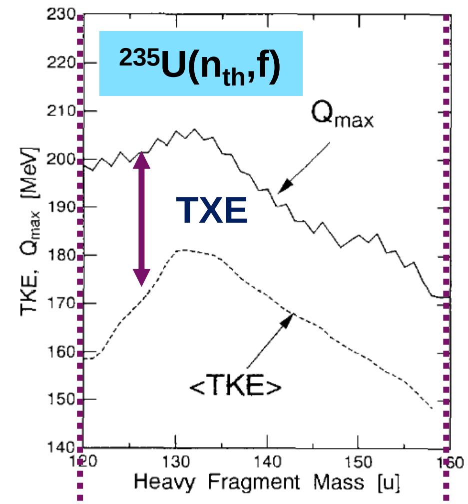
- From measurement of <TKE>(A_H) and calculation of Q_{max}: <TXE>(A_H)= Q_{max}(A)-<TKE>(A_H)

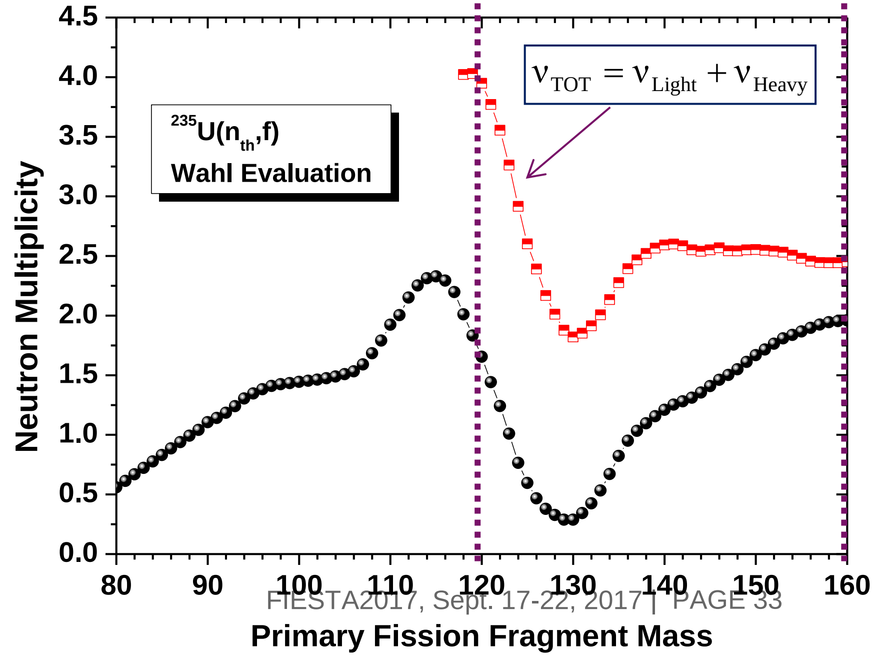
- Symmetry region (around A=118): maximum of TXE leading to a maximum of ν_{Tot} (red curve).
  - ➡ The 2 fragments strongly deformed at scission, leading to a very low TKE and a very high TXE

- Around mass 132: Reverse situation.
  - ➡ Maximum of <TKE>: more compact configuration at scission (shell effect). TXE is minimum, leading to a low value of ν_{tot}

- Above the mass 140: <TXE> rather constant and consequently, ν_{tot} becomes flat

From Nishio, 1998





❑ Prompt neutron multiplicity as a function of pre-neutron mass : <ν>(A)

- At scission: total excitation energy mainly composed of intrinsic excitation energy ($E^{*,SC}_{L,H}$), deformation energy ($E^{Def,SC}_{L,H}$) and collective excitation energy ($E^{Coll,SC}_{L,H}$):

$$\boxed{TXE = E_L^{*,SC} + E_H^{*,SC} + E_L^{Def,SC} + E_H^{Def,SC} + E^{Coll,SC}}$$

If nucleons are treated as a Fermi gas: the intrinsic excitation energy can be written as:

$$\boxed{\begin{aligned} E_L^{*,SC} &= a_L \left(T^{SC}\right)^2 \\ E_H^{*,SC} &= a_H \left(T^{SC}\right)^2 \end{aligned}}$$

where a_L and a_H: level density parameters. Due to the assumed thermodynamic equilibrium at scission, the temperature (T^{SC}) is expected to be the same for both fission fragments.

- Nevertheless, after the acceleration phase of the rotating FF, since the deformation energy is transformed into intrinsic energy (relaxation step), TXE becomes:

$$\boxed{TXE = E_L^* + E_H^* + E_L^{Rot} + E_H^{Rot}}$$

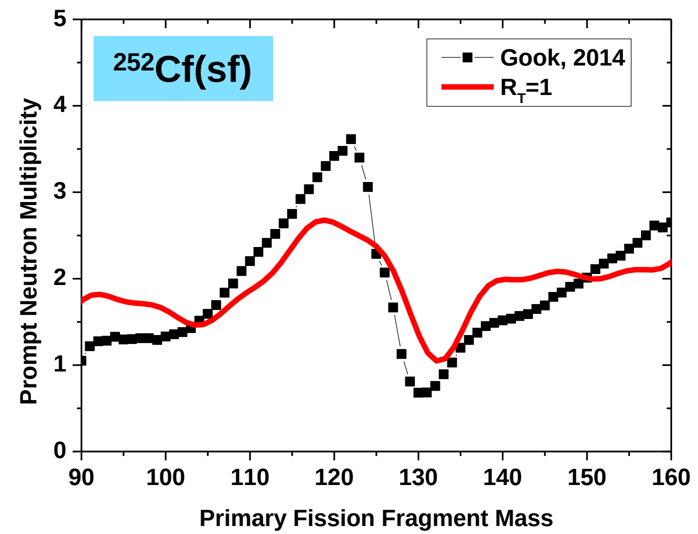
After the full acceleration, temperatures of the light (T_L) and heavy (T_H) fragment, associated to their intrinsic energy, are generally not equal, because deformation of the FF at scission is different.

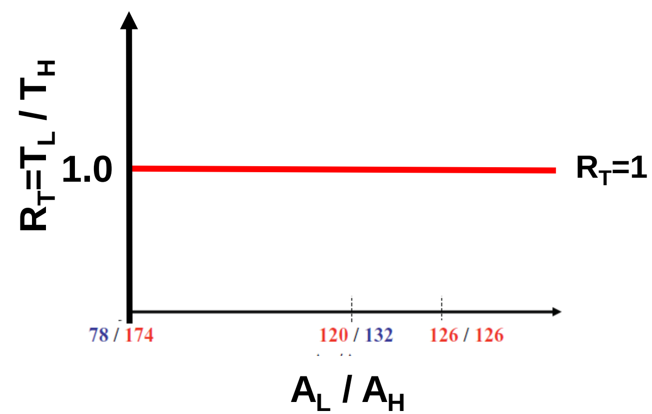
$$\boxed{\begin{aligned} E_L^* &= a_L T_L^2 \\ E_H^* &= a_H T_H^2 \end{aligned}}$$

Prompt neutron multiplicity as a function of pre-neutron mass : <ν>(A)

Impact of non-equal temperatures between the two FF: $T_L \neq T_H$
Three different hypothesis on the temperature ratio $R_T = T_L / T_H$

➡ **$R_T=1$** (Red curve): same temperature for all masses
Experimental saw-tooth cannot be reproduced





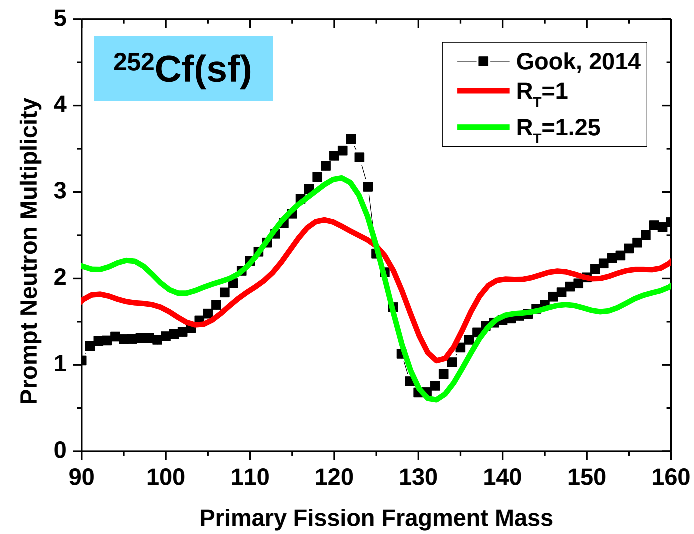
Prompt Neutron Multiplicities

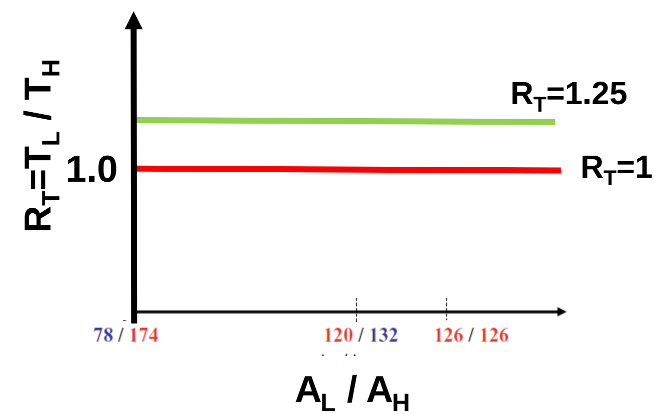
❑ Prompt neutron multiplicity as a function of pre-neutron mass : <ν>(A)

Impact of non-equal temperatures between the two FF: $T_L \neq T_H$
Three different hypothesis on the temperature ratio $R_T=T_L/T_H$

- **$R_T=1$** (Red curve): same temperature for all masses
  Experimental saw-tooth cannot be reproduced

- **$R_T=1.25$** (green curve): $T_L > T_H$ because $\nu_L > \nu_H$.
  Saw-tooth appears, but poor agreement with experimental data
  Note: ν_L increases (compared to $R_T=1$) and ν_H decreases





Prompt Neutron Multiplicities

❑ Prompt neutron multiplicity as a function of pre-neutron mass : <ν>(A)

Impact of non-equal temperatures between the two FF: $T_L \neq T_H$
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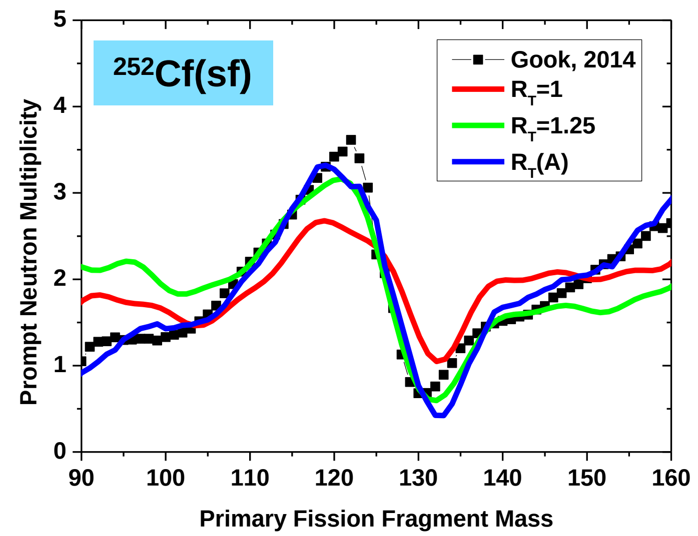
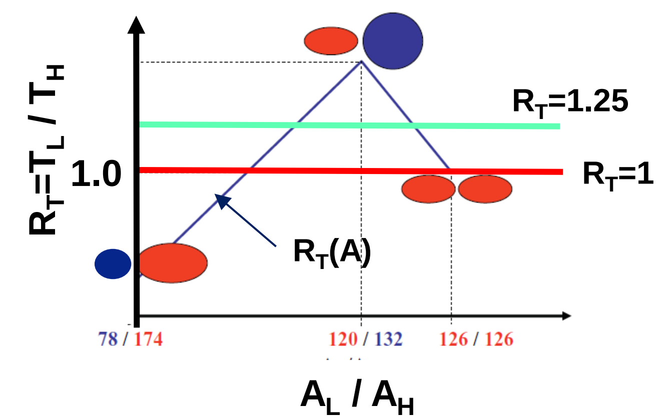
  Saw-tooth appears, but poor agreement with experimental data
  Note: ν_L increases (compared to R_T=1) and ν_H decreases

- $R_T(A)$ (blue curve): Mass-dependent temperature ratio
  For symmetric fission: same temperature
  For light mass number A_L=120, A_H=132: R_T maximum
  For very asymmetric fission, A_L=78, A_H=174: R_T minimum
  Linear law between these three key configurations





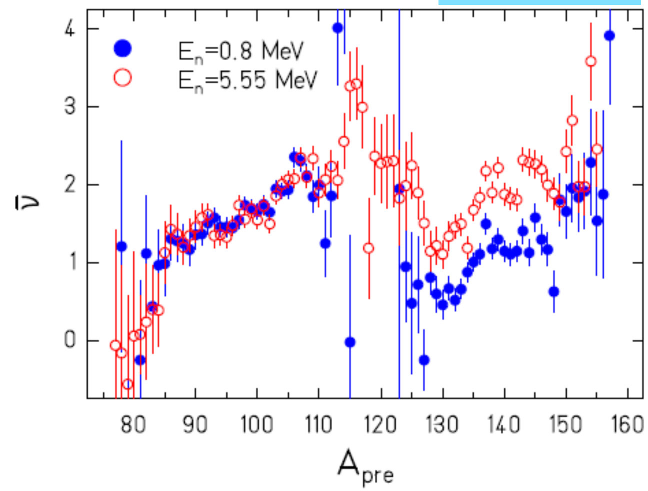
Prompt Neutron Multiplicities

❑ Influence of the incident neutron energy on the ‘saw-tooth’ curve

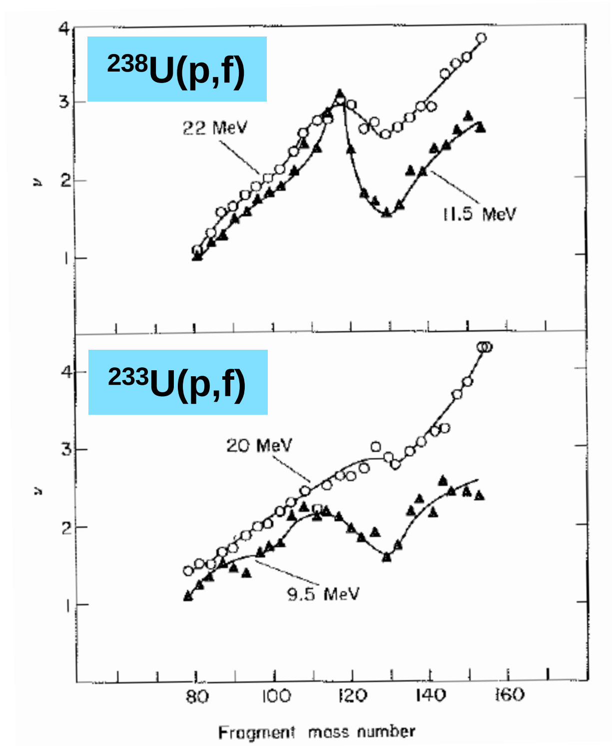
Behavior of the saw-tooth like shape of multiplicity <ν(A)> when the energy of the incident particle increases.

- Additional energy introduced in neutron-induced fission of ^{237}Np: **raises the neutron multiplicities of the heavy fragment, only.**
- Same observation made by Muller in the case of ^{235}U(n,f) reaction as well as in the case of proton induced fission reactions.
- Explanation still controversy (see K.H. Schmidt 2016; Marten 1989; Tudora 2009)

^{237}Np(n,f)



From K.H. Schmidt et al., Nucl. Data Sheets 131 (2016) 107



Vandenbosch and Huizenga, Nuclear Fission, 1973

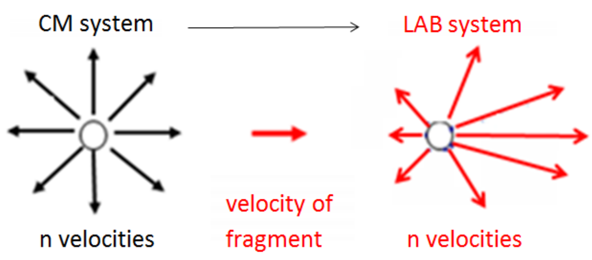
Müller et al., Phys. Rev. C29,885 (1984)
Naqvi et al., Phys. Rev. C34, 218 (1986)

^{235}U(n,f)		^{237}Np(n,f)	
En	$\langle\nu_L\rangle/\langle\nu_H\rangle$	**En**	$\langle\nu_L\rangle/\langle\nu_H\rangle$
0.5 MeV	**1.44 / 1.02**	**0.8 MeV**	**1.59 / 1.14**
5.5 MeV	**1.43 / 1.71**	**5.55 MeV**	**1.59 / 1.87**

Part I: Prompt neutron Emission

- *Angular Distribution of Prompt neutrons*

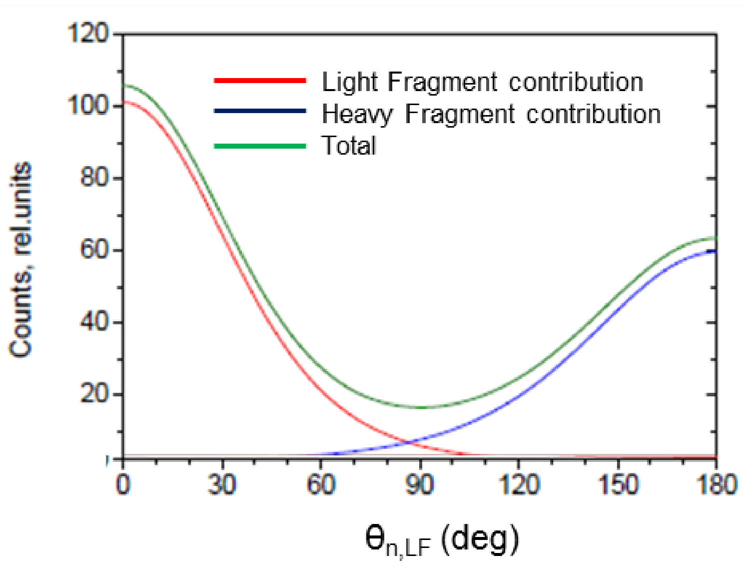
Angular Distribution of Prompt neutrons



From Gonnenwein, lecture FIESTA 2014)

- Assuming an isotropic emission of the neutrons in the center of mass of the FF, then: after transformation in the laboratory frame, prompt neutrons are strongly focused in the direction of the moving FF

‘kinematical focusing’ effect: due to the velocity of the FF and the rules of transformation between center of mass and laboratory systems



Simulation for $^{235}U(n_{th},f)$, from A. Chietera, 2015

- Typical angular distribution has two contributions:
  - Neutrons from the LF (red curve): strongly focused around $\theta_{n,LF}$= 0°
  - Neutrons from the HF (blue curve): strongly focused around $\theta_{n,LF}$= 180°

- Contribution from LF (red) higher than for HF, because $<\nu_L>$ higher than $<\nu_H>$

- Kinematical effect enhanced for LF (narrower distribution), due to their higher velocity ($<\boldsymbol{v}_L>$=1.42 cm/ns, $<\boldsymbol{v}_H>$=0.98 cm/ns)

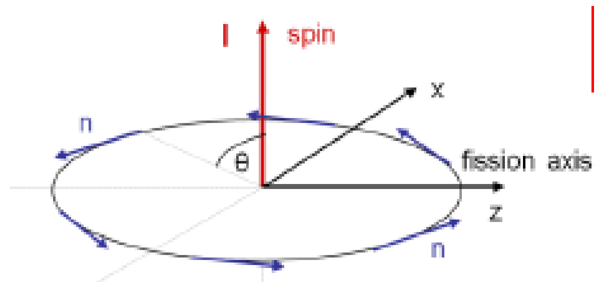
Angular Distribution of Prompt neutrons

Two additional effects can disturb the angular distribution

1. Possible anisotropic emission in the com of the FF may occur due to the angular momenta J (Bowman). Neutrons will preferentially be emitted in the equatorial plane perpendicular to the angular momentum.

Since the spin of the FF is perpendicular to the fission axis, the angular distribution between neutron and fission axis is given by:

$$\boxed{W(\theta_{n,F}) \propto 1 + A_{n,F}\cos^2\theta_{n,F}}$$

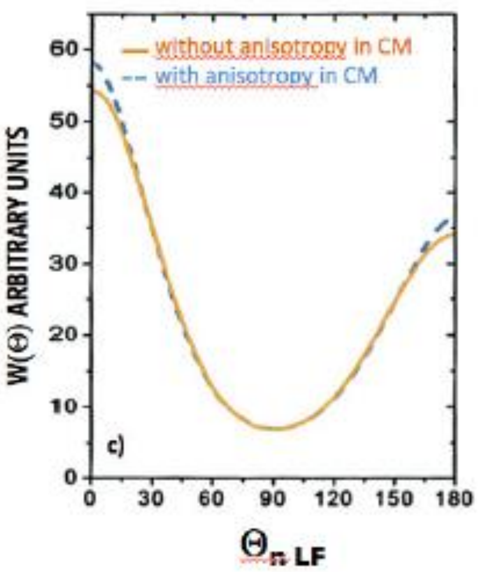


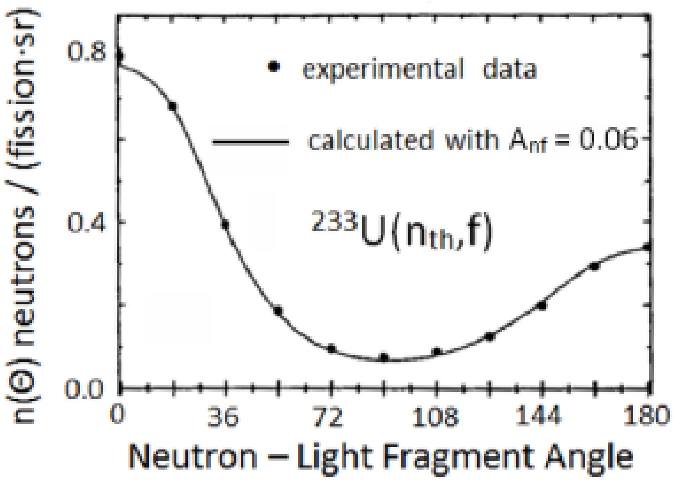
$A_{n,F} = W(0°)/W(90°)-1$

$\vartheta_{n,F}$: angle between neutron direction and the fission axis.

The anisotropy in the center of mass system reinforces the kinematical focusing effect

$^{235}U(n_{th},f)$, from A. Chietera, 2015





By adding anisotropy in the calculation ($A_{n,F}$=0.06), experimental data nicely reproduced

From A.S. Vorobyev, 2009

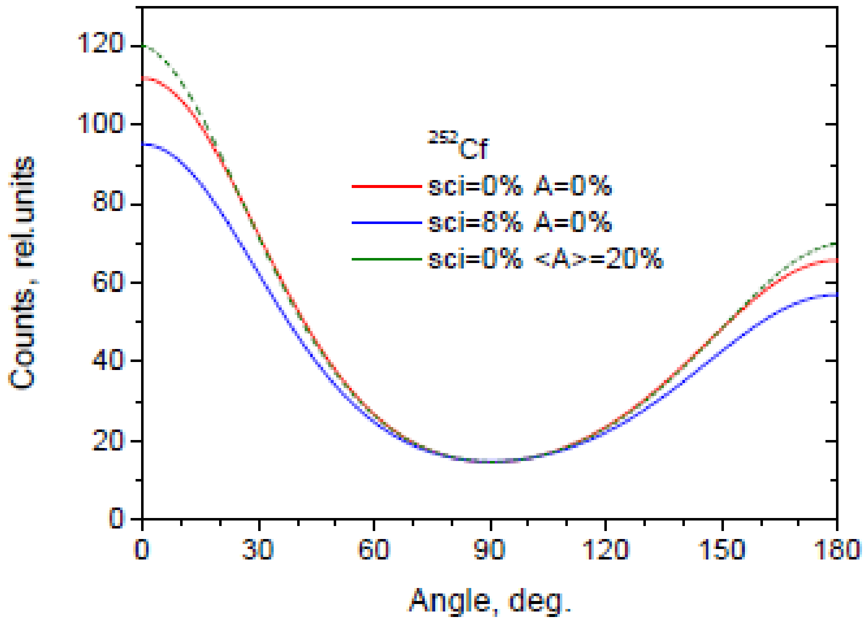
Angular Distribution of Prompt neutrons

2 The second effect is due to the possible existence of scission neutrons.

These neutrons are expected to be emit perpendicular to the fission axis.

Monte Carlo calculation of the angular neutron-FF distribution, including scission neutrons shows that scission neutrons will now decrease the kinematic focusing effect.

$^{235}U(n_{th},f)$, from A. Chietera, 2015



- Both effects (anisotropy due to the spin, existence of scission neutrons) are compensated each others: It is therefore extremely difficult to disentangle each effect separately as shown on this figure.
- An other very promising way to solve this problem is to search for triple coincidence events (n, n, FF).

Part I: Prompt neutron Emission

- *Prompt Fission Neutron Spectrum (PFNS)*
  - Maxwellian
  - Watt
  - Los Alamos Model (LAM)
  - Stochastic approaches

Prompt Fission Neutron Spectrum (PFNS)

❑ Deterministic models used to describe Prompt Fission Neutron Spectra: Maxwellian

- The earliest and simplest model used to describe the Prompt Fission Neutron Spectrum (PFNS), is the single parameter Maxwell-Boltzmann distribution (generally referred to simply as a "Maxwellian"), that depends on a temperature parameter, *T:*

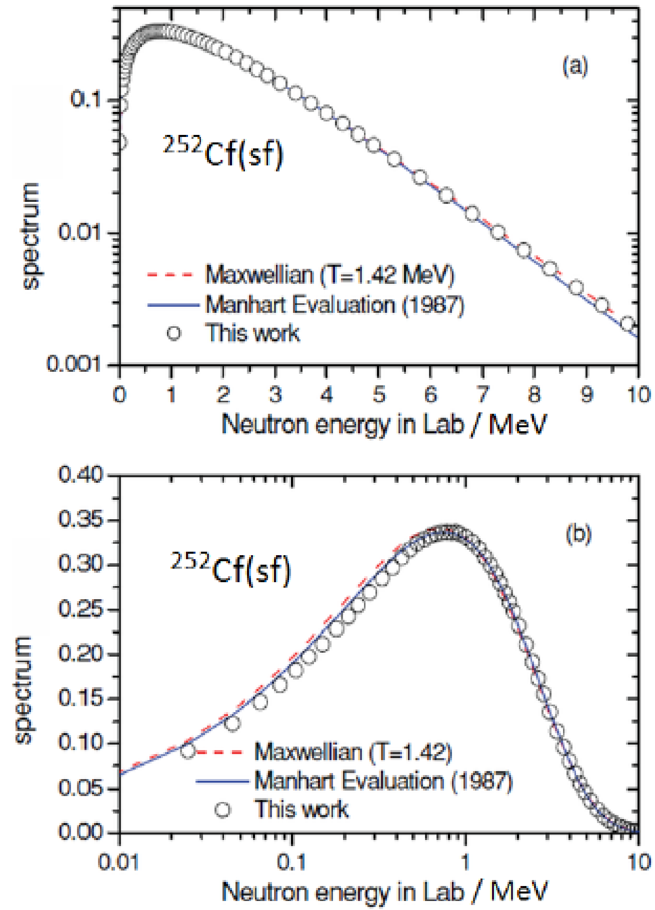
$$N(E) = \left(\frac{2}{\sqrt{\pi}}\right) \times \left(\frac{\sqrt{E}}{T^{3/2}}\right) \exp\left(-\frac{E}{T}\right)$$

- The spectrum is normalized to one and the average energy is given by:

$$< E >= \frac{3}{2} T$$

In the case of $^{252}Cf(sf)$, the best experimental fit is obtained with T=1.42 MeV, leading to <E>=2.13 MeV.

A comparison between the evaluation of the PFNS performed by Mannhart (1987) with a Maxwellian (with T=1.42 MeV) seems to be surprisingly good, as shown in the figure.



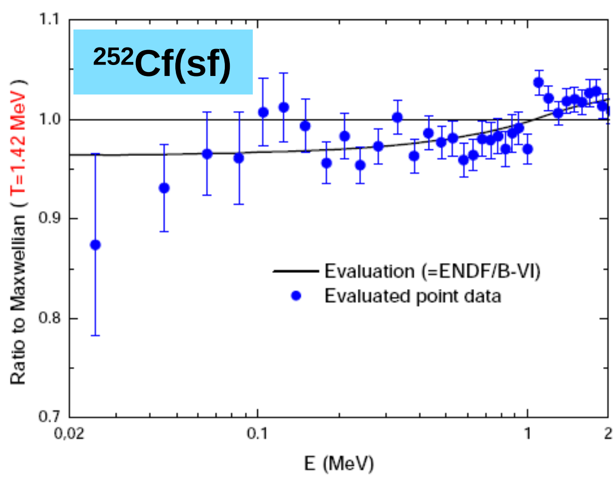
Prompt Fission Neutron Spectrum (PFNS)

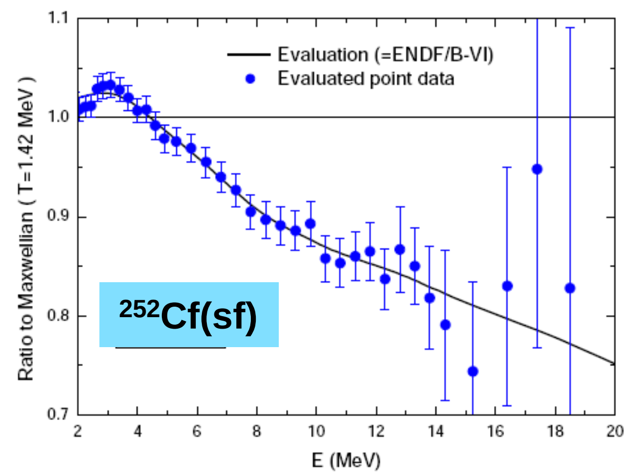
❑ **Deterministic models used to describe Prompt Fission Neutron Spectra: Maxwellian**

- Nevertheless, looking at the PFNS (evaluated by Mannhart) ratio to a Maxwellian (with T=1.42 MeV), it is easier to see the defects of the model.

- This ratio is plotted with lin-log scale (left) to highlight low emission energies and with lin-lin scale (right) to highlight higher energies. We observe that the Maxwellian spectrum cannot reproduce the Mannhart evaluation above 6 MeV.

- Maxwellian still employed for some applications. Nevertheless, all physical aspects of the fission process are neglected and this description has therefore no predictive power.





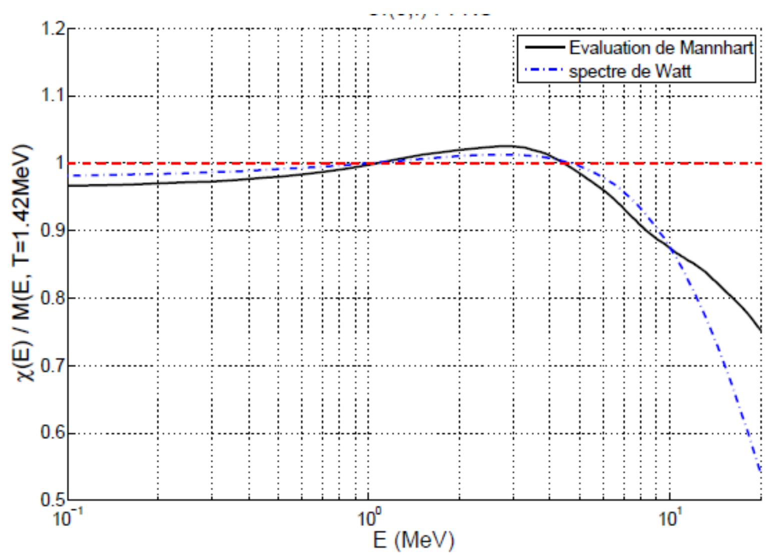
Prompt Fission Neutron Spectrum (PFNS)

❑ Deterministic models used to describe Prompt Fission Neutron Spectra: WATT

- Watt spectrum has two free parameters: T_W and E_F. (The watt spectrum, in the laboratory system, is obtained from a Maxwell spectrum in the center-of-mass system)

$$N(E) = \frac{1}{\sqrt{\pi T_W E_F}} \exp\left(-\frac{E_F + E}{T_W}\right) \times \sinh\left(\sqrt{\frac{4(E_F E)}{T_W^2}}\right)$$

- The best fit obtained with (for $^{252}Cf(sf)$:
  T_W=0.94 MeV;
  E_F=182 MeV/252 nucleon = 0.72 MeV / nucleon.



From L. Berge, 2015

- The PFNS average energy is given by: $< E >= E_F + \frac{3}{2} T_W$.
  We obtain: 2.13 MeV

- The Watt formulation does account only for the center-of-mass motion of an average fragment. Therefore, the Watt distribution, while more physical than a Maxwellian, still has little predictive power.

Prompt Fission Neutron Spectrum (PFNS)

❑ Deterministic models used to describe Prompt Fission Neutron Spectra: Los Alamos model (LAM)

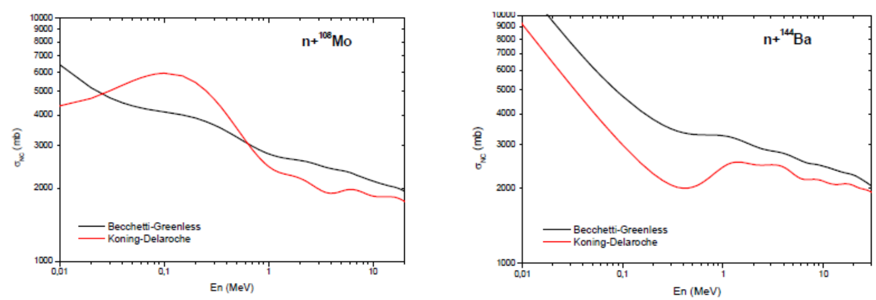
- Los Alamos Model proposed by Madland and Nix in 1982
- Prompt fission neutrons assumed to be emitted from the fully accelerated FF
- In the center of mass of the FF, the evaporation spectrum of prompt neutrons follows a Weisskopf spectrum:

(1)
$$\phi(\varepsilon,T) = \mathrm{k(T)}\ \sigma(\varepsilon)\ \varepsilon \exp(-\varepsilon/\mathrm{T})$$
$$\mathrm{k(T)} = \left(\int_0^\infty d\varepsilon\ \sigma(\varepsilon)\ \varepsilon \exp(-\varepsilon/\mathrm{T})\right)^{-1}$$

ε: center-of-mass neutron kinetic energy
T: residual nuclear temperature after neutron emission
$\sigma(\varepsilon)$: cross section for the inverse process of compound nucleus formation through neutron capture
k(T): normalisation constant

Note: if $\sigma(\varepsilon)$ constant, then $\phi(\varepsilon,T) = \frac{\varepsilon}{\mathrm{T}^2} \exp(-\varepsilon/\mathrm{T})$

Note: To calculate the average spectrum of all neutrons emitted from all FF, Eq. (1) needs to be folded with a distribution of fission fragment temperatures or excitation energies.

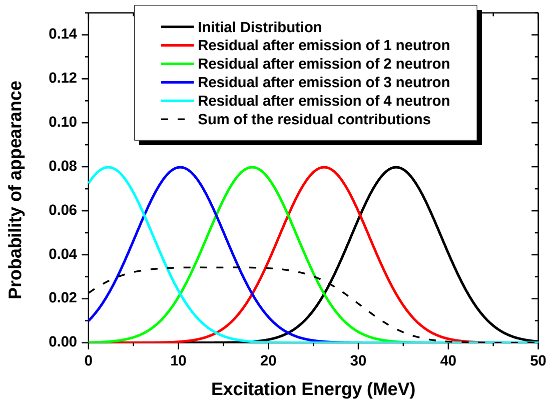


Examples of cross section $\sigma(\varepsilon)$ for the inverse process of compound nucleus for two complementary FF

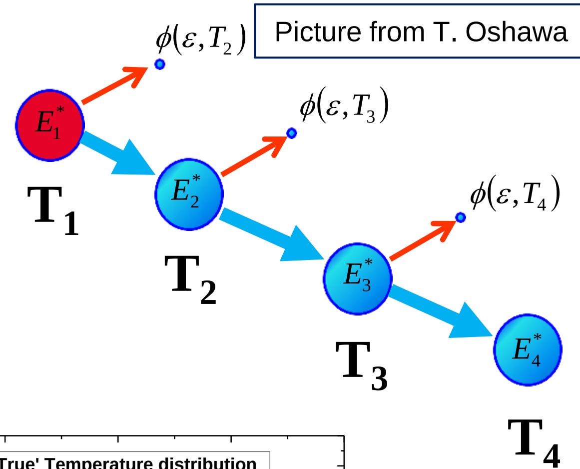
❑ Deterministic models used to describe Prompt Fission Neutron Spectra: Los Alamos model (LAM)

Distribution of FF temperatures derived by Terrell (1959). Starting from an average initial excitation energy distribution (black curve) and after a sequential neutron emission (color curves), the residual excitation energy distribution has a flat behavior (dashed black curve).

Picture from T. Oshawa

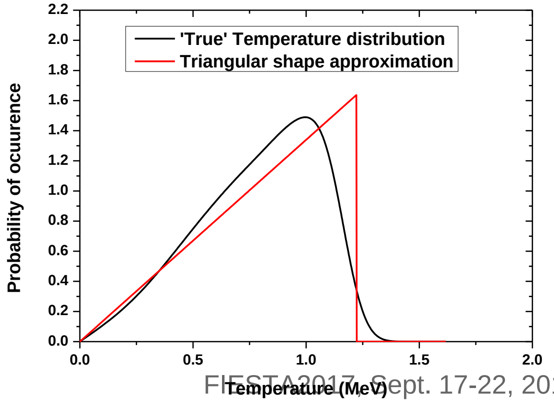


$$E_2^* = E_1^* - Sn - \varepsilon = aT_2^2$$
$$E_3^* = E_2^* - Sn - \varepsilon = aT_3^2$$
$$E_4^* = E_3^* - Sn - \varepsilon = aT_4^2$$



Using Fermi gas model, the residual excitation energy distribution is transformed into temperature distribution, which can be approximated by a triangular distribution

$$E^* = aT^2$$
$$P(E^*) = cste$$
$$P(T)dT = P(E^*)dE^*$$
$$P(T) = cste \times 2aT$$



Prompt Fission Neutron Spectrum (PFNS)

❑ Deterministic models used to describe Prompt Fission Neutron Spectra: Los Alamos model (LAM)

$$P(T)=\begin{cases} 2T/T_{\max}^2 & (\mathrm{T}\le \mathrm{T}_{\max}) \\ 0 & (\mathrm{T}\le \mathrm{T}_{\max}) \end{cases}$$

Residual nuclear temperature distribution (triangular form) is used in the LAM, with

$\mathrm{T}_{\max}^2 = <\mathrm{E}^*>/\mathrm{a}$ ‘a’ is the level density parameter approximated by: $a=A_{CN}/11$ (in the initial model proposed by Madland and Nix, 1982) and <E*>=<TXE>=<Q>+En+Bn-<TKE>

The prompt fission neutron spectrum, in the center of mass system, is then given by folding Eq.(1) over the residual temperature distribution:

$$\Phi(\varepsilon)=\int_0^{\infty}\mathrm{dT}\ \mathrm{P(T)}\ \phi(\varepsilon,T)$$

$$\Phi(\varepsilon)=\frac{2\sigma(\varepsilon)}{T_{\max}^2}\int_0^{T_{\max}}\mathrm{dT}\ \mathrm{k(T)}\ \mathrm{T}\exp(-\varepsilon/\mathrm{T})$$

By considering the two complementary FF, we get:

$$\Phi(\varepsilon)=\frac{1}{2}\left[\Phi\left(\varepsilon,\sigma_C^L\right)+\Phi\left(\varepsilon,\sigma_C^H\right)\right]$$

$$\text{with } \Phi\left(\varepsilon,\sigma_C^L\right)=\int_O^{T_{\max}}\phi\left(\varepsilon,\sigma_C^L\right)P(T)dT$$

The neutron energy spectrum $N(E,E_f)$ in the laboratory system for a fission fragment moving with average kinetic energy per nucleon E_f is obtained by:

$$N(E)==\frac{1}{2}\left[N(E,E_f^L,\sigma_C^L)+N(E,E_f^H,\sigma_C^H)\right]$$

with:

$$N(E,E_f,\sigma_c) = \frac{1}{4\sqrt{E_f}}\int_{(\sqrt{E}-\sqrt{E_f})^2}^{(\sqrt{E}+\sqrt{E_f})^2}\left[\frac{\Phi(\epsilon,\sigma_c)}{\sqrt{\epsilon}}\right]d\epsilon = \frac{1}{2\sqrt{E_f}T_m^2}\int_{(\sqrt{E}-\sqrt{E_f})^2}^{(\sqrt{E}+\sqrt{E_f})^2}\sigma_c(\epsilon)\sqrt{\epsilon}\,d\epsilon\int_0^{T_m}c(T)\,T\exp(-\epsilon/T)\,dT$$

The average kinetic energy per nucleon of the average light fragment A_L and average heavy fragment A_H are obtained using momentum conservation :

$$E_f^{L,H}=(A_{H,L}/A_{L,H})(\langle E_f^{tot}\rangle/A)$$

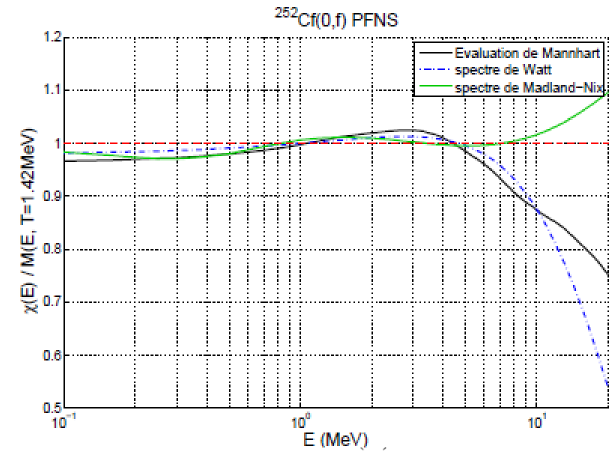
Prompt Fission Neutron Spectrum (PFNS)

❑ Deterministic models used to describe Prompt Fission Neutron Spectra: Los Alamos model (LAM)

The figure (top) shows PFNS ratio to a Maxwellian with T=1.42 (green curve), where the PFNS is calculated with the original LAM

Note: average energy of PFNS given by:

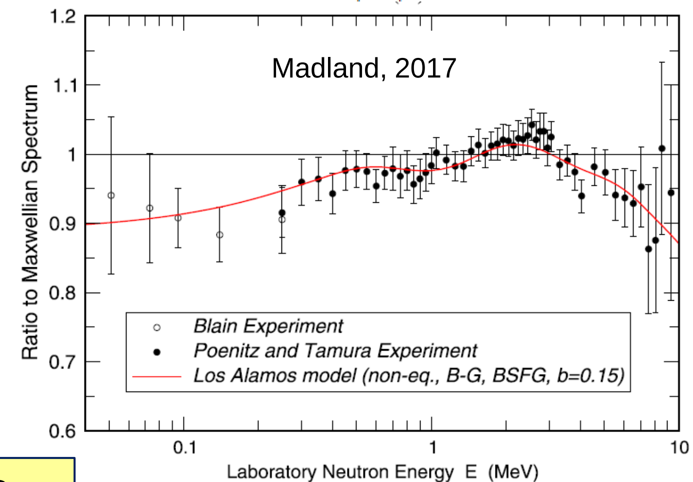
$$\langle E \rangle = \frac{1}{2}(E_f^L + E_f^H) + \frac{4}{3}T_m$$



Improvements of LAM recently proposed

(see Madland 2017, Hambsch 2005, Tudora 2009):

- ❑ Temperatures of the light and heavy fragment not equal
- ❑ Contributions of the light and heavy fragments to the total PFNF are weighted according to their multiplicity
- ❑ Triangular form of P(T): changed by a more realistic form
- ❑ Anisotropic emission in the center of mass introduced
- ❑ Specific level density parameters for the LF and the HF
- ❑ Fission modes incorporated (Brosas'model 1990)



All these modifications allow a much better description of PFNS

Prompt Fission Neutron Spectrum (PFNS)

❑ Stochastic approaches

Several Monte-Carlo codes have been developed recently aiming at: calculating fission observables (PFNS, PFGS, prompt neutron and gamma multiplicities….) and searching for correlations between these observables.

Simulation performed in two steps:

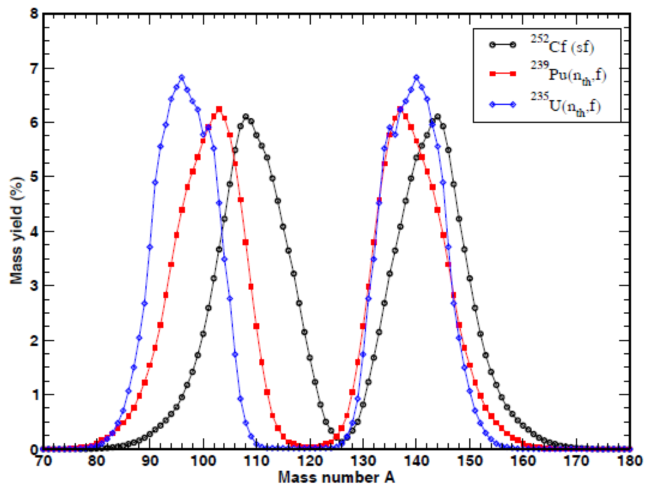
(i) sampling of FF characteristics (A, Z, KE, E*, J, π)
(ii) simulating the deexcitation of both fission fragments

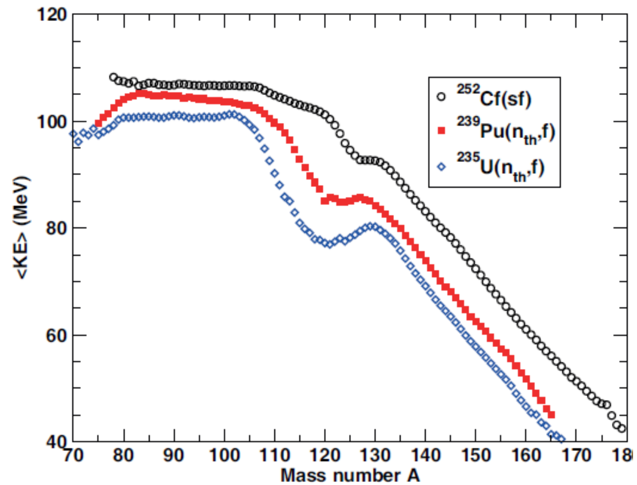
- Code **FREYA,** developed through a collaboration between LLNL and LBNL: Available for downloading
  (Vogt, 2009; Vogt, 2011; J. Randrup, 2009; Vogt, 2012, Verbeke, 2015; Vogt, 2014; Wang, 2016)
- Code **CGMF,** developed at LANL (USA)
  (Talou, 2011; Talou, 2013; Stetcu, 2014; Becker 2013; Lemaire, 2005; Lemaire, 2006)
- Code **FIFRELIN**, developed at CEA-Cadarache (France)
  (Litaize, 2010; Serot, 2014, Litaize, 2015; Regnier, 2016;)
- Code **GEF**, developed at CENBG (France): Available for downloading
  (Schmidt, 2010; Schmidt, 2011; Schmidt, 2016)

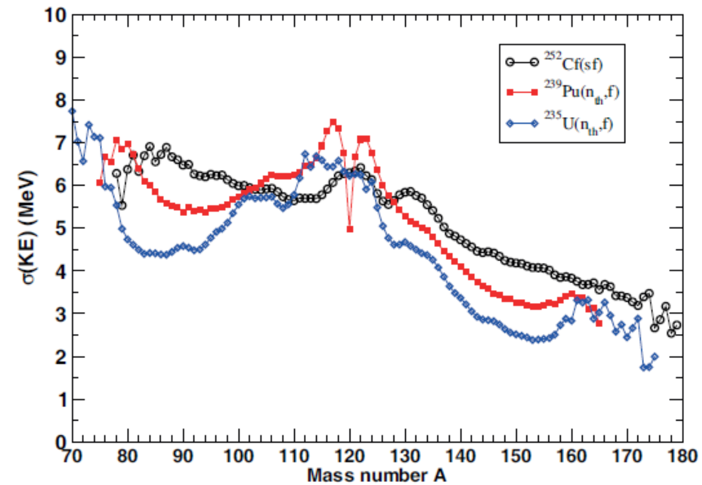
Prompt Fission Neutron Spectrum (PFNS)

❑ Stochastic approaches

O. Litaize, O. Serot, L. Berge, EPJA 51 (2015) 177







Sampling the mass: A
Sampling the nuclear charge: Z
(from UCD + polarisation charge)

Sampling the Kinetic Energy: KE

Sampling the spin: J

$$P(J) = \frac{2J+1}{2\sigma^2} \exp\left\{-\frac{(J+1/2)^2}{2\sigma^2}\right\}$$

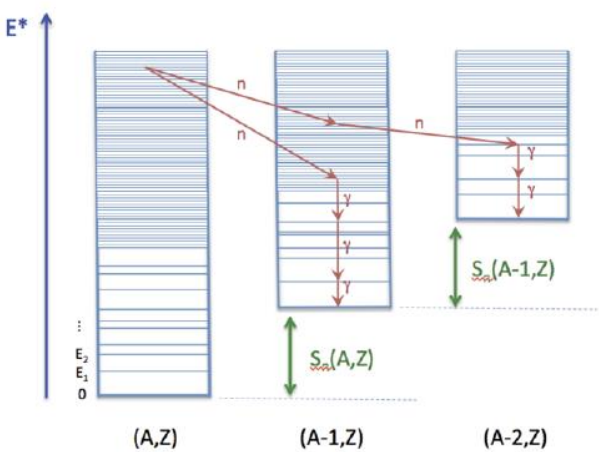
Sampling the parity: π

$$P(\pi=+) = P(\pi=-) = 1/2$$

Prompt Fission Neutron Spectrum (PFNS)

❑ Stochastic approaches

- FF deexcitation simulated from statistical Hauser-Feshbach model (CGMF and FIFRELIN codes): **accounts for the conservation of energy, spin and parity of the initial and final states.**



From R. Capote, 2016

Neutron width (for a given neutron orbital momentum l and total angular momentum j): determined from the neutron transmission coefficients ($T_{l,j}$)

$$\Gamma_n(\varepsilon_n, l, j) = \frac{T_{l,j}(\varepsilon_n)}{2\pi\,\rho(E_i, J_i, \pi_i)}$$

Gamma width (for a transition of type X = E,M and multipolarity L): computed via gamma strength function $f_{XL}(\epsilon_\gamma)$

$$\Gamma_\gamma(\varepsilon_\gamma, XL) = \frac{f_{XL}(\varepsilon_\gamma)\varepsilon_\gamma^{2L+1}}{\rho(E_i, J_i, \pi_i)}$$

Probability of a neutron emission Pn: Competition between neutron and γ accounted for

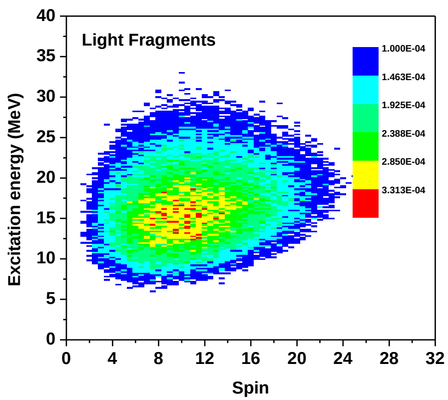
$$P_n = \frac{\Gamma_n}{\Gamma_n + \Gamma_\gamma}$$

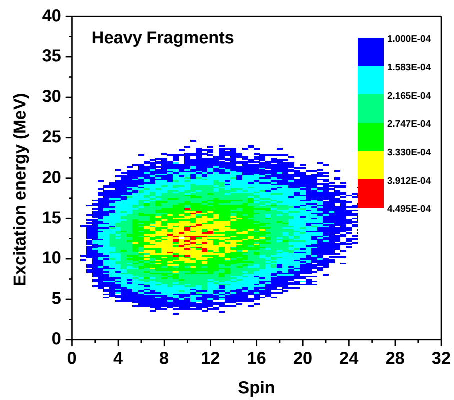
- In FREYA code: neutron emission simulation based on Weisskopf evaporation model.

Prompt Fission Neutron Spectrum (PFNS)

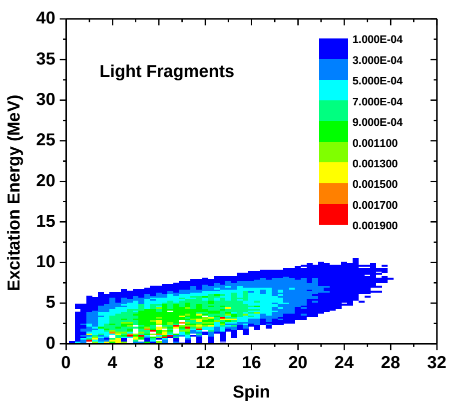
❑ Stochastic approaches

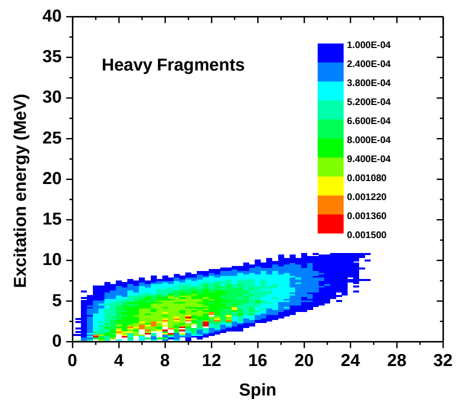
Initial (E*, J) distributions



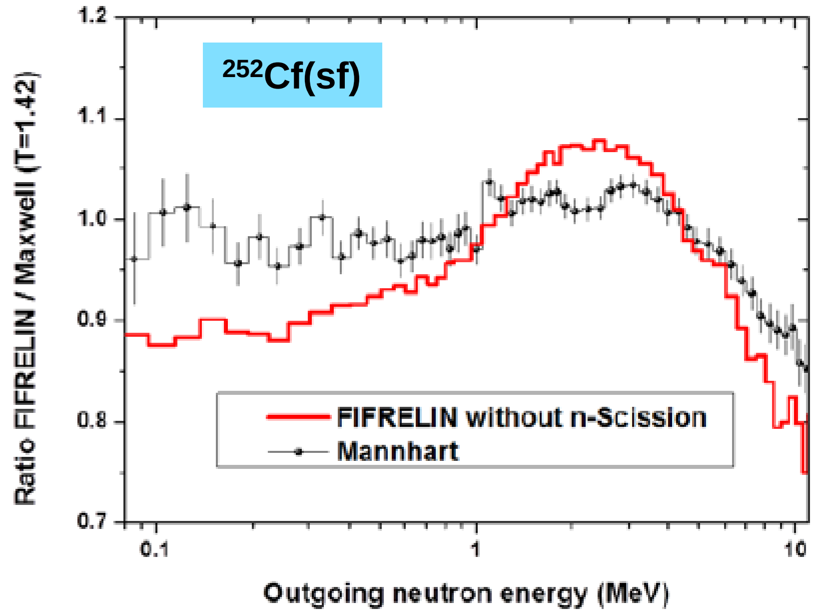


(E*, J) distributions after prompt neutron emission





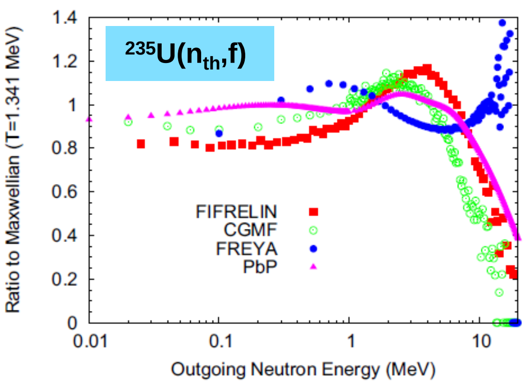
Calculated PFNS

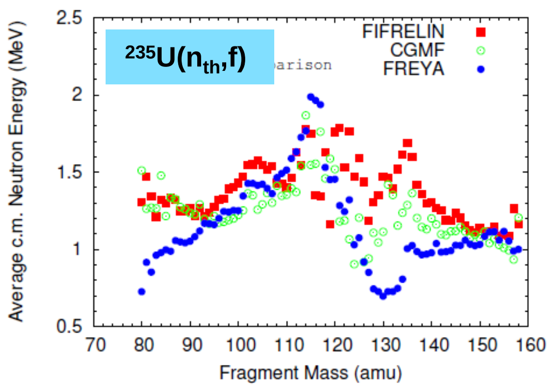


Many ingredients are involved:
- Pre neutron data
- Fission models (sharing the excitation energy between both FF, Initial spin distributions,…)
- Nuclear structure models of the FF (level schemes, strength functions,…)

Prompt Fission Neutron Spectrum (PFNS)

❑ Stochastic approaches





From R. Capote, 2016

- Comparison between three Monte Carlo codes (FIFRELIN, CGMF, FREYA) and the Point-by-Point model (extension of the Los Alamos Model)

A common set of fission fragment yield as a function of mass, charge, and kinetic energy was used for these calculations

- Results on PFNS ratio to a Maxwellian (with T=1.341MeV) (top): **significant differences between the codes.**

- Results on Mass-dependent neutron kinetic energy in the center of mass system, $<\varepsilon>(A)$ (bottom): **Large discrepancies also observed**, probably due to the level density prescriptions used in the calculations

Differences observed between the codes: mainly due to the deexcitation procedure used, but also to the way of sharing the available excitation energy between the two FF

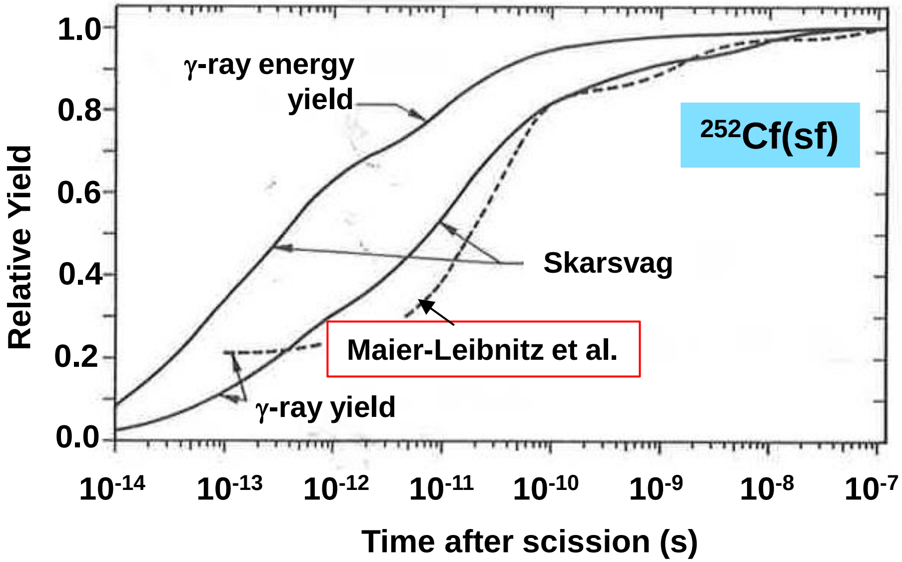
Part II
Prompt gamma Emission

- *Time scale for prompt and 'late' gamma emission*
- *Available Energy for Prompt gamma Emission*
- *Prompt Fission Gamma spectrum (PFGS)*
- *Prompt Fission Gamma-ray Multiplicity*

⇒ Prompt gammas contribute to the heating of reactor cores: precise knowledge of the energy release by gamma emission required for reactor applications

⇒ Strong experimental efforts done during last 10 years

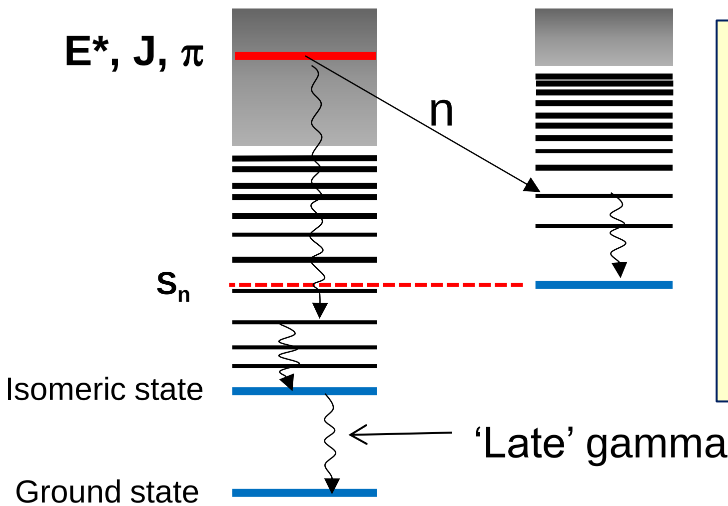
Time scale for prompt and 'late' gamma emission



Relative yields of γ-rays and γ-ray energy as a function of time after scission plotted: All curves are normalized at time of 120 ns after scission

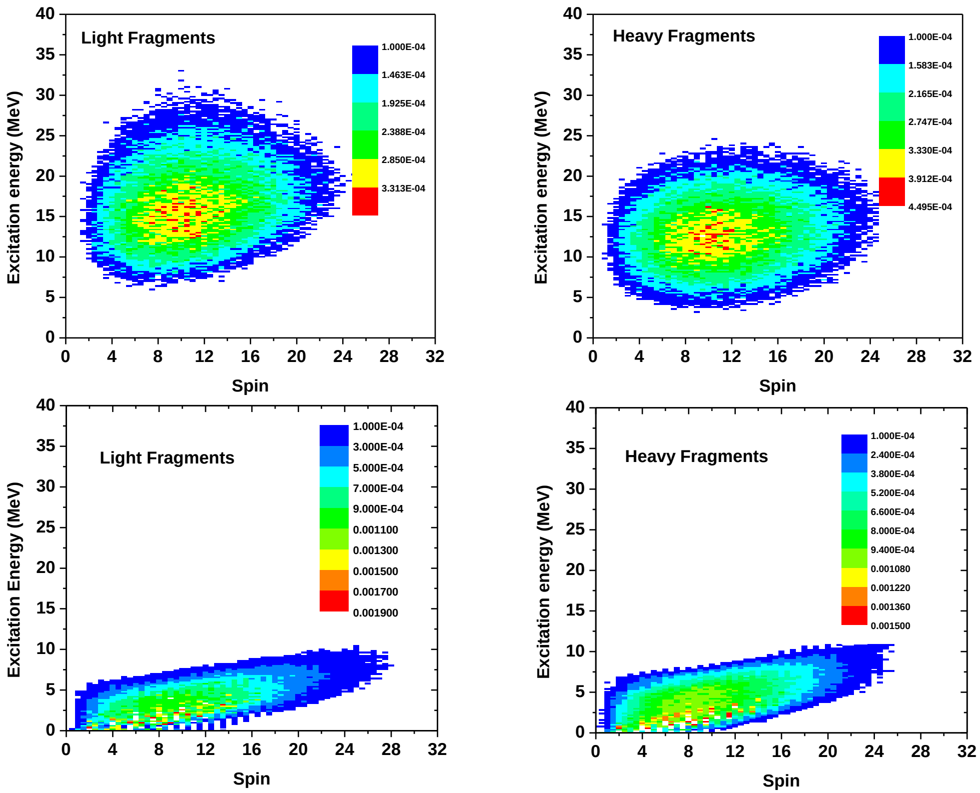
Straight lines: measurements performed by Skarsvag Dashed line: evaluation made by Maier-Leibnitz

Note. The total photon energy increases faster with time than the total number of photons: reflects the fact that early gammas have higher energies.



- **According to Skarsvag: more than 90% of the γ-rays are emitted prior to 1ns.**
- The earliest gammas appear at about 10^{-14} s after scission
- The bulk of prompt gammas is emitted within 100 ns
- 'Late' gammas can be emitted by fragments up to about 1 ms: from **isomeric states** which can be populated during the deexcitation of the fission fragments

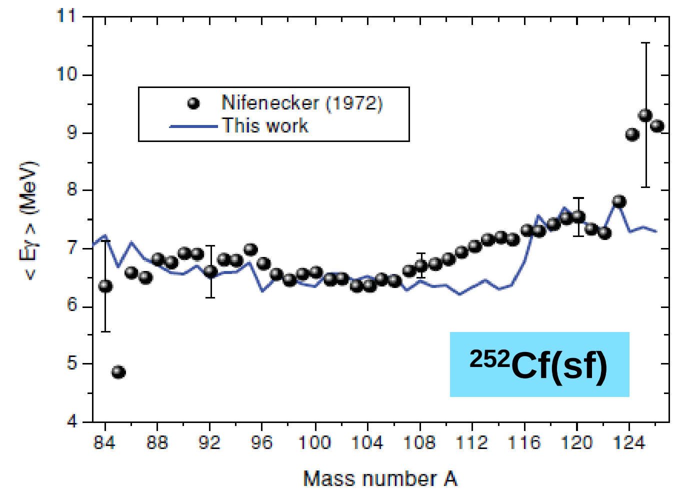
Available Energy for Prompt gamma Emission



- Example of Monte Carlo calculation showing the (E*,J) distributions for the LF (left) and the HF (right), before prompt neutron emission (top) and after prompt neutron emission (bottom).

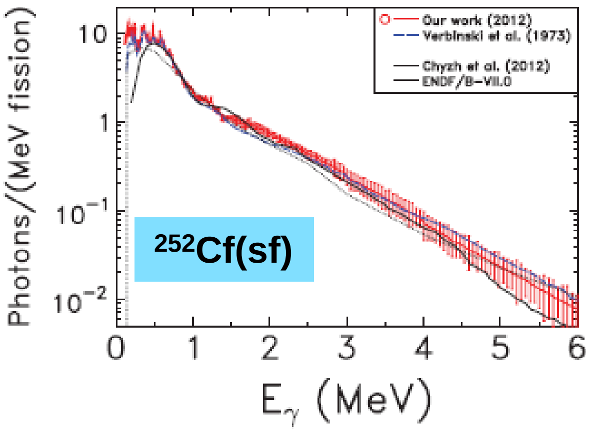
- Gives an idea of the average remaining energy available to emit prompt γ-rays.

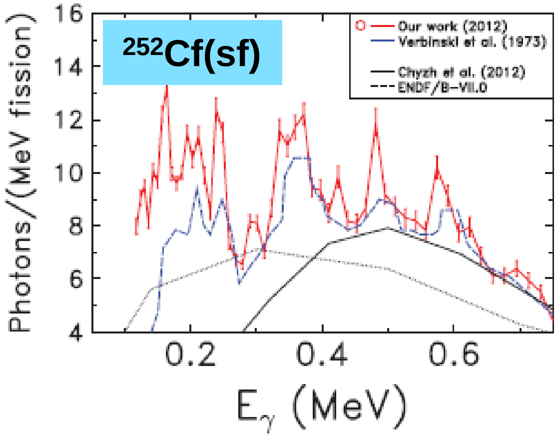
- Average excitation energy <Eγ>(A) available for the two complementary FF to emit prompt γ-rays: <Eγ>(A) plotted as a function of the light fragment mass shows a rather flat behavior (right figure).



Litaize and Serot, 2010

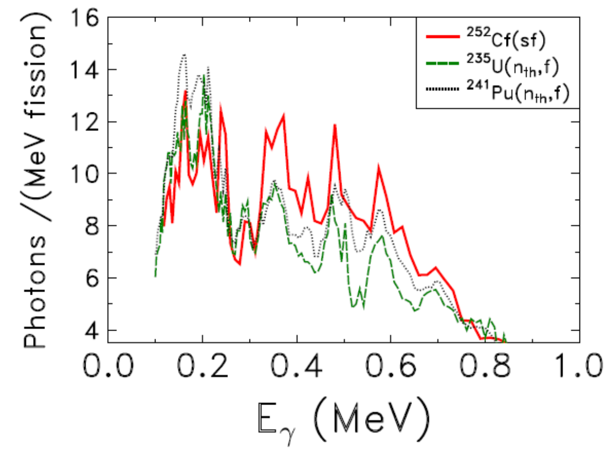
Prompt Fission Gamma Spectrum (PFGS)





From Bilnert, 2013

- The prompt fission gamma spectrum measured by Bilnert (2013), is shown: from 0 to 6 MeV (top) and between 0 and 0.75 MeV (bottom).
- At low energy (below typically 1 MeV), some structures are clearly visible (except in case of poor experimental energy resolution).
- Similar structures appear for other fissioning nuclei: mainly attributed to collective rotational levels of even-even fission fragments



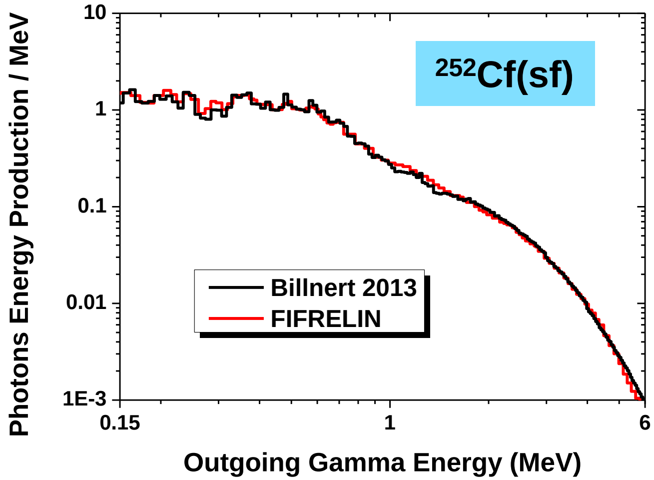
From S. Oberstedt, 2015

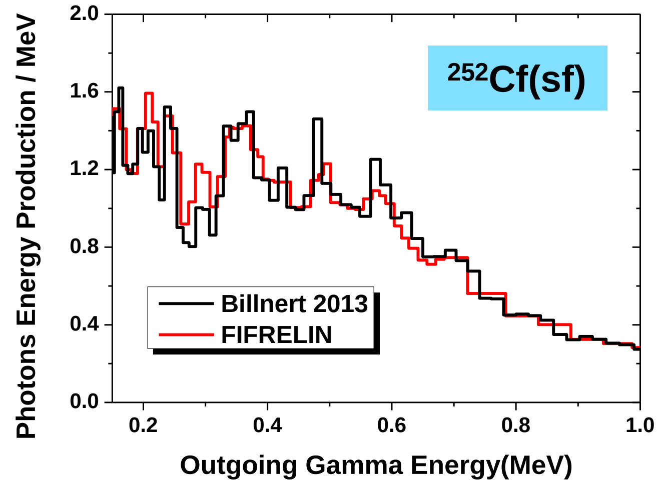
Most of the data are obtained under two experimental constrains:

- ❑ Detection threshold (typically 100keV)
- ❑ Time window: coincidence time used for the detection of the FF and the γ-rays (several ns, typically).

Prompt Fission Gamma Spectrum (PFGS)

- As shown on the figure: Monte Carlo calculation can reproduce reasonably well the shape of the experimental PFGS as well as the structures at low energy.

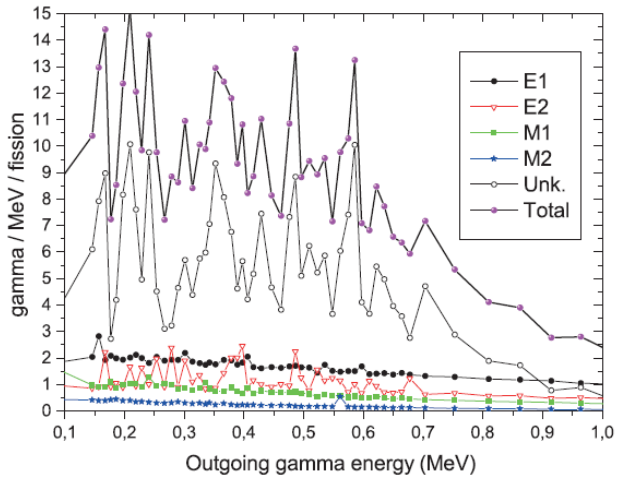




From Serot, 2017

- Advantage of a Monte Carlo simulation: possibility to characterize each gamma transitions (energy, type (electric: E1, E2 or magnetic: M1, M2))

- Contributions of each transitions can be calculated and the angular distribution (γ, FF) deduced (A. Oberstedt, in EPJ web of Conference, (2017), to be published)



From Litaize, 2015

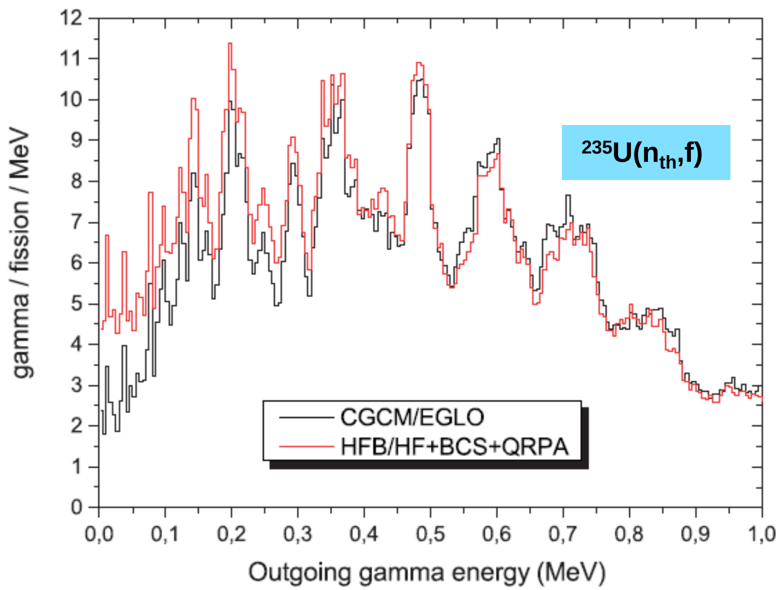
Prompt Fission Gamma Spectrum (PFGS)

In the case where Monte Carlo codes describes the deexcitation of the FF from Hauser-Feshbach theory: level density and the strength function models have an impact on the calculated PFGS. Good experimental data can be therefore used to test the models.

Example:

Calculation 1 (black curve): Composite Gilbert Cameron (CGCM) model for the level density, and Enhanced Generalized LOrentzian model (EGLO) for the photon strength function

Calculation 2 (red curve): tabulated values from HFB calculations for the level density, and tabulated values from microscopic calculations (noted HF+BCS+QRPA) for the photon strength function



From O. Litaize, private communication

➡ Below around 200 keV, calculation 1 predicts a lower gamma multiplicity.

Accurate measurement of PFGS can be therefore a good test of the level density and strength function models

Prompt Fission Gamma-ray Multiplicity

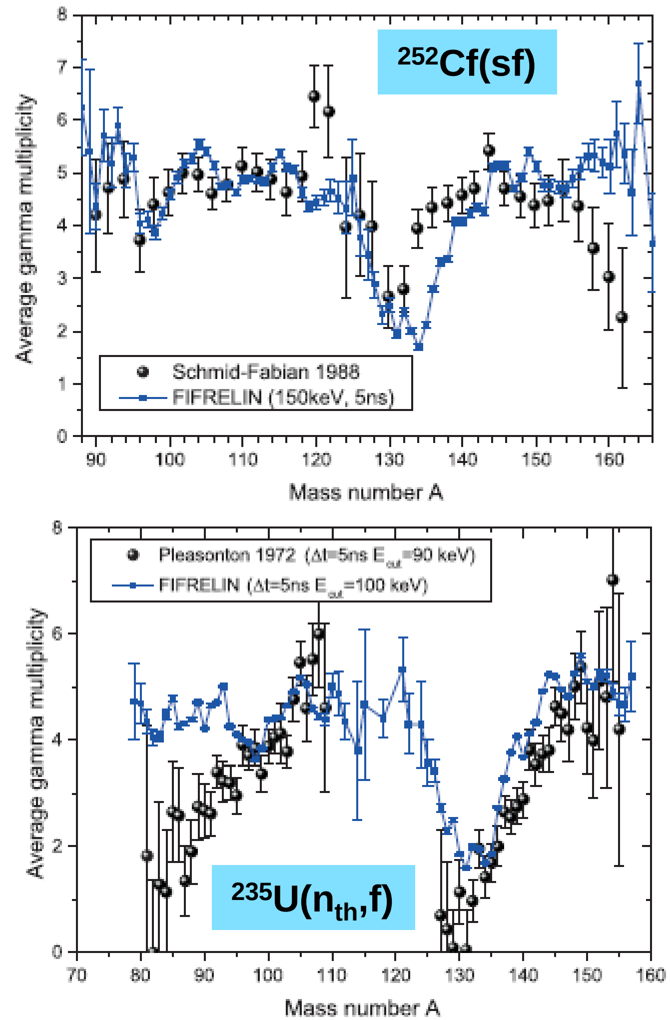
- Mass-dependent average prompt gamma multiplicity: $\langle M\gamma \rangle(A)$

Measured for ^{252}Cf(sf) (top) and for ^{235}U(n_{th},f) (bottom)

- Note: for ^{252}Cf(sf), except in the mass region around 132, a rather flat behavior is observed. It is not the case for ^{235}U(n_{th},f) reaction, where a saw-tooth shape appears (similar as for prompt neutron multiplicity)

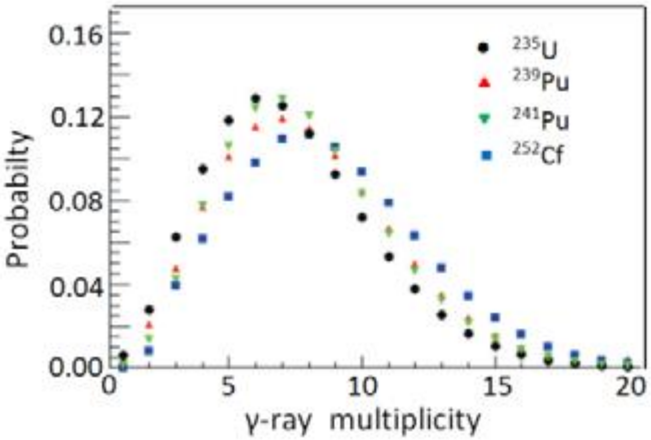
- Monte Carlo simulations (blue curves): exhibit a rather flat behavior, except in the [125–135] mass region (lower gamma multiplicity related to near spherical nuclei)

Simulations impacted by the spin distribution of the FF after prompt neutron emission, which are unfortunately poorly known (big experimental challenges)

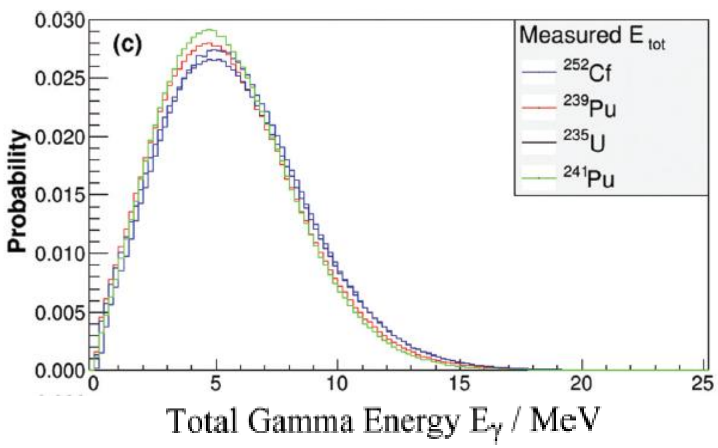


From O. Litaize, 2015

Prompt Fission Gamma-ray Multiplicity



Fom Gonnenwein, lecture given at FIESTA 2014



From Chyzh, 2014.
The γ-ray energy was measured with the spectrometer DANCE from LANSCE in a time window of 40 ns after fission.

- Prompt γ-ray multiplicity distribution (normalized to one): Similar distributions for various fissioning systems (top)
  Up to 20 γ-quanta per fission can be detected !
- γ-ray energy distributions (bottom): also very similar behavior for various fissioning nuclei

$^{235}U(n_{th},f)$	ΔE	Δt	$<M_\gamma>$	$<\varepsilon_\gamma>$	$<E_\gamma>$
	MeV	ns		MeV	MeV
Verbinski 1973:	0.14-10.0	10	6.7(3)	0.97(5)	6.5(3)
Chyzh 2013:	0.15-9.5	100	6.95(30)	1.09	7.57
Oberstedt 2013:	0.1-6.0	~ 10	8.19(11)	0.85(2)	6.92(9)
$^{252}Cf(sf)$	ΔE	Δt	$<M_\gamma>$	$<\varepsilon_\gamma>$	$<E_\gamma>$
Verbinski 1973:	0.14-10.0	10	7.8(3)	0.88(4)	6.84(30)
Skarsvag 1980:	> 0.114	12	9.7(4)	0.72	7.0(3)
Chyzh 2012:	0,15-9.5	10	8.15	0.96	7.8
Billnert 2013:	0.1–6.0	<1.5	8.3(1)	0.80(1)	6.64(8)

Examples of average quantities: <Mγ>, <Eγ> and $<\varepsilon_\gamma>$ (table), including experimental detection parameters

Fom Gonnenwein, lecture given at FIESTA 2014

Part III
Delayed neutron and Gamma Emission

- *Origin of the delayed neutron and gamma emission*
- *Main precursors*
- *Examples of delayed neutron and gamma spectra*
- *Influence of incident neutron energy on DN multiplicity*

Origin of the delayed neutron and gamma emission

Delayed neutrons emitted by the fission products several seconds or even minutes after the fission are of crucial importance for the **control and the safety of nuclear reactors**. Accurate knowledge data on delayed neutron characteristics are therefore requested by nuclear industry.

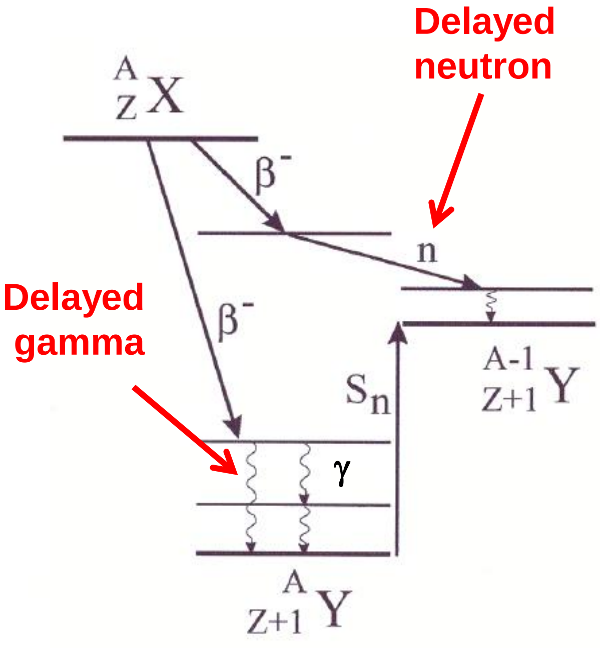
- **Delayed neutron precursors:** Fission products that emit delayed neutrons

- Almost all FPs are neutron-rich β^- emitters. This β^- emission can leave the daughter nucleus into an excited state, with sufficient energy available to emit a neutron: (β^-, n) disintegration

- These neutrons are called **delayed neutrons**. Their 'delay' is linked to the lifetime of the β- decay: typically: from milliseconds to several hundred seconds

- Probability to emit a neutron after a β- decay: Pn; Corresponds to the branching ratio: Pn = (β^-,n) / β^-

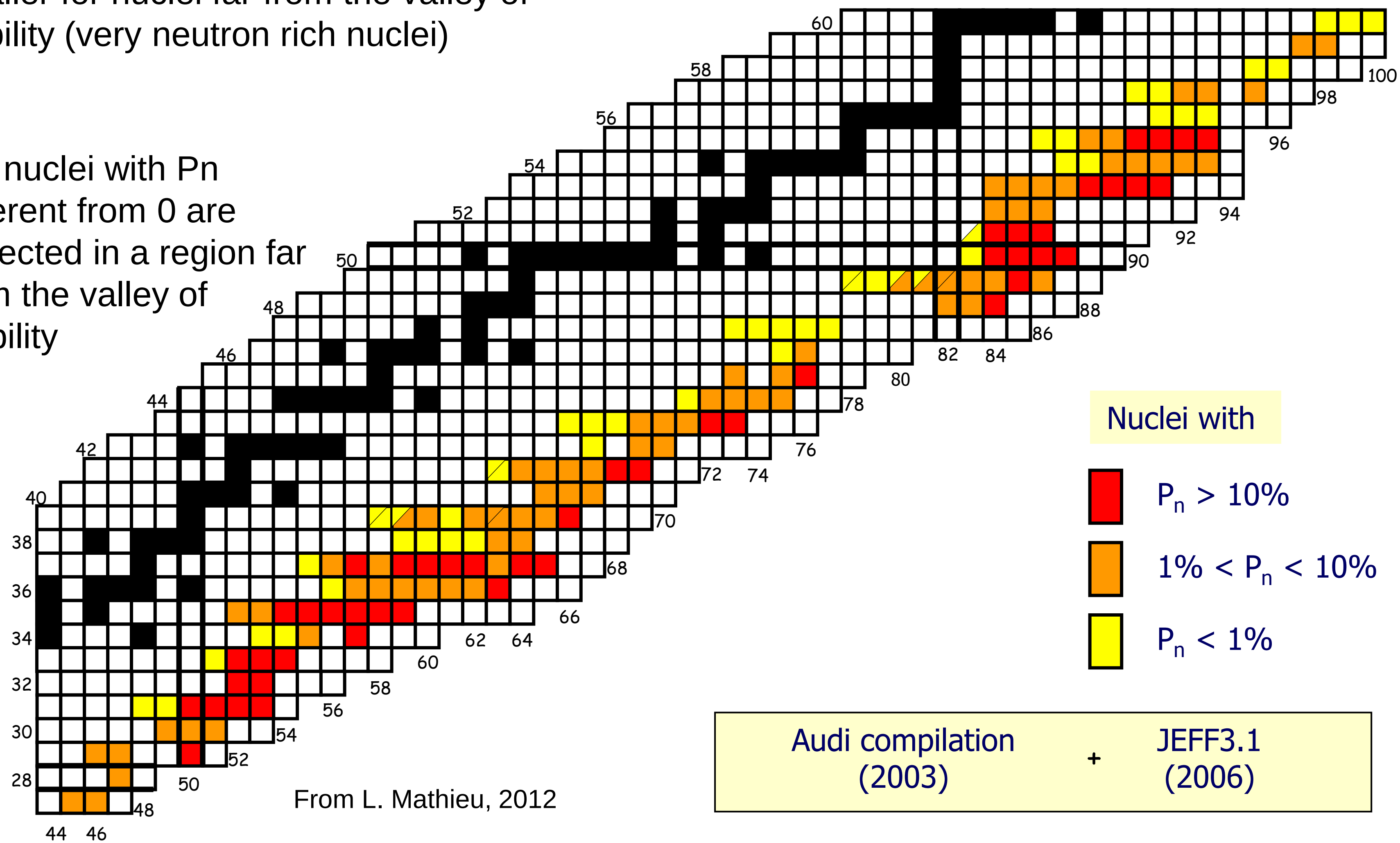
- After a β- decay or a (β-,n) decay: the daughter nucleus can reach its ground state by γ-ray emission ⇨ **'delayed' gamma**



Main precursors

Usually: neutron separation energy is smaller for nuclei far from the valley of stability (very neutron rich nuclei)

So: nuclei with Pn different from 0 are expected in a region far from the valley of stability



From L. Mathieu, 2012

Main precursors

- Delayed neutron multiplicity generally given in pcm (for one hundred thousand)
- Examples of average multiplicity $<\nu_{del}>$ for various fissioning nuclei (Table 1)
- Example of contribution of the main precursors to the total delayed neutron multiplicity (Table 2, $^{235}U(n_{th},f)$ reaction)

Table 1 (from JEFF Report 20, NEA OECD, 2009)

Reaction	$< \nu_{del} >$ (pcm)
n+^{235}U (En=thermal)	1654 ± 2.5 %
n+^{238}U (En=400 keV)	4511 ± 1.3 %
n+^{239}Pu (En=thermal)	624 ± 3.8 %
n+^{240}Pu (En=400 keV)	960 ± 11.4 %
n+^{241}Pu (En=thermal)	1560± 10.2 %
n+^{242}Pu (En=400 keV)	2280 ± 11.0 %

Table 2

Precursor	Contribution (%)
^{137}I	14.6
^{89}Br	11.7
^{94}Rb	9.3
^{90}Br	7.9
^{88}Br	7
^{85}As	5.6
^{138}I	4.8
^{98}mY	4.6
^{95}Rb	3.7
^{139}I	3.7

Main precursors

- For nuclear energy applications: delayed neutrons usually described by using 8 universal groups
- Each group characterized by an average half lives (Table 3)
- For a given fission reaction: abundance of each group is needed to calculate the time-dependent delayed neutron multiplicity (figure below)

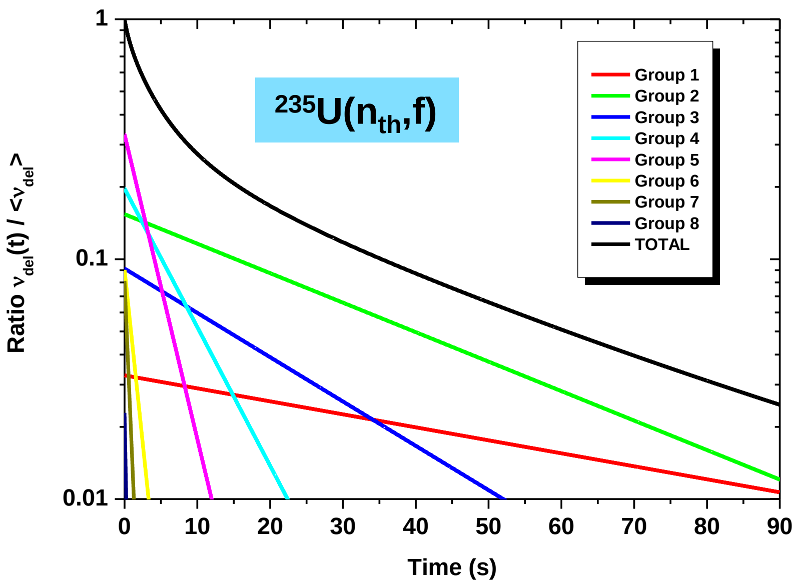
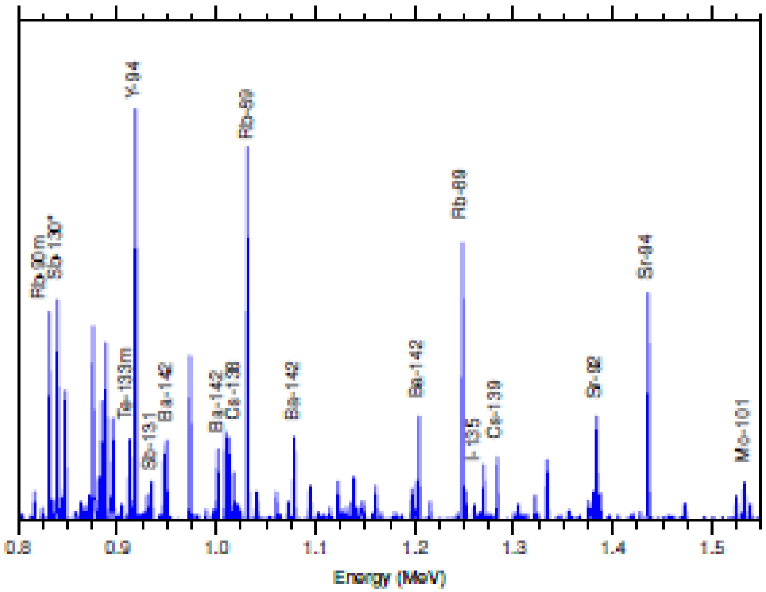


Table 3, $^{235}U(n_{th},f)$, NEA-WPEC6, 2002

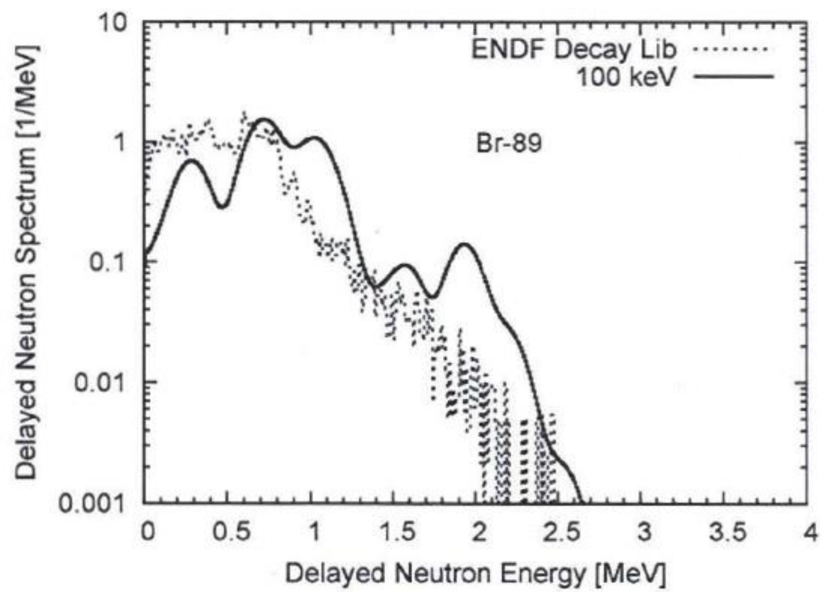
Group Number	Main Precursors	Half-life (s)	Group Average Half-lives (s)	Abondance
1	Br-87	55.6	55.6	(3.28 ± 0.42) %
2	I-137	24.5	24.5	(15.40 ± 0.68) %
3	Br-88	16.3	16.3	(9.14 ± 0.90) %
4	I-138 Rb-93 Br-89	6.46 5.93 4.38	5.21	(19.7 ± 2.3) %
5	Rb-94 I-139 As-85 Y-98	2.76 2.30 2.08 2.00	2.37	(33.1 ± 0.66) %
6	Kr-93 Cs-144 I-140	1.29 1.00 0.86	1.04	(9.03 ± 0.45) %
7	Br-91 Rb-95	0.542 0.384	0.424	(8.12 ± 0.16) %
8	Rb-96 Rb-97	0.203 0.170	0.195	(2.29 ± 0.95) %

Examples of delayed neutron and gamma spectra

The figures below represent: a delayed gamma spectrum measured at 1000 s after fission (left) and a delayed neutron spectrum of the ^{89}Br (one of the main precursor)

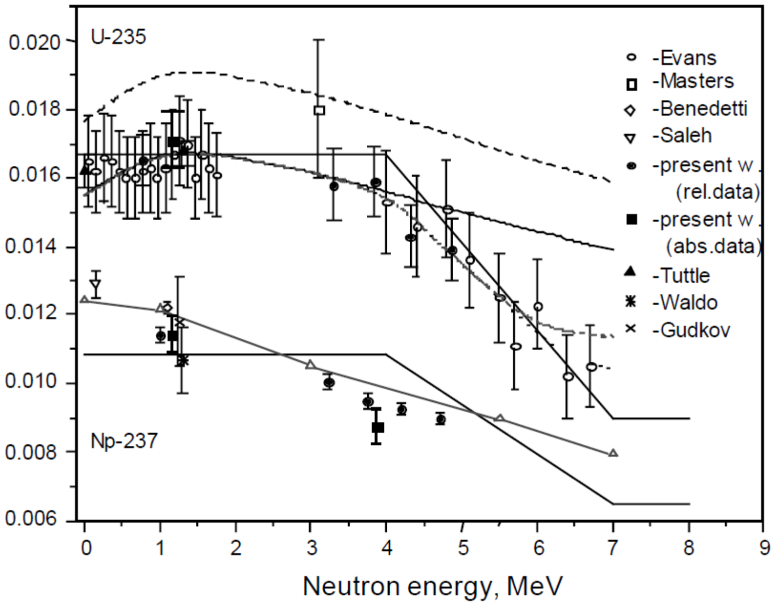


Delayed γ-ray spectrum for ^{235}U at 1000 seconds. Some precursors can be clearly identified (From T.K. Lane, 2015)



Delayed neutron energy spectrum of the ^{89}Br Given in the ENDF/decay data library and calculated within QRPA-Hauser-Feshbach model (From T. Kawano, 2008)

Influence of incident neutron energy on DN multiplicity



From NEA/WPEC-6 Report (2002)

- We know that by increasing the energy of the incident neutron, fission product yields become higher in the symmetric mass region.
- Yet, in this symmetric mass region, neutron precursors are fewer.
- Therefore, the total average delayed neutron multiplicity is expected to decrease when incident neutron energy grows. This is illustrated on the figure, where the total delayed neutrons yields for neutron-induced fission of ^{235}U and ^{237}Np are plotted.

Conclusion

- Very early after the discovery of nuclear fission, a report on the observation of fission neutrons has been published (H. von Halban et al., Nature 143, 470 (1939); O. Hahn and F. Strassmann: Naturwiss. 27, 89 (1939))

- Due to their importance for nuclear applications, the main characteristics of the prompt neutron and prompt gamma were investigated by the experimentalists and the theoreticians.

- It is generally accepted that the main contribution of the prompt neutron emission is coming from the evaporation of the fully accelerated fission fragments. Nevertheless, it seems that an additional neutron source, which could be the scission neutrons, is needed to describe the main prompt neutron properties.

- After prompt neutron emission, the FF released the remaining excitation energy by gamma emission (neglecting the n/γ competition). Due to their importance for reactor applications, strong experimental efforts have been made in the last years, to improve our knowledge of the prompt gamma properties (multiplicity, spectra).

- Monte Carlo codes have been recently developed aiming at calculating fission observables (PFNS, PFGS, prompt n and g multiplicities….) and searching for correlations between these observables.

Conclusion

- Still some open questions and some nuclear data are still highly requested

  - Knowledge of the spin distributions acquired by the FF, which are highly desired to simulate in particular the prompt fission gamma properties:
    - Mechanism used during the fission process to generate the FF spins: still not clear
    - Experimental spin distributions are needed

  - How the available excitation energy at scission is shared between the two fragments ?
    Experimental correlations between fission observables are strongly requested for answering this question: it gives constraints to the models…

  - Existence of scission neutrons: still an open question. Measure in triple coincidences (n, n, FF) may be a nice way to answer

  - Pre-neutron mass and charge yields and pre-neutron kinetic energy are needed for additional fissioning nuclei and for higher incident neutron energies: very important for Monte Carlo calculations

  - Prompt n and γ experimental data: still scarce at high incident neutron energy. Needed for testing the models and for nuclear energy applications

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