DE LA RECHERCHE À L'INDUSTRIE

# INFLUENCE OF SCISSION NEUTRONS ON PROMPT FISSION NEUTRON SPECTRUM CALCULATIONS

***Olivier SEROT, Olivier LITAIZE, Abdelaziz CHEBBOUBI***

*CEA-Cadarache*

*Bat. 230, F-13108 Saint Paul lez Durance*

*France*


www.cea.fr


1 **Context**

2 **'Reference Calculation': PFNS calculated without scission neutron**

3 **The three source model revisited: PFNS calculated including scission neutrons**

- Presentation of the model
- Calculation procedure
- Results

4 **Conclusion**

**PFNS=**
**Prompt Fission Neutron Spectrum**

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# Context

**Our aim:** Try to reproduce PFNS by using the Monte Carlo code FIFRELIN (developed at CEA-Cadarache) by by including a scission neutron component (neutrons emitted at the scission point)

## Why scission neutrons ?

- The hypothesis that all prompt neutrons are emitted from the evaporation of the fully accelerated fission fragments does not reproduce PFNS with enough accuracy
- Another source of neutrons is needed: could be the scission neutrons (see Kornilov Ref)
- There exist many ternary light charged particles (emitted at scission): p, t, $^{4}He$,… 'Ternary neutrons' (scission neutrons) should exist and could be the most produced ternary particle: no Coulomb barrier has to be overcome for their emission

**Study of $^{252}Cf(sf)$ PFNS where the Mannhart evaluation is a standard**

# Context / Experimental data

1 **Poor experimental knowledge** regarding scission neutron due to the difficulty to distinguish evaporated neutrons and scission neutrons

→ The existing results on scission neutrons are very contradictory

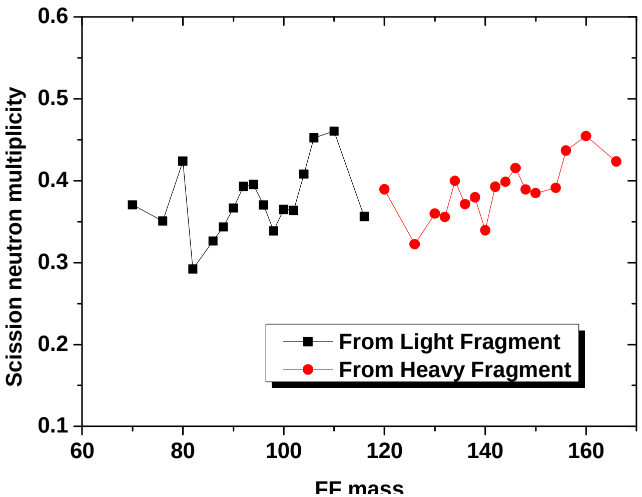
Some examples found in the literature:

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

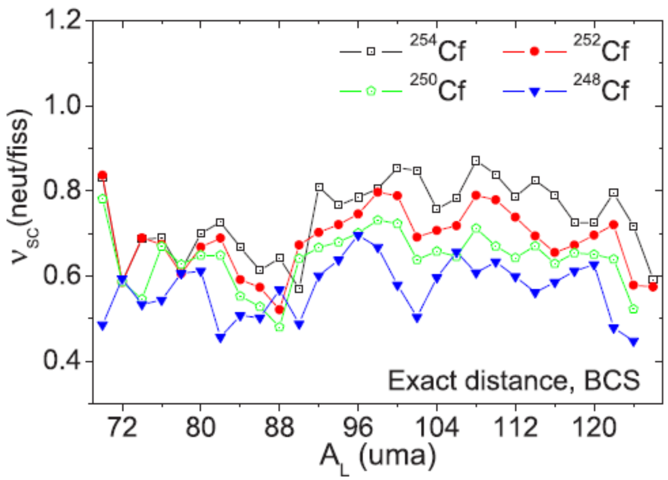
2 Many attempts have been already done to incorporate scission neutrons, within the deterministic models (Madland-Nix or Watt or Maxwell). See for example:

- ***O. Iwamoto, Journal of Nucl. Science and Technology, vol.45, 910 (2008)***
  Contribution of scission neutrons: between 10 and 15% for $^{252}$Cf(sf)
- ***N. Kornilov, Fission Neutrons (Springer International, Switzerland, 2015)***
  Contribution of scission neutrons: 10% for $^{252}$Cf(sf)

3 **Theoretical work**: characteristics of the scission neutrons calculated from the so-called 'sudden approximation' model




N. Carjan, et al., PRC85, 044601 (2012)
Calculation for $^{235}$U($n_{th}$,f): **~ 33%**




R. Capote, et al., PRC93, 024609 (2016)
For $^{252}$Cf(sf): **~ 19%**

These results represent an **upper limit** (reabsorption of unbound neutrons not taken into account)

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# ‘Reference Calculation’ (without scission neutron)

**“Reference calculation”** performed with the **Monte-Carlo code ‘FIFRELIN’**

- Calculate post-fission observables (spectra and multiplicities of the prompt neutron and gamma particles; energies released):
**useful tool for nuclear reactor applications**

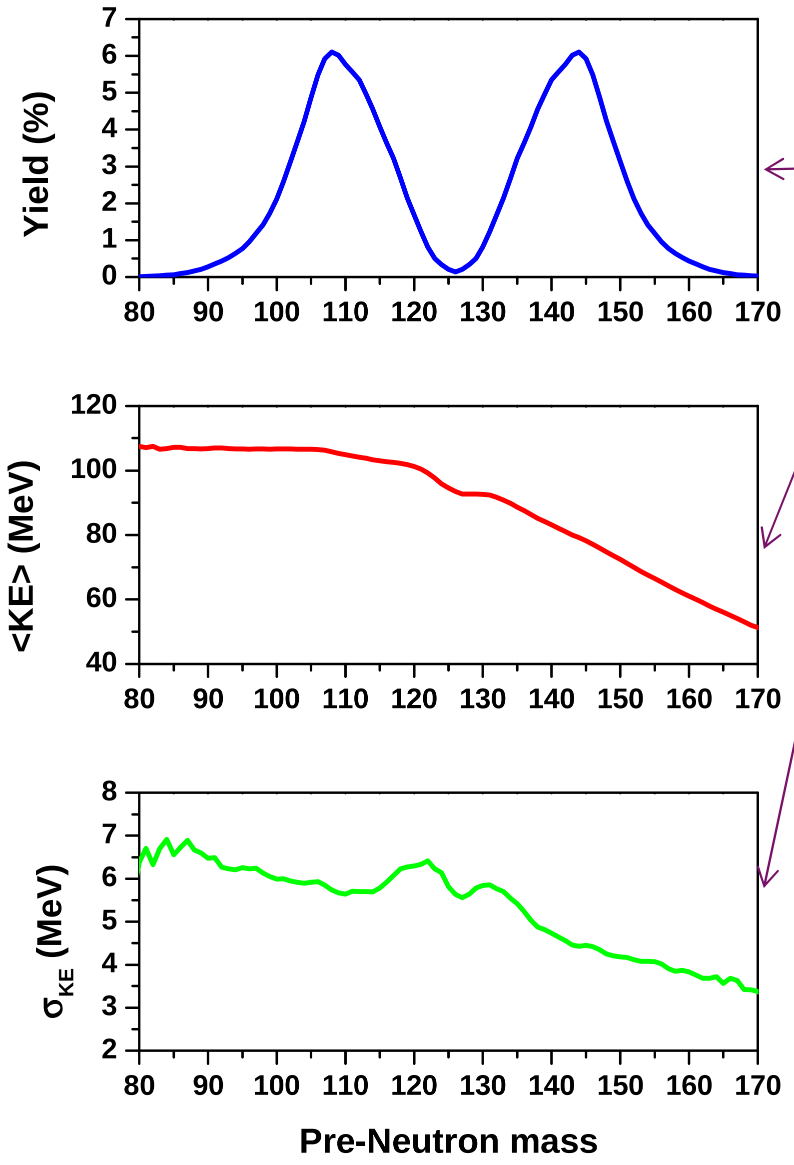
- Investigate correlations between fission observables:
**useful for our understanding of the fission process**


O. Litaize, O. Serot
Phys. Rev. C 82, 054616 (2010)

O. Litaize, O. Serot, L. Berge
Eur. Phys. J. A. 51, 177 (2015)

D. Regnier, O. Litaize, O. Serot
Comp. Phys. Commun. 201, 19 (2016)

# 'Reference Calculation' (without scission neutron)




N. Varapai, et al., *Proc. of the Int. Workshop on Nuclear Fission and Fission Product Spectroscopy, 2005*,

**Initial data used (input data)**

- **Mass A, Kinetic energy:** From experiment
- **Nuclear Charge: Z** based on Walh model
- **Spin J, parity: π**

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

- **Excitation energies: E***

from a mass dependent temperature ratio law $R_T(A)$

**$A_L$, $Z_L$, $KE_L$, $E^*_L$, $J_L$, $\pi_L$**

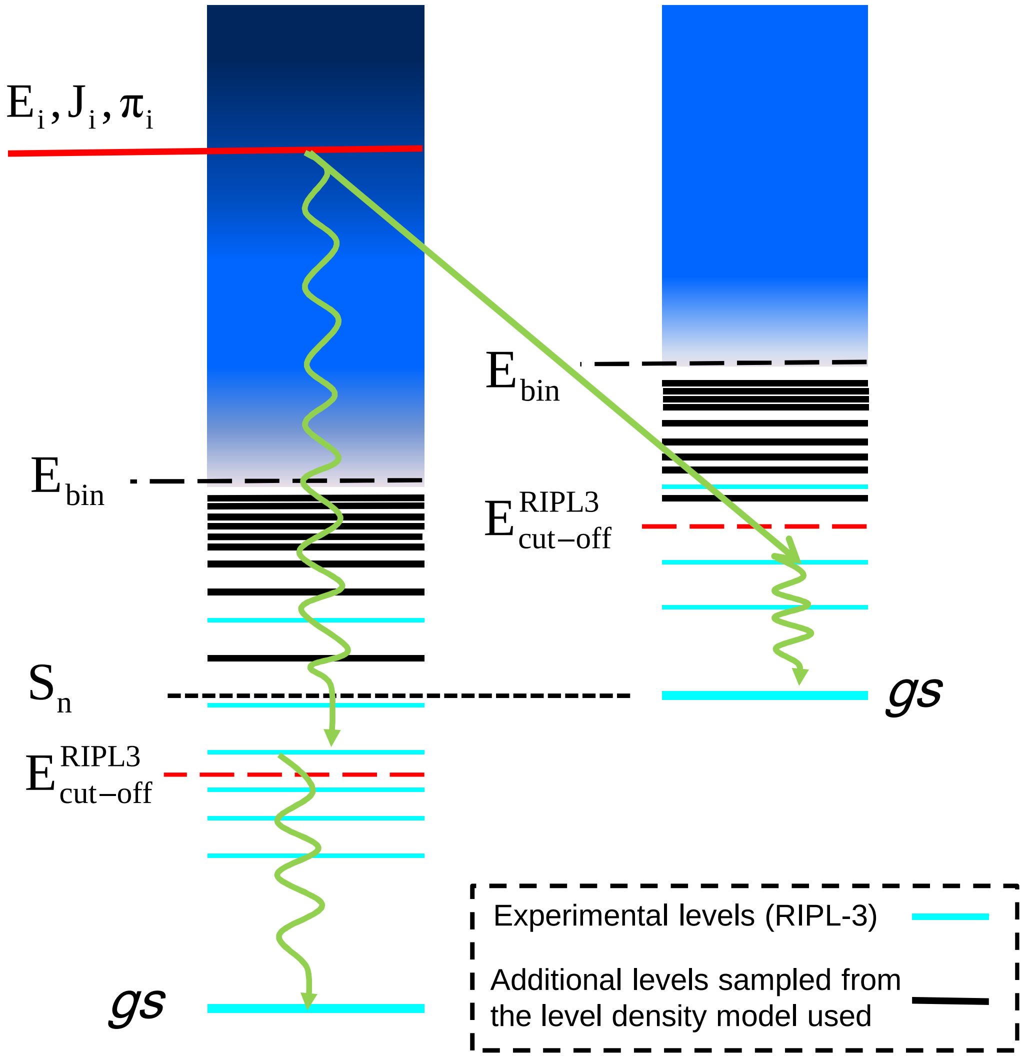
**$A_H$, $Z_H$, $KE_H$, $E^*_H$, $J_H$, $\pi_H$**

Known for both FF

# 'Reference Calculation' (without scission neutron)

**De-excitation of the FF: A, Z, E*, J, π (Hauser-Feshbach formalism and following the Becvar's procedure)**

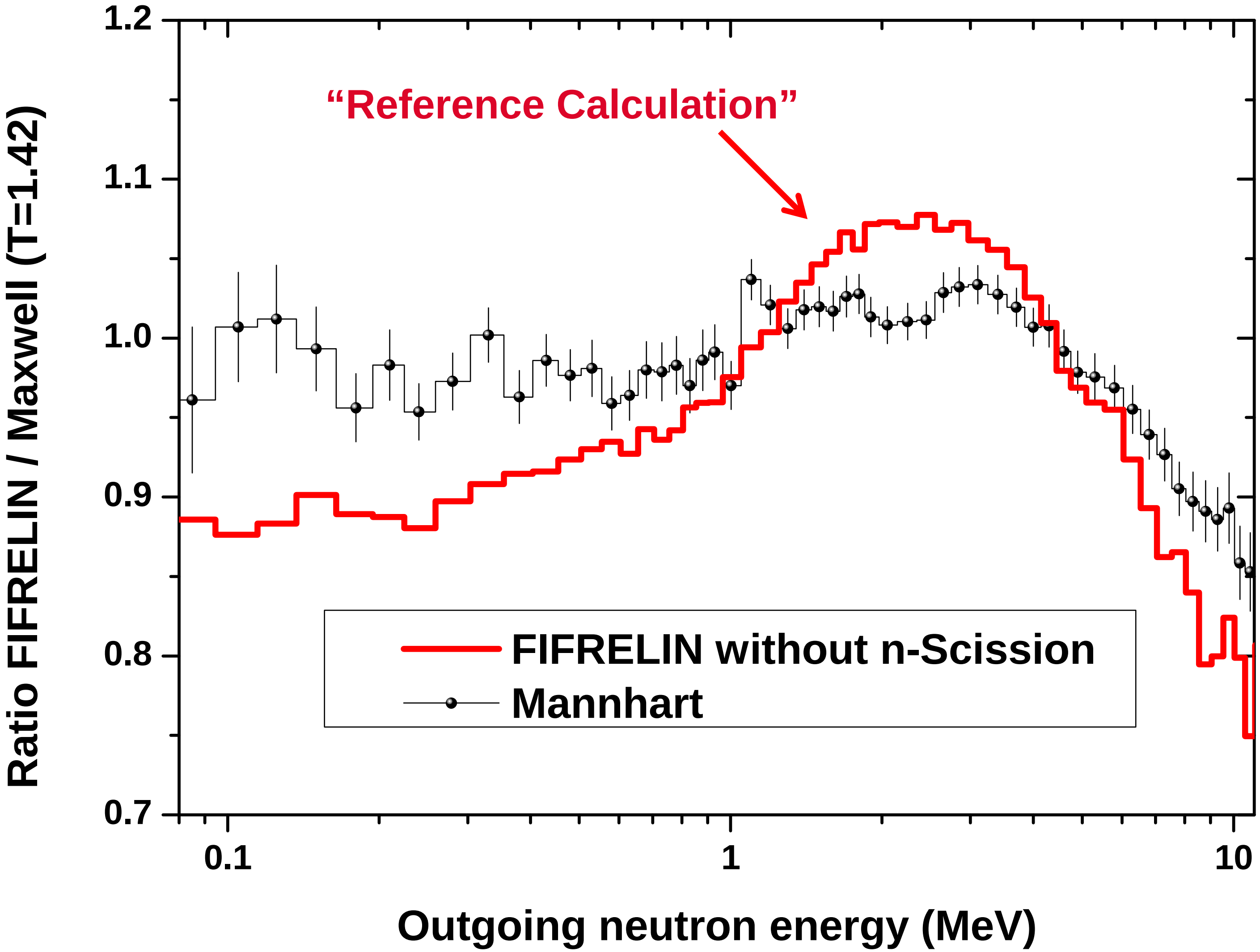
- competition n and γ
- conservation laws: energy, spin and parity of the initial and final states




- γ–strength function: EGLO
- Neutron transmission coefficients: TALYS with KD optical model
- Level density model: CGCM
- Level density parameter: Ignatyuk with shell corrections from Mengoni-Nakajima

# 'Reference Calculation' (without scission neutron)

**Prompt Fission Neutron Spectrum: $^{252}$Cf(sf)**




- A nice improvement was obtained by using Mengoni-Nakajima shell corrections **(See Talk given by O. Litaize)**
- Nevertheless, the agreement with Mannhart is still not perfect


1 Context

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# The Three Source Model Revisited / Presentation

The three source model already proposed by Kornilov:

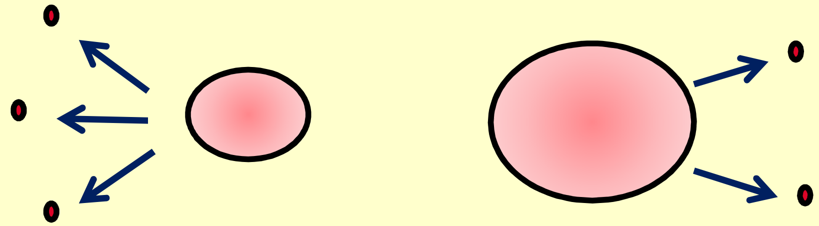
- *N. Kornilov, A.B. Kagalenko, S.V. Poupko et al., Nucl. Phys. A686,187–203 (2001)*
- *N. Kornilov, Fission Neutrons, Springer International, Switzerland, 2015*

| **Kornilov model** | | **Present work** |
|---|---|---|
| Watt spectra adopted for the evaporated neutrons | ⇒ | FIFRELIN calculations |
| The ratio of the neutron multiplicity for L and H fragments was ½ | ⇒ | FIFRELIN calculations |
| Two arbitrary components were introduced to describe scission neutron spectra | ⇒ | One component determined from physical grounds |

# The Three Source Model Revisited / Presentation

Case without scission neutron **$(1-b^{SC})$**

After fission of the nucleus A, the evaporated neutrons are emitted from the fully accelerated FF:



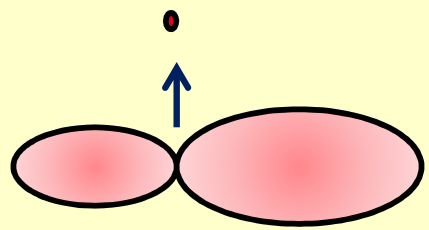
$$(1-b^{SC})\ \left\{ <\nu^{EVAP}_{Light}(E^{*}_{Light})> + <\nu^{EVAP}_{Heavy}(E^{*}_{Heavy})> \right\}$$

Case where one scission neutron is emitted **$(b^{SC})$**

**Phase 1:**

One scission neutron is emitted.

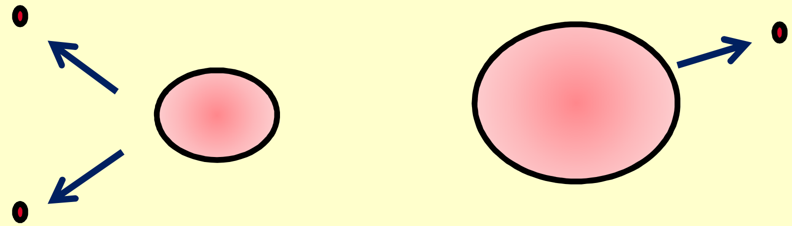
**$E^{SC}$** **:** energy required



Scission-n multiplicity: $\nu^{SC} = b^{SC}\ \nu_{TOT}$

**Phase 2:**

Then, after fission of the nucleus A-1, the evaporated neutrons are emitted from the fully accelerated FF having less excitation energy:



$$b^{SC}\ \left\{ <\nu^{EVAP}_{Light}(E^{*}_{Light} - 0.5\,E^{SC})> + <\nu^{EVAP}_{Heavy}(E^{*}_{Heavy} - 0.5\,E^{SC})> \right\}$$

# The Three Source Model Revisited / Presentation

**1rst component**: evaporated neutrons when no scission neutron is emitted

$$< \nu_{TOT} > \chi_{TOT} =$$

$$(1-b^{SC}) \left\{ < \nu^{Evap}_{Light}(E^*_{Light}) > \chi^{Evap}_{Light}(E^*_{Light}) + < \nu^{Evap}_{Heavy}(E^*_{Heavy}) > \chi^{Evap}_{Heavy}(E^*_{Heavy}) \right\} +$$

$$b^{SC} \left\{ < \nu^{Evap}_{Light}(E^*_{Light} - \frac{E^{SC}}{2}) > \chi^{Evap}_{Light}(E^*_{Light} - \frac{E^{SC}}{2}) + < \nu^{Evap}_{Heavy}(E^*_{Heavy} - \frac{E^{SC}}{2}) > \chi^{Evap}_{Heavy}(E^*_{Heavy} - \frac{E^{SC}}{2}) \right\} +$$

$$< \nu^{SC} > \chi^{SC}$$

**2nd component**: evaporated neutrons after emission of scission neutrons ($E^{SC}$ is assumed to be equally shared between the light and the heavy fragment)

**3rd component**: scission neutrons with $< \nu^{SC} > = b^{SC} < \nu_{TOT} >$

- Notation: $\chi^{Evap}_{Light}(E^*_{Light})$ = Evaporated PFNS from Light fragment with an average excitation energy of $E^*_{Light}$

# The Three Source Model Revisited / Procedure

**Ingredients needed for PFNS calculations**

**a** Choice of the scission neutron spectrum: → $\chi^{SC}$

**b** Calculation of the evaporated neutron multiplicities: → $< \nu^{Evap}_{Light}(E^{*}_{Light}) >$, $< \nu^{Evap}_{Heavy}(E^{*}_{Heavy}) >$

**c** Calculation of the evaporated neutron spectra: → $\chi^{Evap}_{Light}(E^{*}_{Light})$, $\chi^{Evap}_{Heavy}(E^{*}_{Heavy})$

# The Three Source Model Revisited / Procedure

**a** **Choice of the scission neutron spectrum: $\chi^{SC}$**

P. D'hondt et al., Nucl. Phys. A346, 461 (1980)
KE distribution of ternary particles from $^{235}U(n_{th},f)$

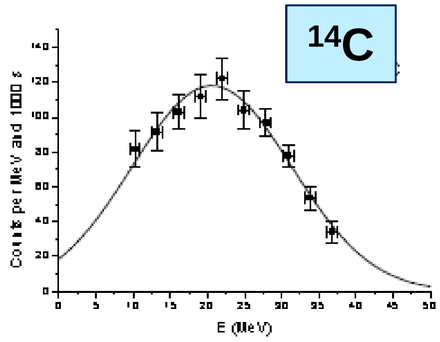
- All ternary particles have a Gaussian KE distribution type
- For the charged ternary particles, their average KE is strongly dependent of the Coulomb barrier
- Therefore, for the scission neutrons (no Coulomb barrier), the average KE is expected to be close to zero

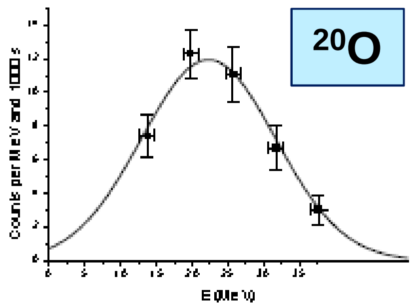
$\chi^{SC}$ is assumed to be a Gaussian with:

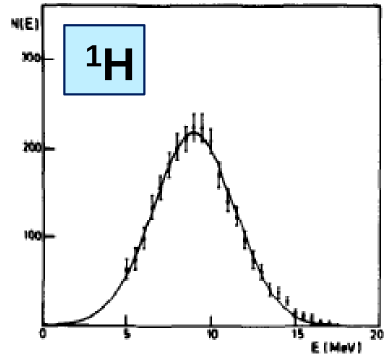
**$<\varepsilon^{SC}>$=0.25 MeV**

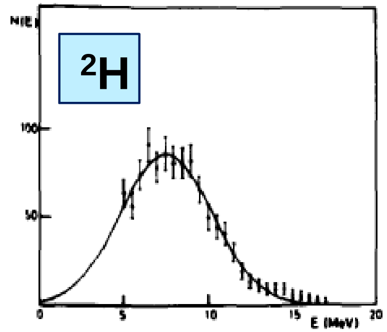
close to the value suggested by R. Capote
in R. Capote et al., Nucl. Data Sheets 131 (2016) 1-106

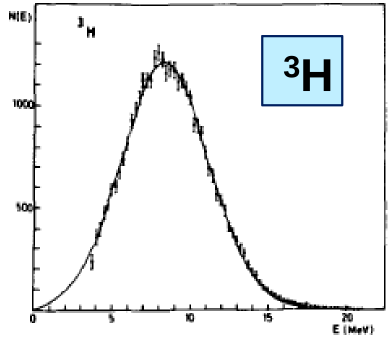
U. Koster et al., PhD thesis, 1999
KE distribution of ternary particles from $^{241}Pu(n_{th},f)$



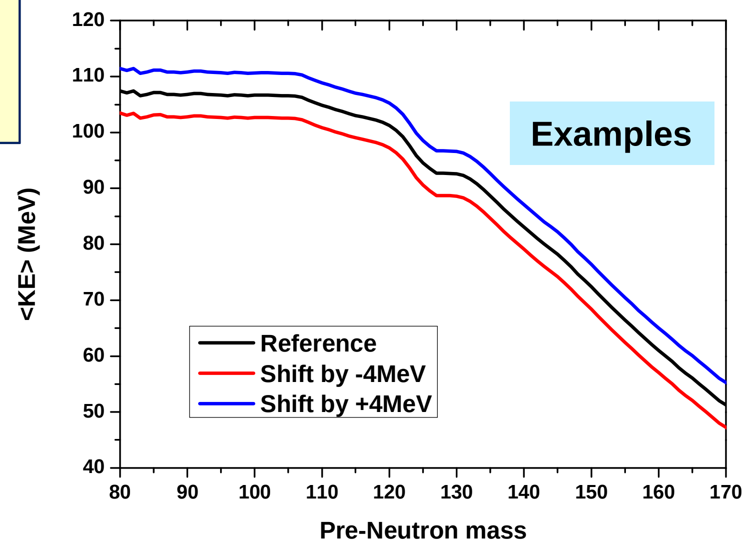
# The Three Source Model Revisited / Procedure

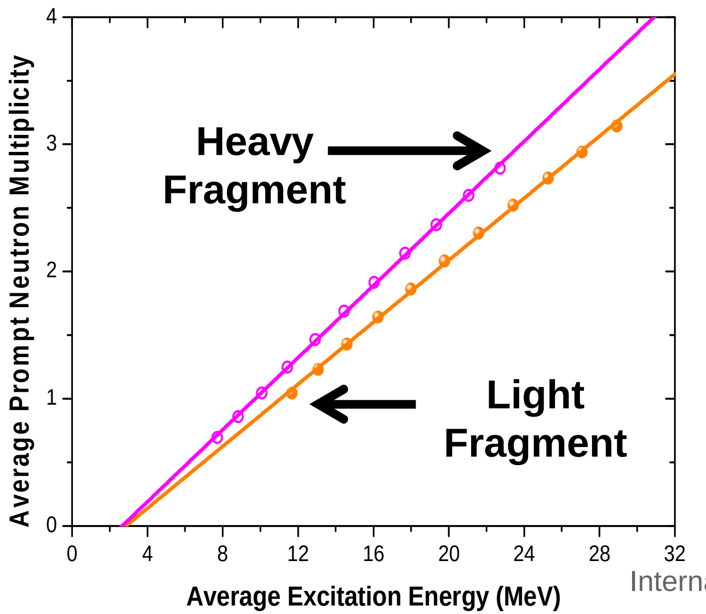
**b**

## Calculation of the evaporated neutron multiplicities for several <E*>

Calculations done with a shift on <KE(A)> for all masses

| | $< E^*_{Light} >$ | $< E^*_{Heavy} >$ | $< \nu^{EVAP}_{Light}(E^*_{Light}) >$ | $< \nu^{EVAP}_{Heavy}(E^*_{Heavy}) >$ |
|---|---|---|---|---|
| Shift by -4 MeV | 23.42 MeV | 17.69 MeV | 2.52 | 2.14 |
| Reference | 19.77 MeV | 14.44 MeV | 2.08 | 1.69 |
| Shift by +4 MeV | 16.25 MeV | 11.43 MeV | 1.64 | 1.25 |




A clear linear correlation between $\nu^{EVAP}$ and E* is established

$$< \nu^{EVAP}_{Light}(E^*_{Light}) > = a_{Light} + b_{Light} < E^*_{Light} >$$

$$< \nu^{EVAP}_{Heavy}(E^*_{Heavy}) > = a_{Heavy} + b_{Heavy} < E^*_{Heavy} >$$

$$a_{Light} = -0.350$$

$$b_{Light} = 0.122 \text{ n/MeV}$$

$$a_{Heavy} = -0.377$$

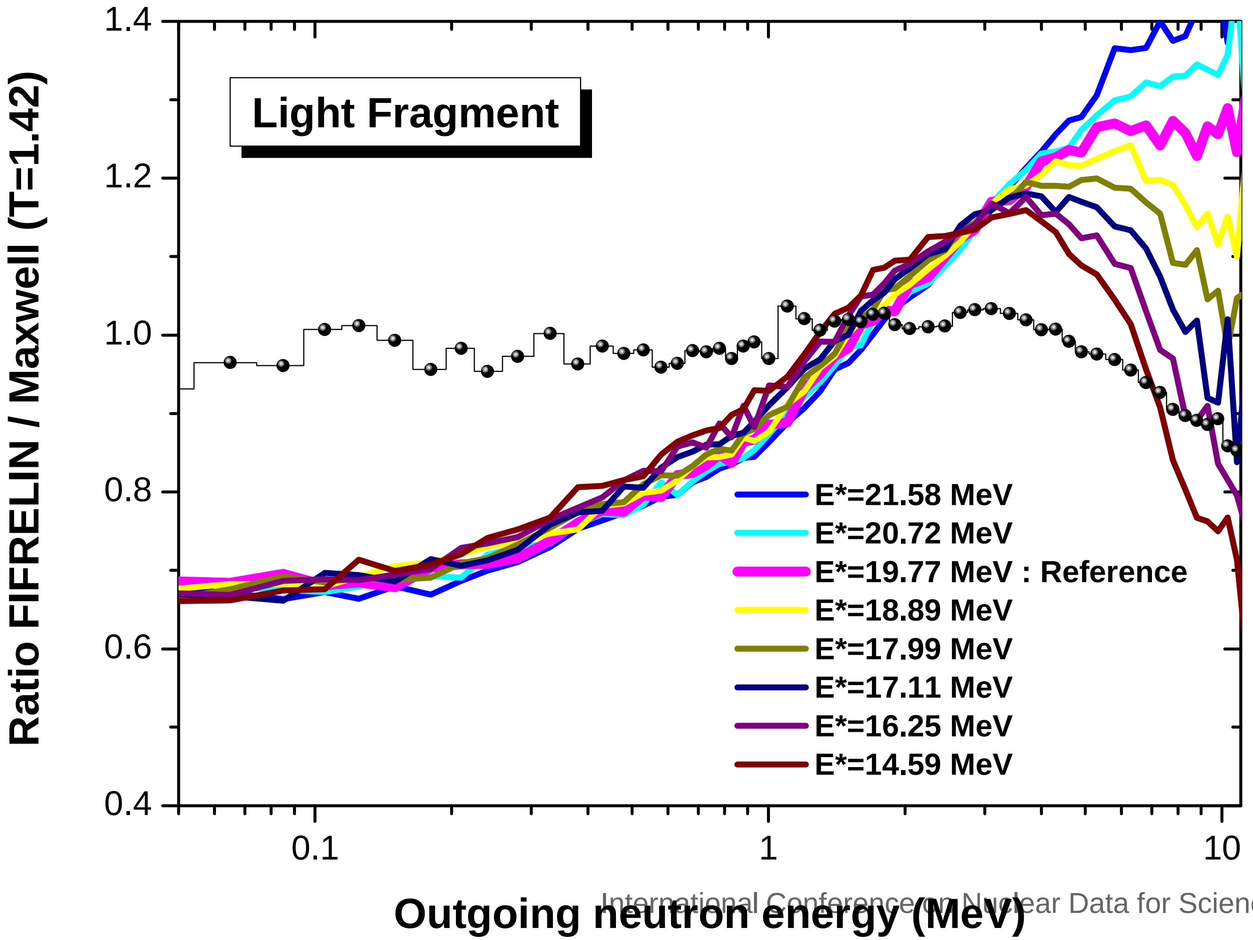
$$b_{Heavy} = 0.142 \text{ n/MeV}$$

# The Three Source Model Revisited / Procedure

## c Calculation of the evaporated neutron spectra from Light fragment

From the previous FIFRELIN calculations, the corresponding PFNS can also be deduced:

$$<\chi^{Evap}_{Light}(E^*_{Light})>=\frac{\sum_{A\in Light} Y_{pre}(A)\,\nu_A(E^*_{Light})\,\chi_A(E^*_{Light})}{\sum_{A\in Light} Y_{pre}(A)\,\nu_A(E^*_{Light})}$$



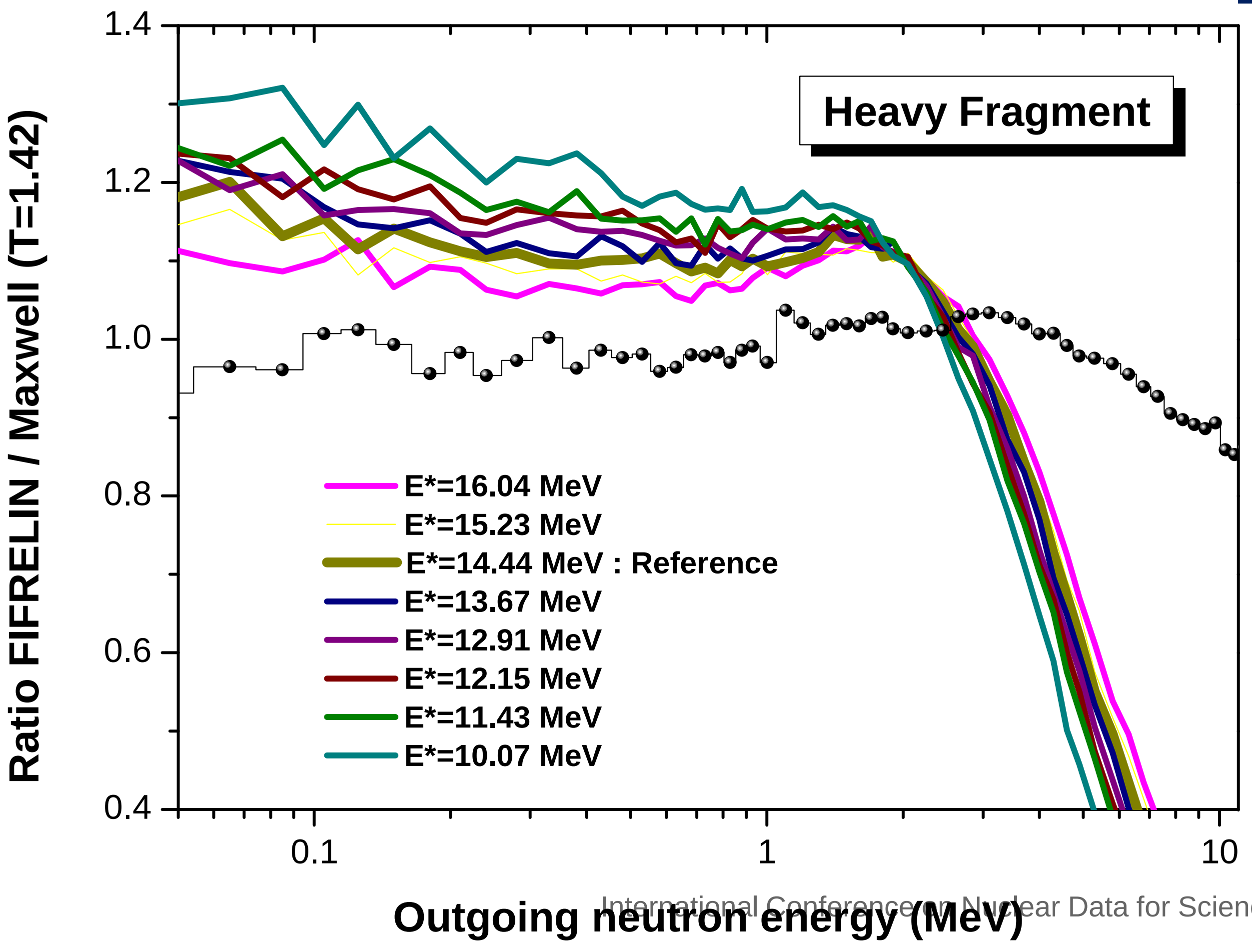

**For the light fragments:**
The available excitation energy does not impact PFNS below about 3 MeV but has a strong influence above

# The Three Source Model Revisited / Procedure

## c Calculation of the evaporated neutron spectra from Heavy fragment

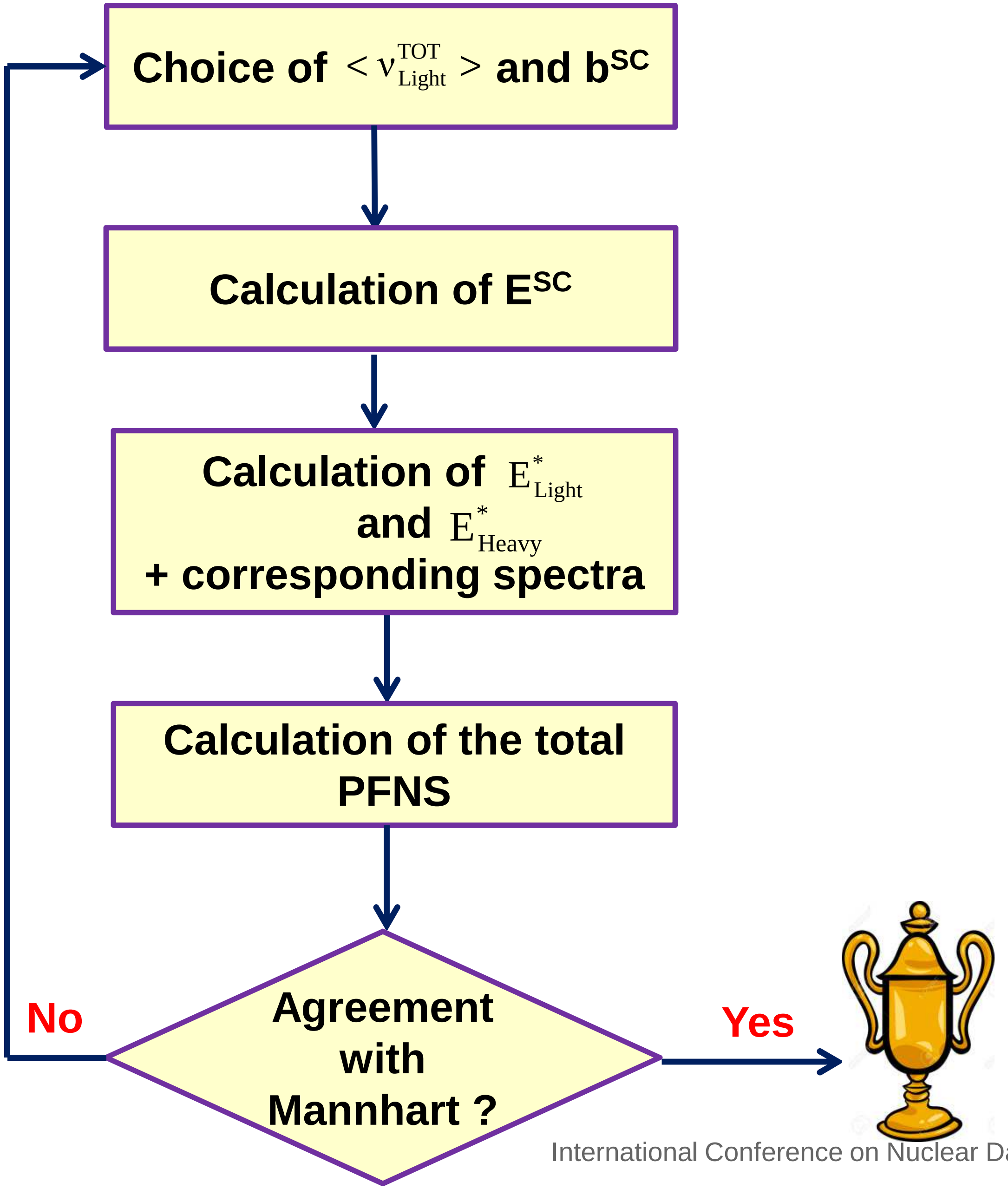
From the previous FIFRELIN calculations, the corresponding PFNS can also be deduced:

$$<\chi^{Evap}_{Heavy}(E^*_{Heavy})>=\frac{\sum_{A\in Heavy} Y_{pre}(A)\,\nu_A(E^*_{Heavy})\,\chi_A(E^*_{Heavy})}{\sum_{A\in Heavy} Y_{pre}(A)\,\nu_A(E^*_{Heavy})}$$

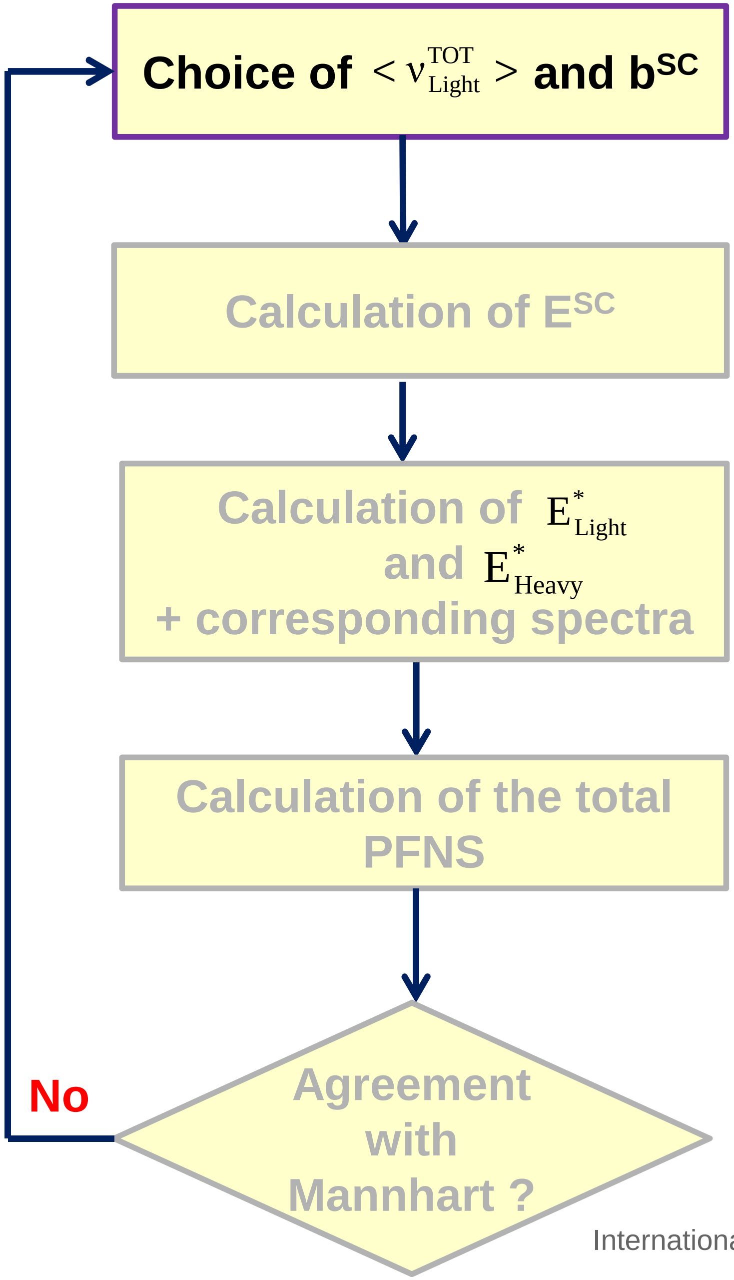



**For the Heavy fragments:**
The available excitation energy does not impact PFNS above 2 MeV but has a strong influence below

# The Three Source Model Revisited / Procedure



# The Three Source Model Revisited / Procedure



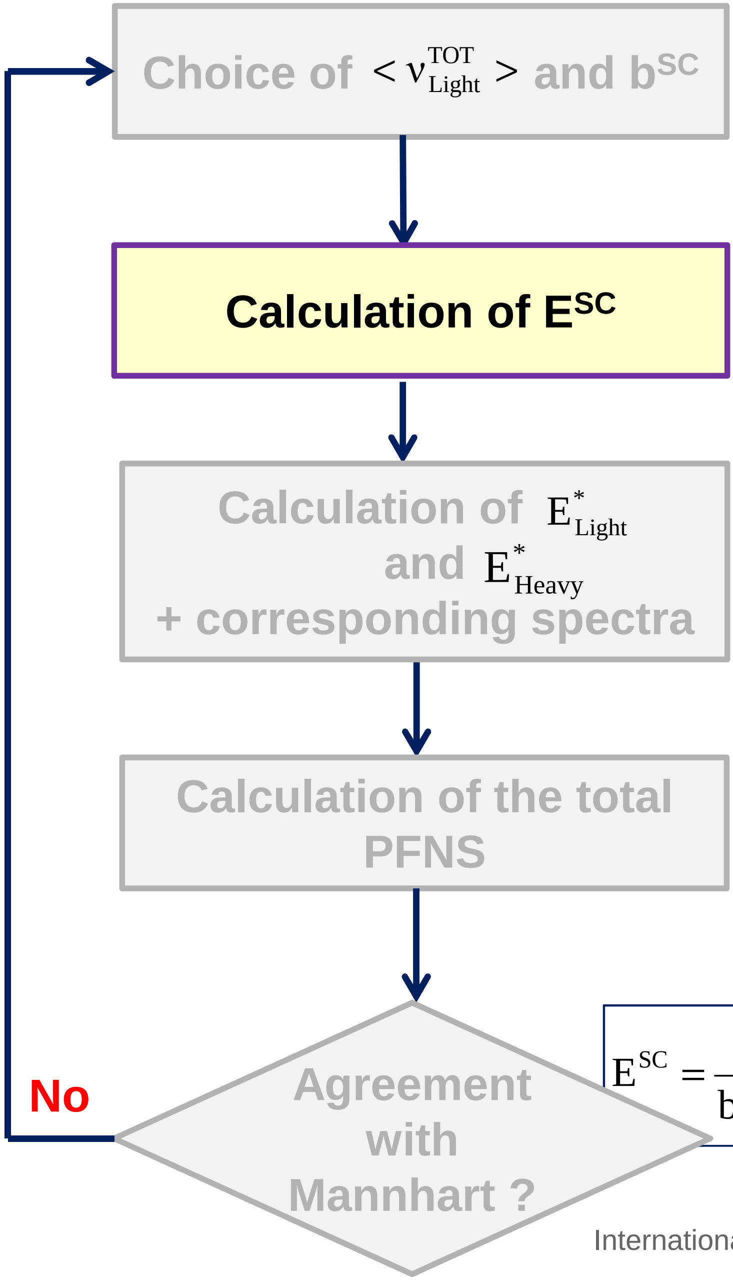

$< \nu^{TOT}_{Light} >$ : **Free parameter**

$$< \nu^{TOT}_{Heavy} > = < \nu_{TOT} > - < \nu^{TOT}_{Light} >$$

$< \nu_{TOT} >$ = **3.76**

$b^{SC}$ : **Free parameter**

# The Three Source Model Revisited / Procedure




- For the Light fragment:

$$<\nu_{Light}^{TOT}> = (1-b^{SC}) <\nu_{Light}^{EVAP}(E^*_{Light})> + b^{SC} <\nu_{Light}^{EVAP}(E^*_{Light} - 0.5\,E^{SC})> + 0.5\,b^{SC} <\nu_{TOT}>$$

With: $<\nu_{Light}^{EVAP}(E^*_{Light})> = a_{Light} + b_{Light}\,E^*_{Light}$

$$E^*_{Light} = \frac{1}{b_{Light}}\left[<\nu_{Light}^{Tot}> - a_{Light} + 0.5\,b^{SC}\left(b_{Light}E_{SC} - <\nu_{TOT}>\right)\right]$$

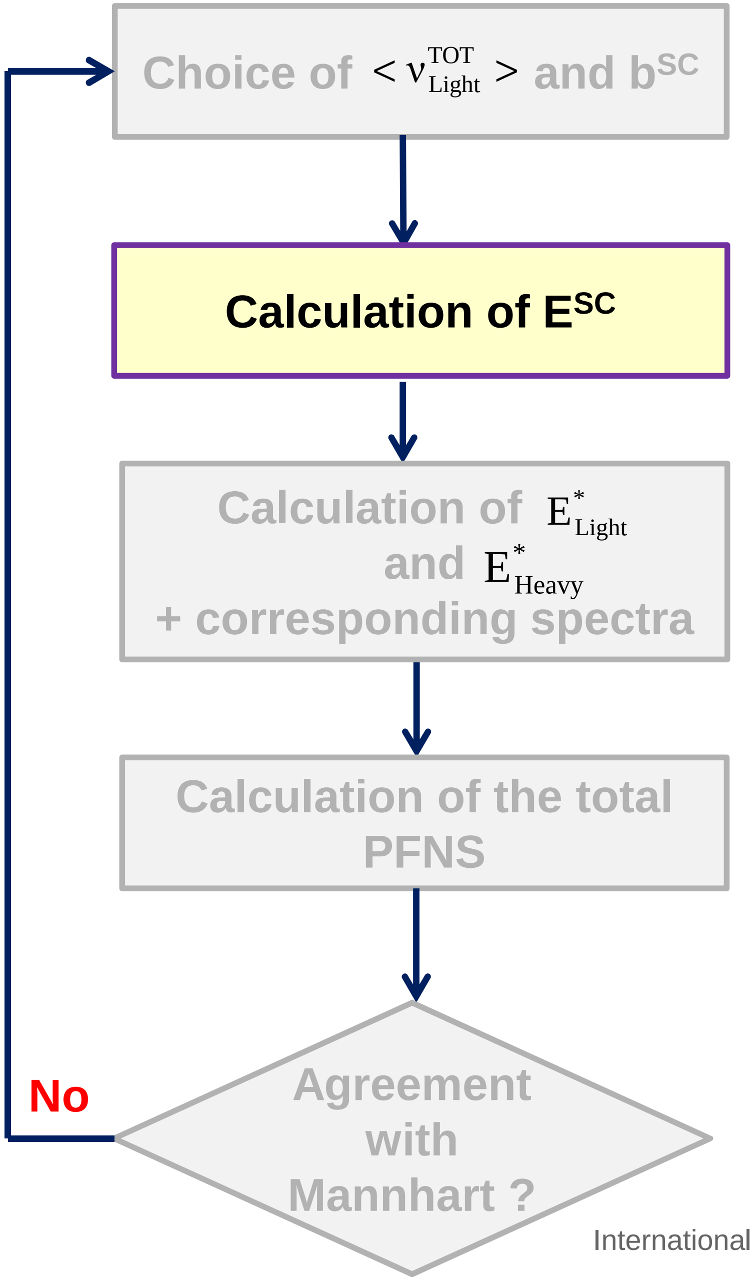
- Same for the Heavy fragment:

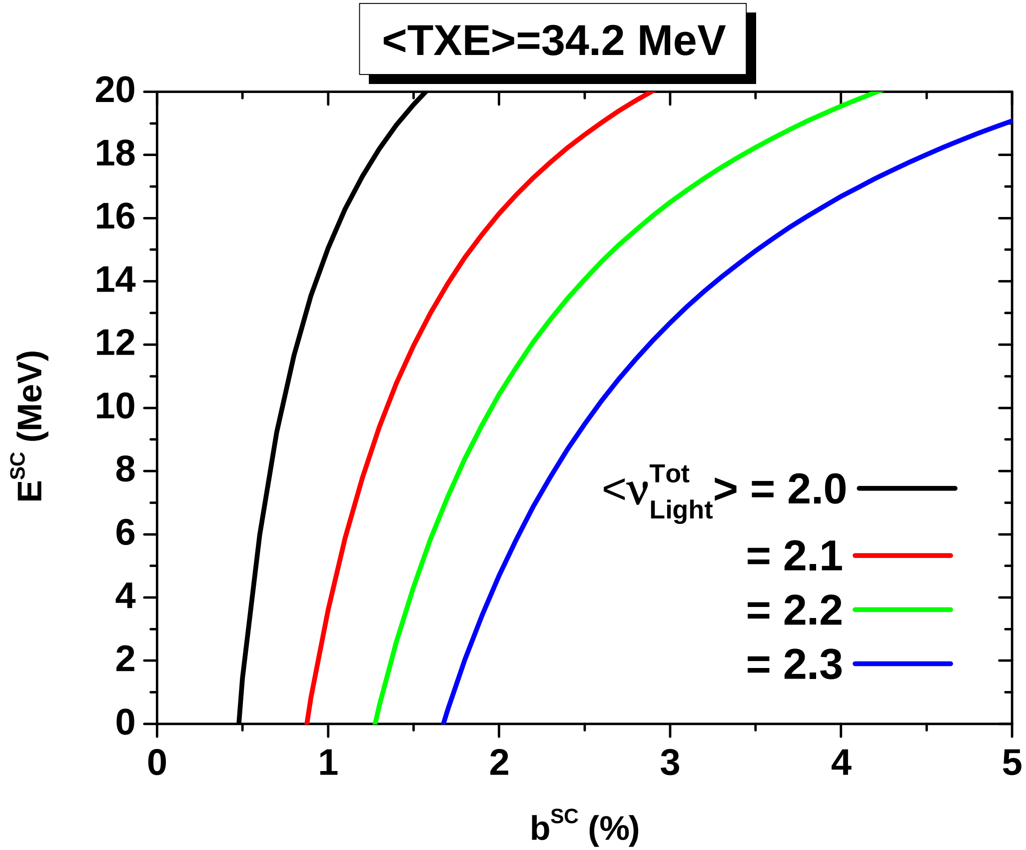
$$E^*_{Heavy} = \frac{1}{b_{Heavy}}\left[<\nu_{Heavy}^{Tot}> - a_{Heavy} + 0.5\,b^{SC}\left(b_{Heavy}E_{SC} - <\nu_{TOT}>\right)\right]$$

- Using <TXE>=34.2 (P. Heeg, PhD thesis, 1990) a relation between $E^{SC}$ and $b^{SC}$ can be established

$$E^{SC} = \frac{1}{b^{SC}}\left[<TXE> - \frac{<\nu_{Light}^{TOT}>}{b_{Light}} - \frac{<\nu_{Heavy}^{TOT}>}{b_{Heavy}} + \frac{a_{Light}}{b_{Light}} + \frac{a_{Heavy}}{b_{Heavy}}\right] + \frac{1}{2}<\nu_{TOT}>\left(\frac{1}{b_{Light}} + \frac{1}{b_{Heavy}}\right)$$

# The Three Source Model Revisited / Procedure



# The Three Source Model Revisited / Procedure

Choice of $<\nu^{TOT}_{Light}>$ and $b^{SC}$

Calculation of $E^{SC}$

**Calculation of $E^{*}_{Light}$ and $E^{*}_{Heavy}$ + corresponding spectra**

Calculation of the t
PFNS

Agreement with Mannhart ?

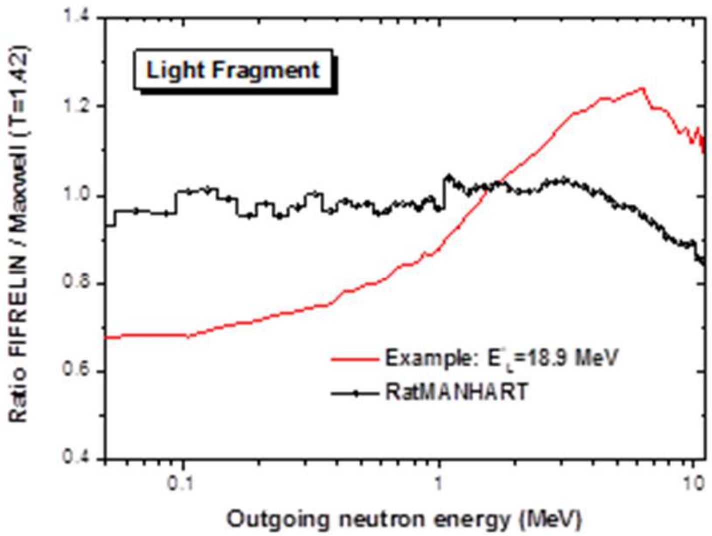
No

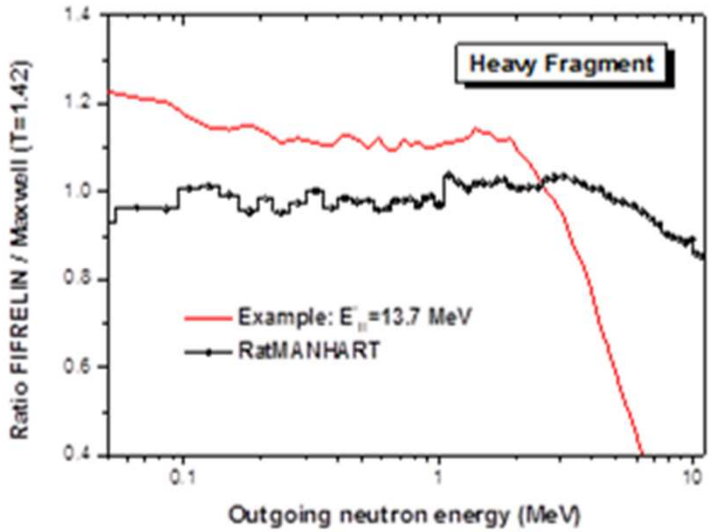
- As seen, the average excitation energy for the Light and Heavy fragments can be deduced:

$$E^{*}_{Light} = \frac{1}{b_{Light}}\left[<\nu^{Tot}_{Light}> - a_{Light} + 0.5\, b^{SC}\left(b_{Light} E_{SC} - <\nu_{TOT}>\right)\right]$$

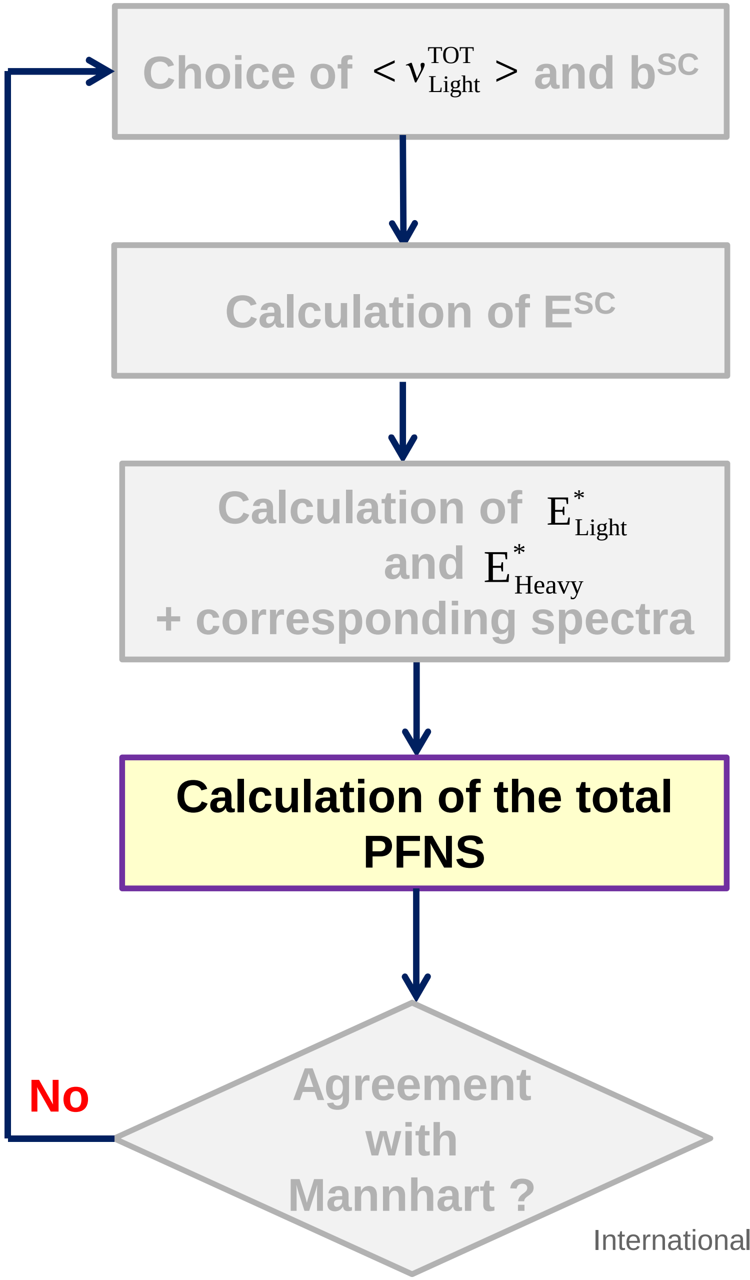
$$E^{*}_{Heavy} = \frac{1}{b_{Heavy}}\left[<\nu^{Tot}_{Heavy}> - a_{Heavy} + 0.5\, b^{SC}\left(b_{Heavy} E_{SC} - <\nu_{TOT}>\right)\right]$$

- The corresponding spectra must be calculated



# The Three Source Model Revisited / Procedure




All the ingredients needed for the total PFNS calculation are known:

$$
\begin{aligned}
<\nu_{TOT}>\chi_{TOT} = \; & (1-b^{SC})<\nu^{Evap}_{Light}(E^*_{Light})> \; \chi^{Evap}_{Light}(E^*_{Light}) \; + \\
& (1-b^{SC})<\nu^{Evap}_{Heavy}(E^*_{Heavy})> \chi^{Evap}_{Heavy}(E^*_{Heavy}) \; + \\
& b^{SC} <\nu^{Evap}_{Light}(E^*_{Light} - 0.5E^{SC})> \; \chi^{Evap}_{Light}(E^*_{Light} - 0.5E^{SC}) \; + \\
& b^{SC} <\nu^{Evap}_{Heavy}(E^*_{Heavy} - 0.5E^{SC})> \chi^{Evap}_{Heavy}(E^*_{Heavy} - 0.5E^{SC}) + \\
& b^{SC} <\nu_{TOT}> \chi^{SC}
\end{aligned}
$$

# The Three Source Model Revisited / Results

**A very nice agreement compared to Mannhart evaluation could be achieved with:**

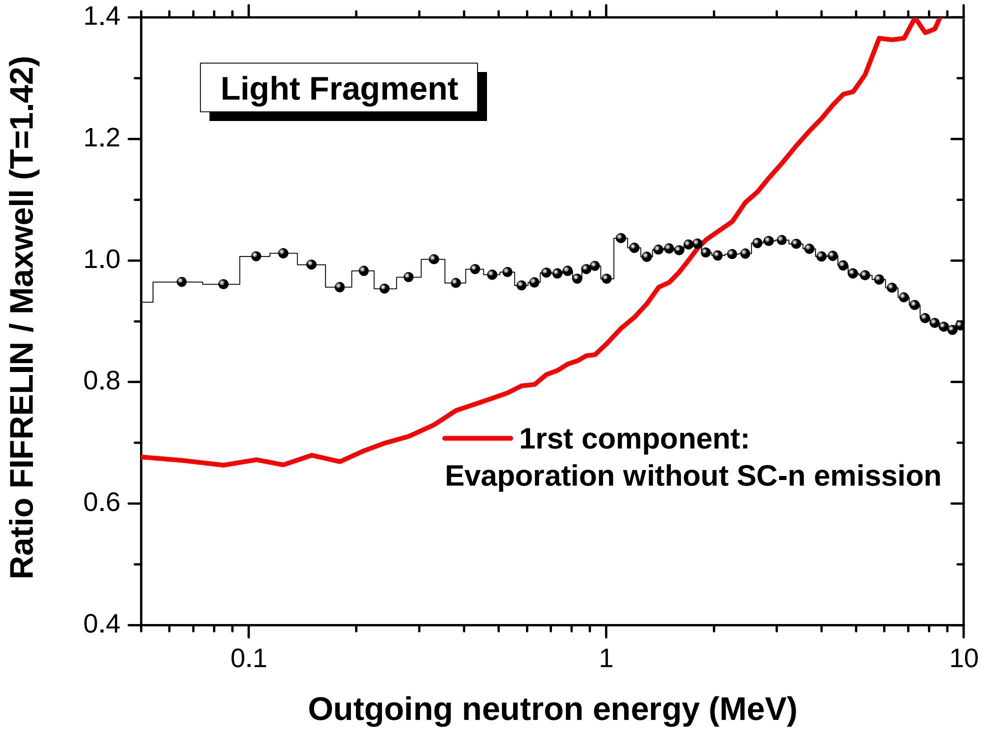
$$\left(1-b^{SC}\right) < \nu^{Evap}_{Light}\left(E^{*}_{Light}\right) > = 2.22$$

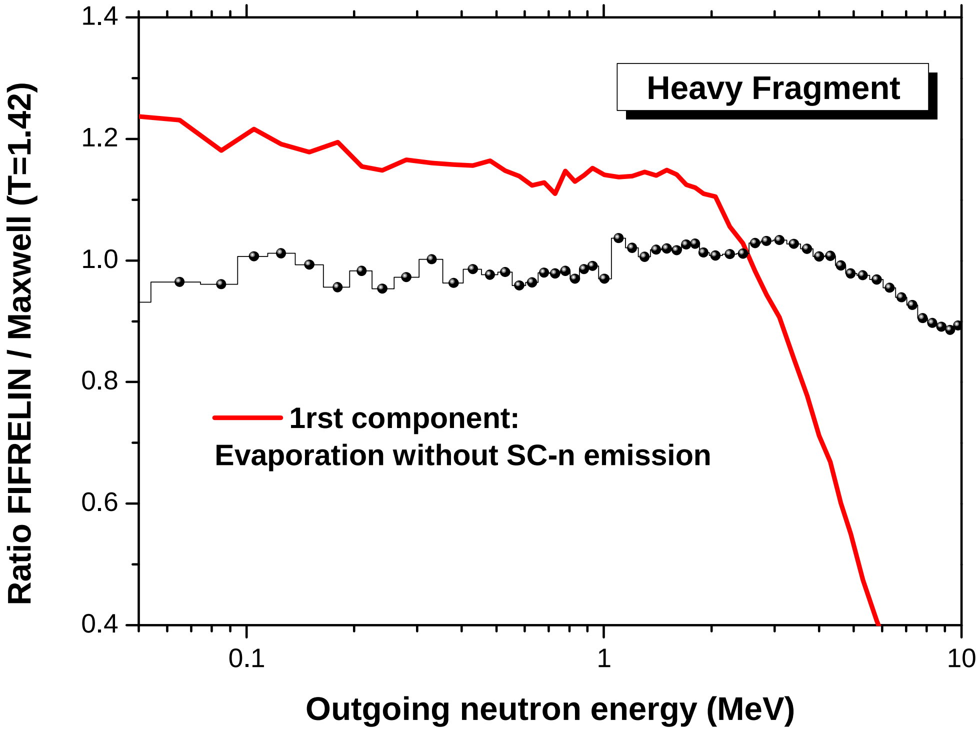
$\nu^{Scission} = 0.08$

$E^{*}_{Light} = 21.48\ \text{MeV}$

$E^{*}_{Heavy} = 12.72\ \text{MeV}$

$$\left(1-b^{SC}\right) < \nu^{Evap}_{Heavy}\left(E^{*}_{Heavy}\right) > = 1.40$$



# The Three Source Model Revisited / Results

**A very nice agreement compared to Mannhart evaluation could be achieved with:**

$$\left(1-b^{SC}\right) < \nu^{Evap}_{Light}\left(E^{*}_{Light}\right) >=2.22$$

$$b^{SC} < \nu^{Evap}_{Light}\left(E^{*}_{Light} - 0.5\,E_{SC}\right) >=0.04$$

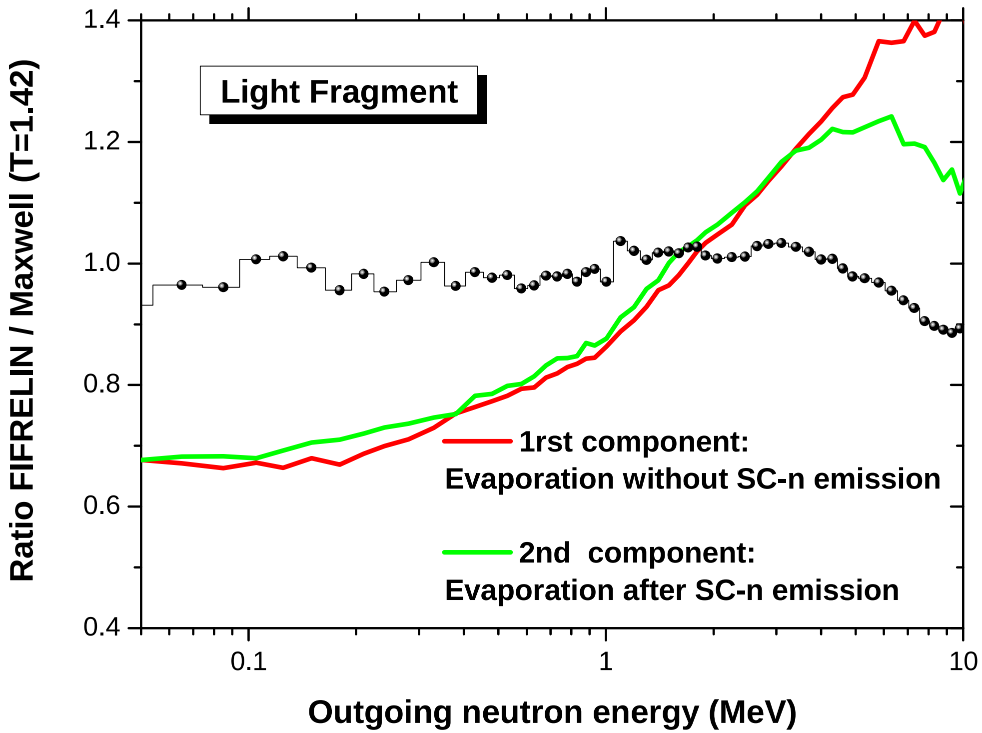
$$\nu^{Scission} = 0.08$$

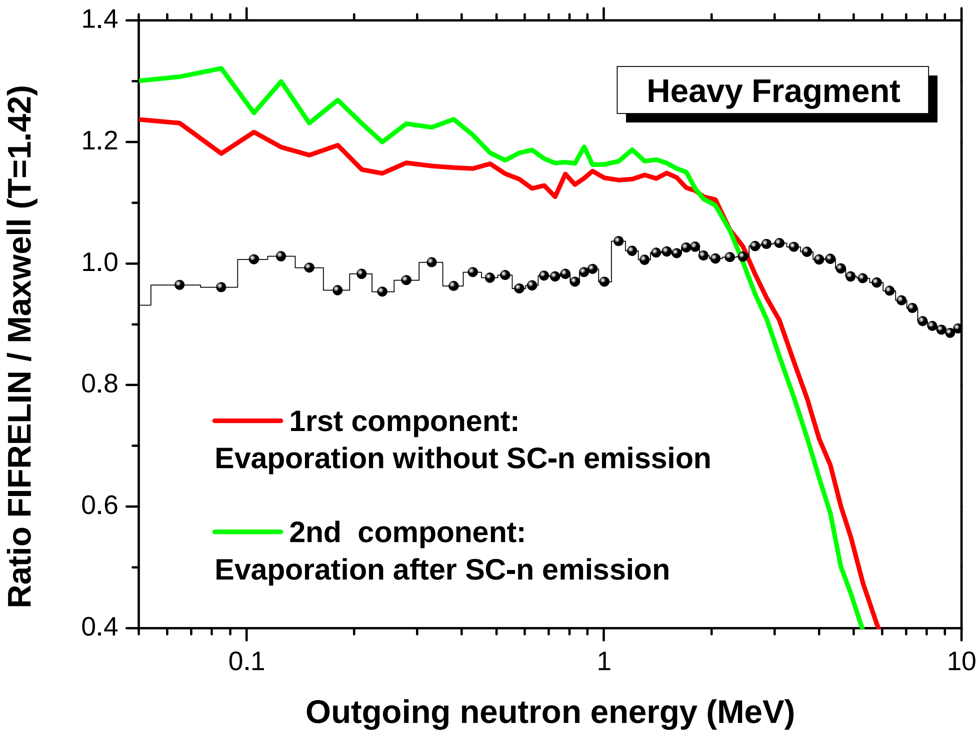
$$E^{*}_{Light} = 21.48\ \mathrm{MeV}$$

$$E^{*}_{Heavy} = 12.72\ \mathrm{MeV}$$

$$\left(1-b^{SC}\right) < \nu^{Evap}_{Heavy}\left(E^{*}_{Heavy}\right) >=1.40$$

$$b^{SC} < \nu^{Evap}_{Heavy}\left(E^{*}_{Heavy} - 0.5\,E_{SC}\right) >=0.02$$



# The Three Source Model Revisited / Results

A very nice agreement compared to Mannhart evaluation could be achieved with:

$TXE = 34.2\ MeV$

$< \nu^{Tot}_{Light} > = 2.30$

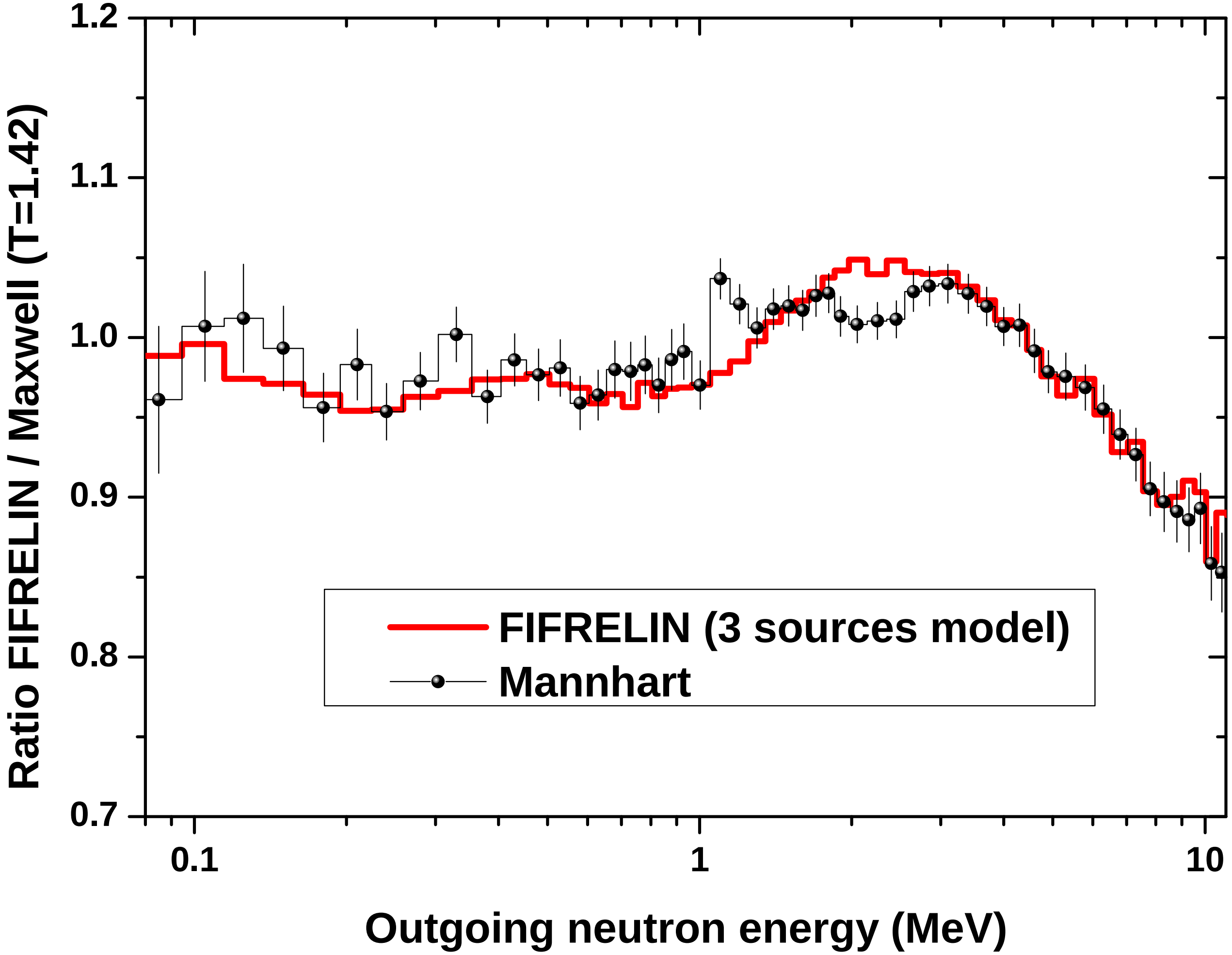
$< \nu^{Tot}_{Heavy} > = 1.46$

$< \nu^{Tot} > = 3.76$

$E^{SC} = 4.7\ MeV$

$b^{SC} = 2\%$

$< \varepsilon^{SC} > = 0.25\ MeV$




- Only 2% scission is needed to get a very nice agreement with Mannhart (between 80 keV up to 11 MeV)
- $E^{SC}$ : in agreement with the calculation performed by Carjan
- An overestimation of the total prompt neutron multiplicity for the light fragment (2.3) compared to the experiment (2.09) is required


1 Context

2 'Reference Calculation': PFNS calculated without scission neutron

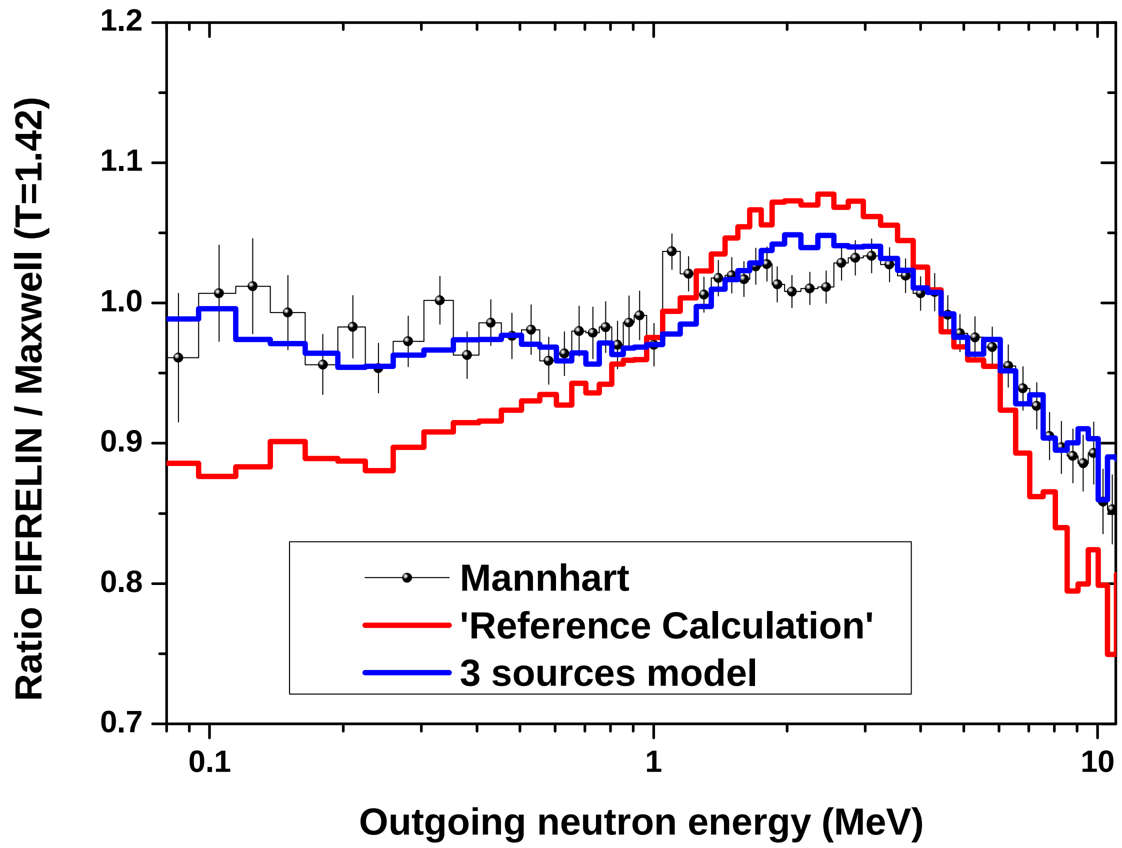
3 The three source model revisited: PFNS calculated including scission neutrons

- Presentation of the model
- Calculation procedure
- Results

# 4 Conclusion

# Conclusion

- The three source model proposed by Kornilov has been revisited
- The evaporation neutrons are simulated with the Monte Carlo code FIFRELIN and the scission neutrons are represented by a Gaussian (with an average energy of 0.25 MeV)
- All components are calculated in a consistent way in order to respect the total prompt neutron multiplicity (3.76) and the average total excitation energy (34.2 MeV)
- A very nice agreement with the Mannhart evaluation was obtained by using a low scission neutron component : 2%



Commissariat à l'énergie atomique et aux énergies alternatives
Centre de Saclay | 91191 Gif-sur-Yvette Cedex
T. +33 (0)1 XX XX XX XX | F. +33 (0)1 XX XX XX XX

Direction
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Etablissement public à caractère industriel et commercial | RCS Paris B 775 685 019