Prompt Fission Neutrons as Probes to Nuclear Configurations at Scission

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Nuclear Fission... a fascinating topic!

- Nuclear Fission can be seen as the **most dramatic rearrangement of nuclear matter** that we know of.
- After more than half a century of research, it continues to fascinate us (statistical and dynamical aspects, interplay between collective and single-particle effect, interplay between macroscopic (classical) and microscopic (quantum) effects, ...).
- Historical paper of **N.Bohr and J.A.Wheeler ("The Mechanism of Fission", 1939**) is quite remarkable in how much of this process they could understand from extremely limited experimental data. Energy release, fissility parameter, fission and fusion barriers, spontaneous fission lifetime, delayed neutrons, ...
- **Newer discoveries:** the role of shell effects on top of the fission barrier, fission isomers, asymmetric vs. symmetric mass distributions, fission modes, etc.
- **But many challenges remain:** dynamic aspects of fission, dissipation mechanism from saddle to scission, fully microscopic prediction of fission fragments mass and charge yields, and their intrinsic characteristics (excitation energy, angular momentum, ...), ...
- Nuclear fission also represents a doorway to the production of neutron-rich nuclear species, such as in the r-process nucleosynthesis.

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The physics near the scission point

Some unsolved questions:

- What are the nuclear configurations near scission?
- How much dissipation is there between the saddle and scission points?
- What is the spin generation mechanism in low-energy fission?
  ["orientation pumping"? Mikhailov and Quentin, Phys. Lett. B 462,7 (1999)]
- How is the total "free energy" at scission shared among the kinetic energy and intrinsic excitation energy?
- How is the total excitation energy shared among the two fragments?

Some clues:

- Experimental yields of fission products Y(A,Z,TKE)
- Odd-even effects in low-energy fission
- Average FF spin extracted from isomer-to-ground-state population ratios
- Prompt neutrons and gamma-rays
- Ternary fission
- TRI and ROT effects
  [F.Gönnenwein, Phys. Lett. B 652, 13 (2007)]
- Scission neutrons?

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What do we know about prompt neutrons?

Experimentally

Surprisingly, not that much...

For some nuclei and incident neutron energies E_{inc}

- average outgoing prompt neutron energy $<\epsilon_n>$
- average spectrum $N(\epsilon_n)$
- average prompt neutron multiplicity $<\nu>$

For very few systems and incident energies

- $<\epsilon_n>(A,TKE)$
- $<\nu>(A,TKE)$
- $P(\nu)$

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What do we know about prompt neutrons? (cont'd)

Theoretical Modeling & Nuclear Data Evaluations

- V.F.Weisskopf [Phys. Rev. 52, 295 (1937)]: compound nucleus, statistical assumption, evaporation process => Maxwellian spectrum in c.m.

- B.E.Watt [Phys. Rev. 87, 1037 (1952)]: Watt spectrum in lab. frame.

- J.Terrell [Phys. Rev. 113, 527 (1959)]: adjusted parameters to fit Maxwellian spectra for different nuclei.

- Madland-Nix model [NSE 81, 213 (1982)]: distribution of initial FF nuclear temperatures; energy-dependent inverse compound-nucleus formation cross section; multiple-chance fission.

  This model constitutes the basis for all nuclear data evaluations today.
  It calculates $\chi(E_{inc},E_{out})$, <ν> and $N(\epsilon_n)$. Limited to a few fission fragment masses.

- *More recent work:*

  - "Point-by-point" approach (Vladuca, Tudora) [Tudora *et al.*, Nucl. Phys. A756, 176 (2005)]
  - T. Ohsawa, non-equitemperature at scission [report INDC(NDS)-251 (1991)]
  - Multi-modal fission model [Hambsch *et al.*,Nucl. Phys. A726, 248 (2003)]

What about...

An approach that would provide a description “as complete as possible” of the evaporation stage of the fission fragments?

- <ν>, $X(E_{inc},E_{out})$, $N(\epsilon_n)$
- <ν>(A,Z,TKE), $P(\nu)$
- $N(\epsilon_n)$ for 1, 2, ... neutrons out
- n-n, n-FF correlations (e.g., angular distributions)
- same quantities for prompt gamma-rays

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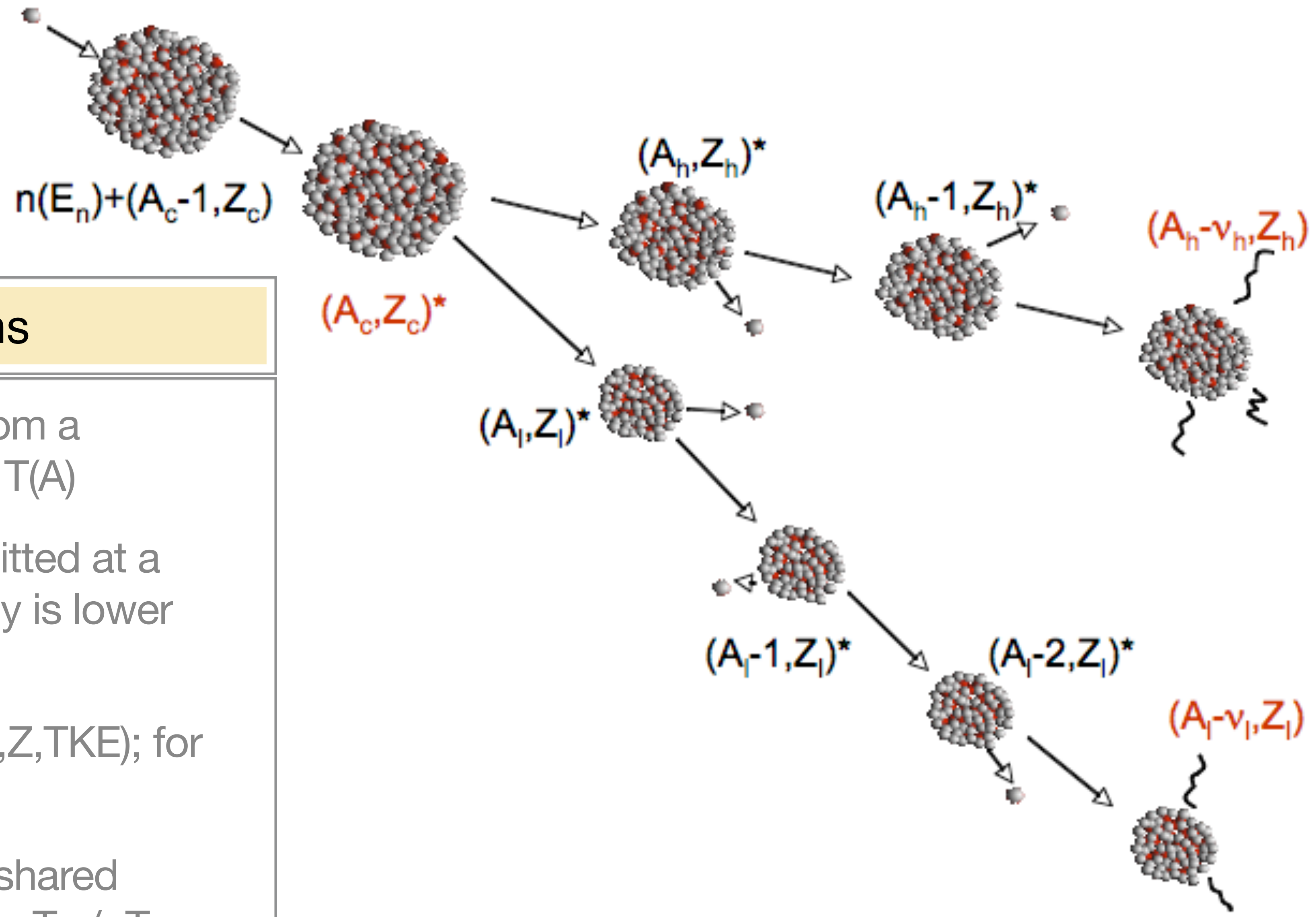
The Monte Carlo approach



Monte Carlo Simulations

- Neutrons are emitted sequentially from a Weisskopf spectrum at temperature T(A)
- Gamma-rays are assumed to be emitted at a latter stage, when the residual energy is lower than the neutron binding energy
- Sampling over initial distribution Y(A,Z,TKE); for now, taken from experimental data
- Total excitation energy TXE=Q-TKE shared according to a temperature ratio $R_T=\langle T_l \rangle / \langle T_h \rangle$ (model parameter-- see discussion later)

First Applications to ^{235}U+n and ^{252}Cf(sf):
S.Lemaire, P.Talou, T.Kawano, M.B.Chadwick, D.G.Madland, Phys. Rev. C**72**, 024601 (2005); Phys. Rev. C**73**, 014602 (2006).

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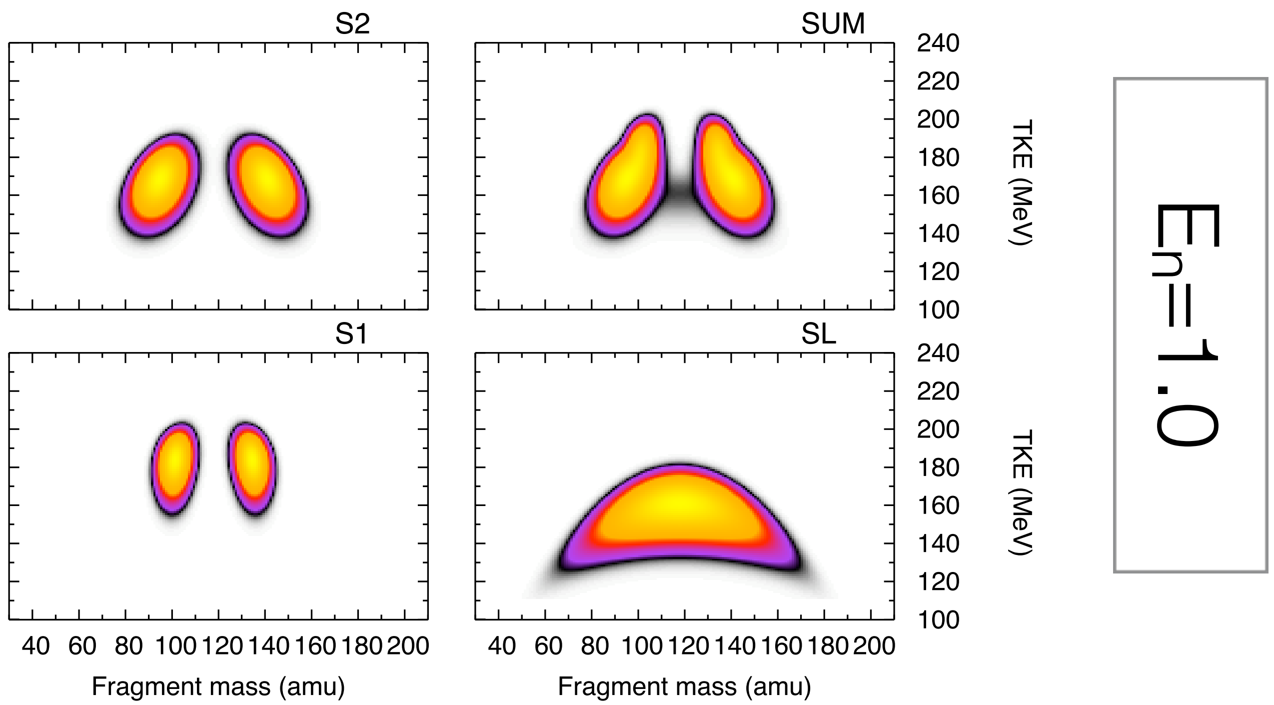
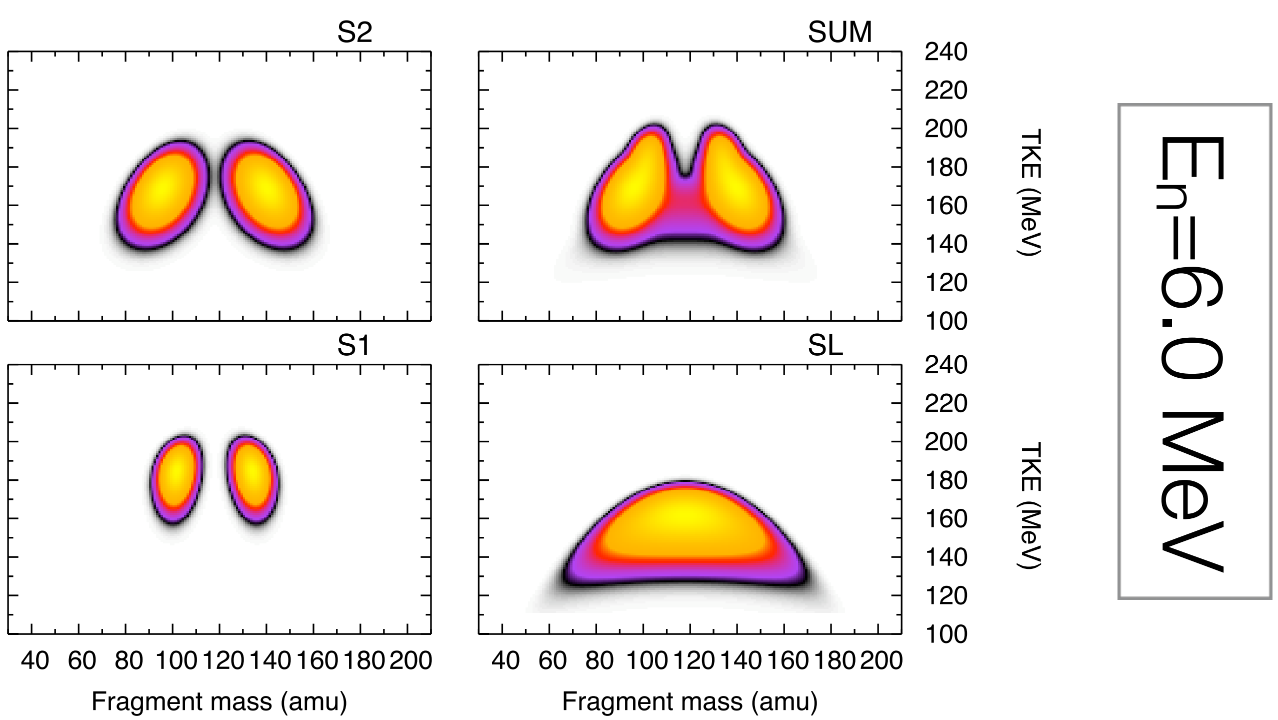
Application to n+^{235}U *(with E_n=0.5 to 6 MeV)* & Relation to Fission Modes

F.-J.Hambsch data, IRMM, Geel





Decomposition in three modes:

S1 (standard I), **S2** (standard II) and **SL** (super-long)

Mean energies for E_n=0.5 MeV

Mode	$\overline{E_r}$ (MeV)	$\overline{TKE}$ (MeV)	$\overline{TXE}$ (MeV)
S1	192.6	182.3	17.4
S2	185.3	167.4	24.9
SL	190.6	157.6	40.1
Sum	187.2	171.2	23.0
Exp.	187.1	171.1	23.0

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R_T parameter = <T_l>/<T_h>

Equal temperatures

Ohsawa

[T.Ohsawa, INDC(NDS) report 251 (1991)]

Present work

Experiment

Mode	$\overline{\nu}_L$	$\overline{\nu}_H$	$\overline{\nu}$	$\overline{\epsilon}_{cm}$ (MeV)	$\overline{\epsilon}_{lab}$ (MeV)
R_T=1.0					
S1	0.93	0.66	1.59	0.82	1.63
S2	1.17	1.63	2.80	1.05	1.75
SL	2.31	2.11	4.43	1.30	1.98
Sum	1.11	1.38	2.49	0.99	1.72
R_T=1.13					
S1	1.06	0.53	1.59	0.81	1.66
S2	1.37	1.42	2.78	1.04	1.77
SL	2.78	1.56	4.35	1.55	2.27
Sum	1.29	1.19	2.48	0.98	1.74
R_T=1.34					
S1	1.23	0.35	1.58	0.84	1.74
S2	1.64	1.12	2.76	1.05	1.84
SL	2.90	1.45	4.35	1.34	2.06
Sum	1.54	0.92	2.46	1.00	1.81
R_T=1.3 / 1.2 / 1.0*					
S1	1.20	0.38	1.58	0.84	1.73
S2	1.47	1.31	2.77	1.04	1.79
SL	2.31	2.11	4.43	1.30	1.98
Sum	1.40	1.07	2.47	0.99	1.80
Experimental					
Nishio [10]	1.42	1.01	2.47	1.265	2.046
Müller [11]	1.44	1.02	2.46		

Standard I
associated with spherical shell closure at N=82

Standard II
associated with deformed shell closure at N=88

Super-long
mass symmetric

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Skyrme-Hartree-Fock calculations

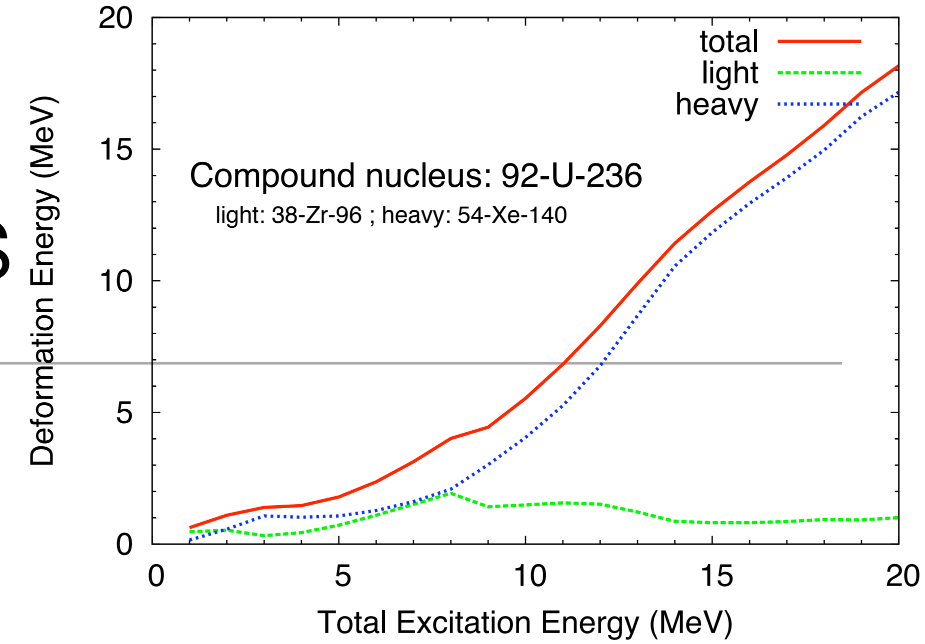
- Skyrme-Hartree-Fock plus BCS-pairing calculations
  [L.Bonneau, P.Quentin and I.N.Mikhailov, Phys. Rev. C75, 064313 (2007)]

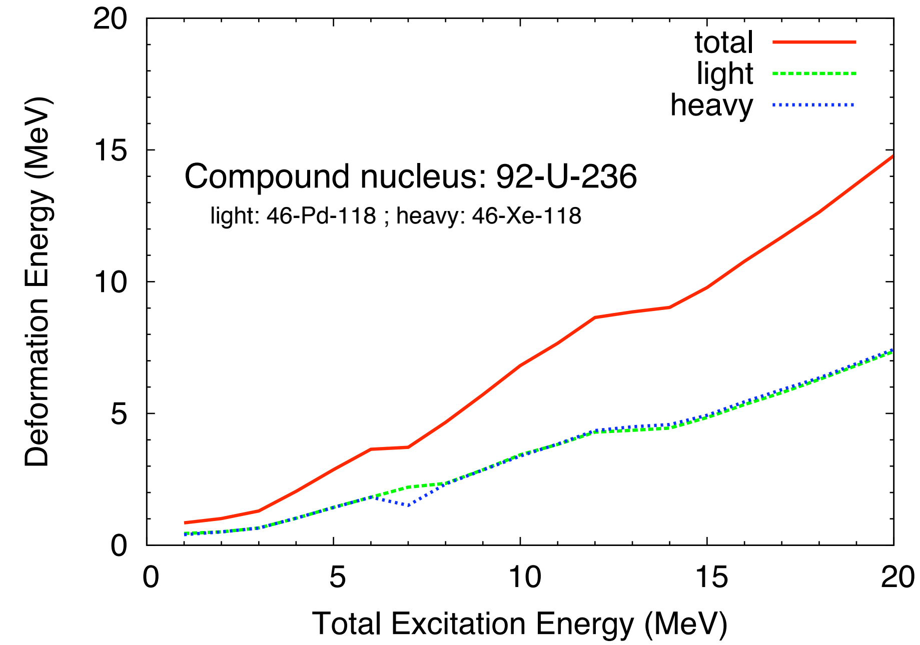
- Scission configurations as a function of TXE, weighted with $e^{-E_{sc}/\theta}$

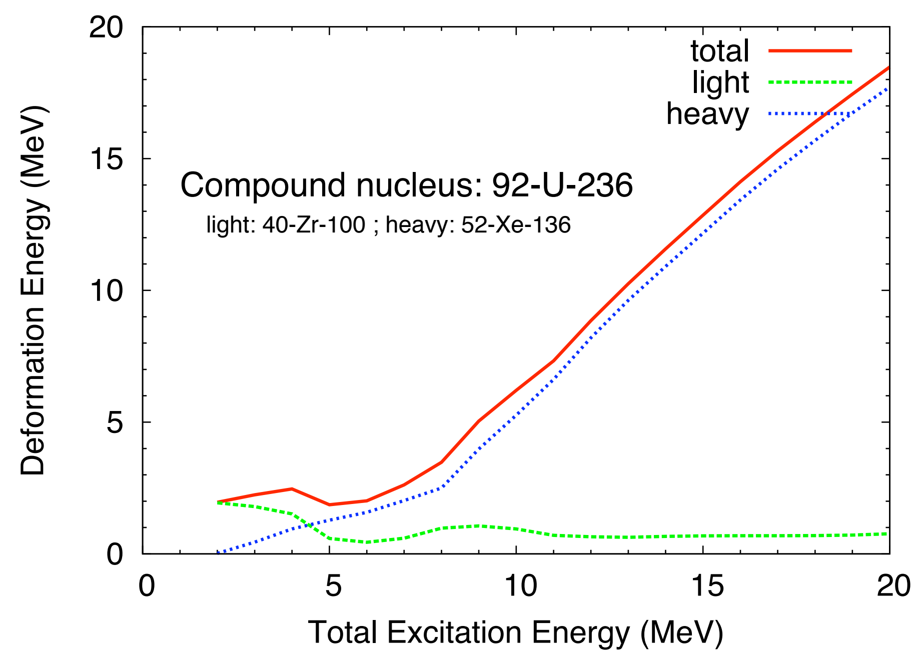
- Scission criterion:

- Three parameters:
  - temperature Θ;
  - scission criterion value η;
  - f such that

Preliminary







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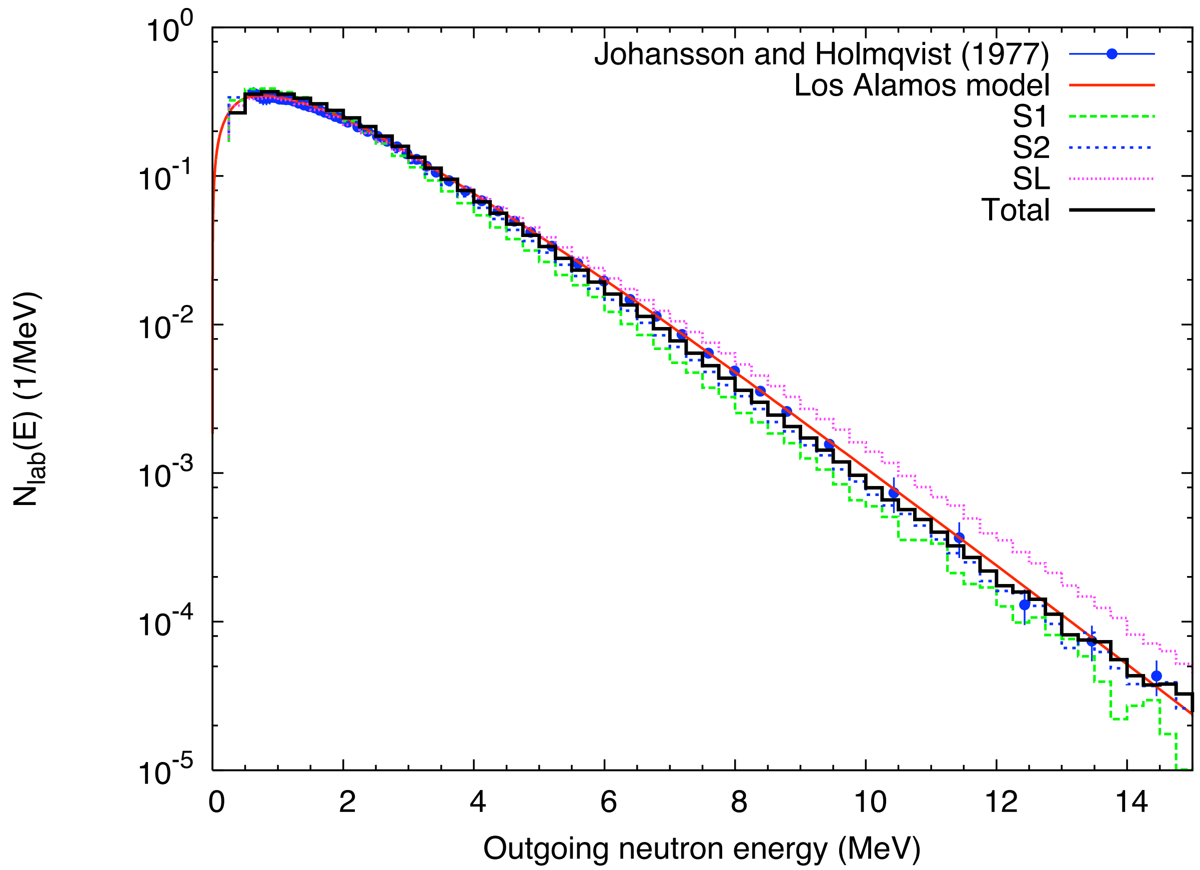
Prompt Fission Neutrons Spectrum... and more!

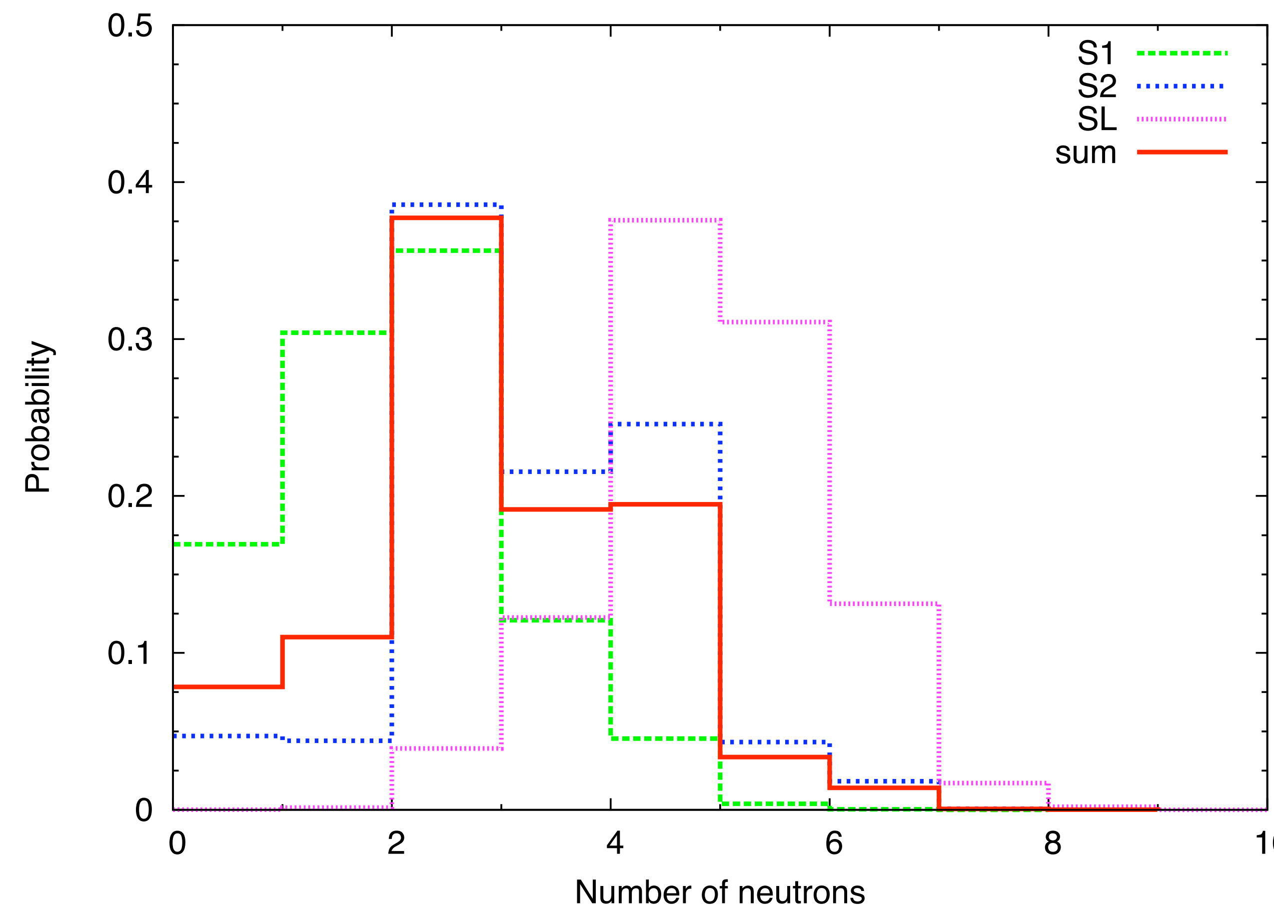


Calculated spectrum slightly too soft in the 6-10 MeV energy region

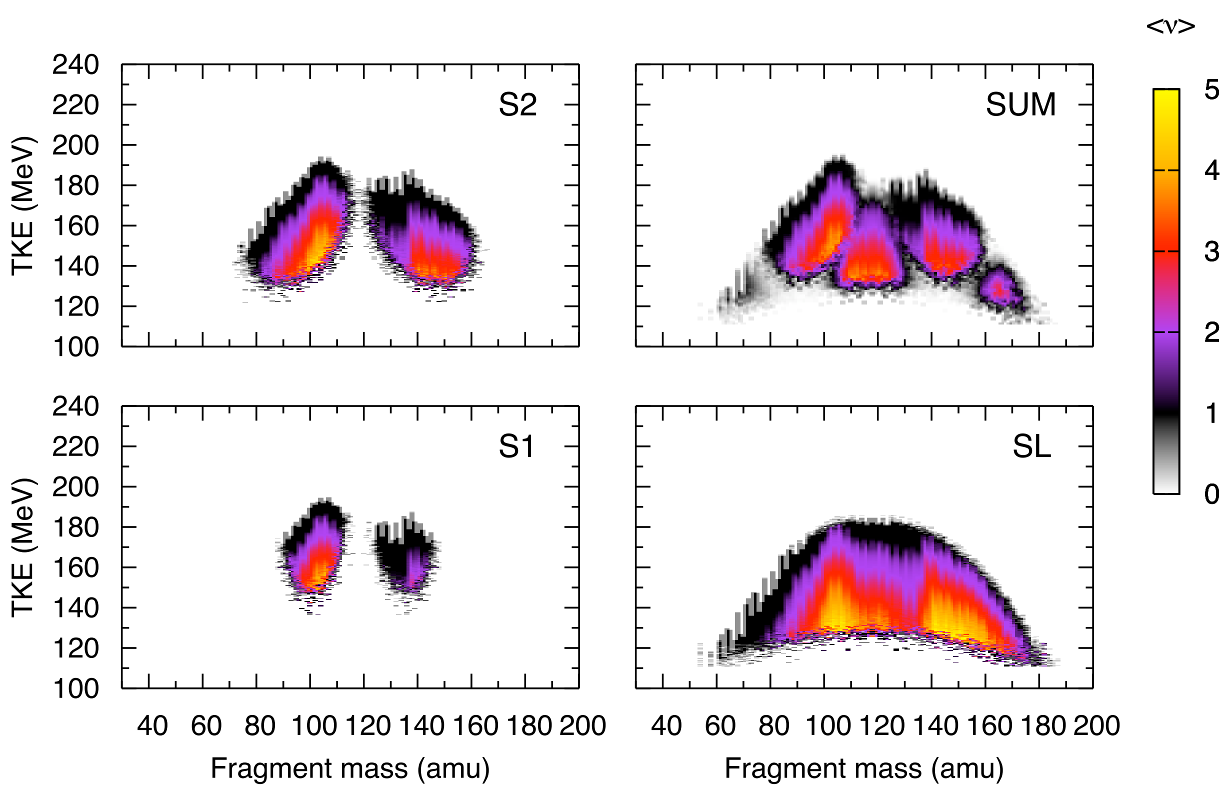
$\langle\nu\rangle_{calc}=2.47$; $\langle\nu_l\rangle_{calc}=1.40$; $\langle\nu_h\rangle_{calc}=1.07$

Müller (1984) $\langle\nu\rangle=2.46$; $\langle\nu_l\rangle=1.44$; $\langle\nu_l\rangle=1.02$
Nishio (1998, n_{th}) $\langle\nu\rangle=2.47$; $\langle\nu_l\rangle=1.42$; $\langle\nu_h\rangle=1.01$

Not only $\langle\nu\rangle$ but also $P(\nu)$!



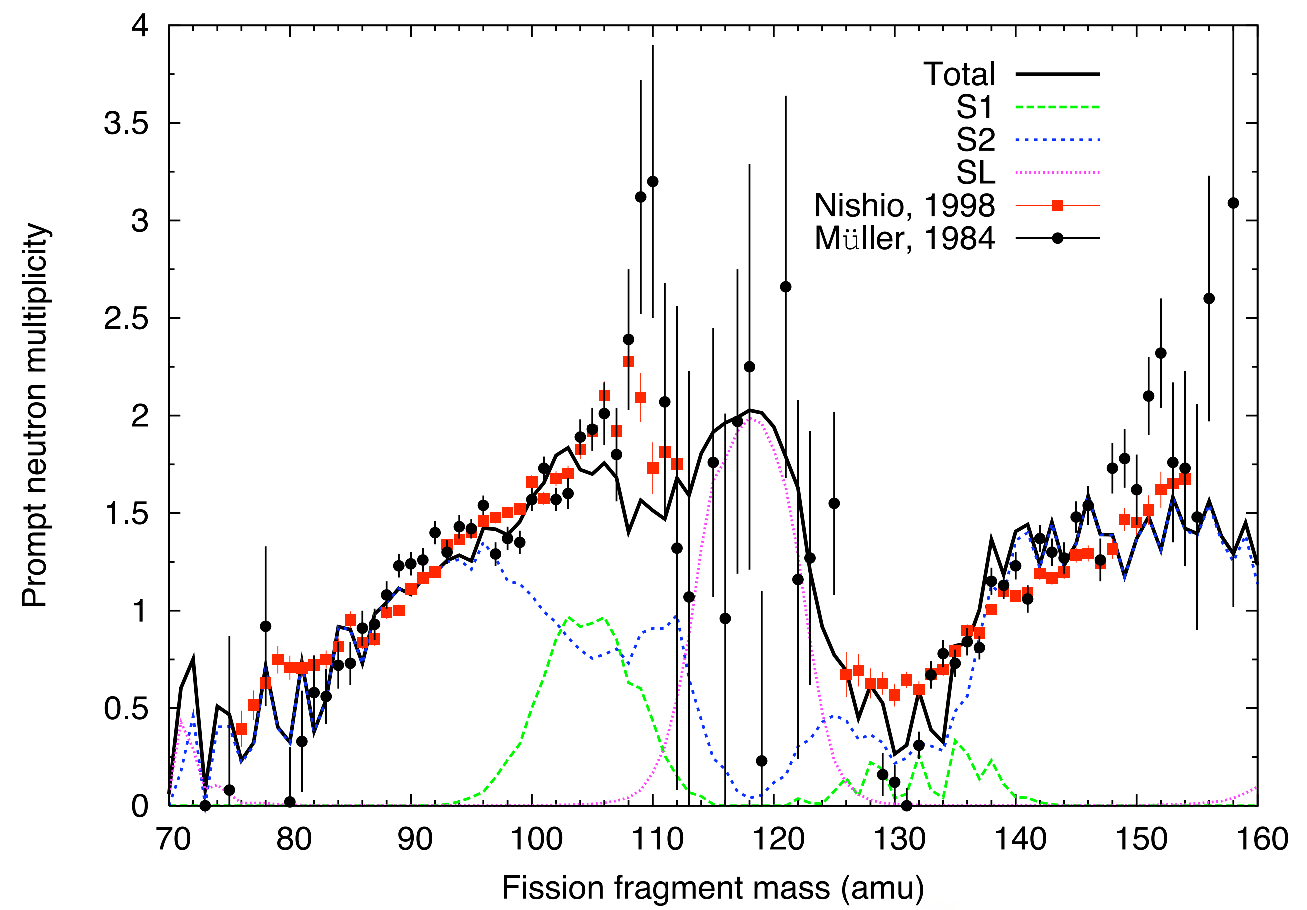
$\langle\nu\rangle$(A,TKE) and $\langle\nu\rangle$ distributions



Complete $\langle\nu\rangle$(A,TKE) distribution results from the competition between different energies:

energy release E_r, total kinetic energy TKE, and Q of the fission reaction

Bump in the symmetric region due to the dominance of the SL mode with a large $\langle\nu\rangle_{SL}$.



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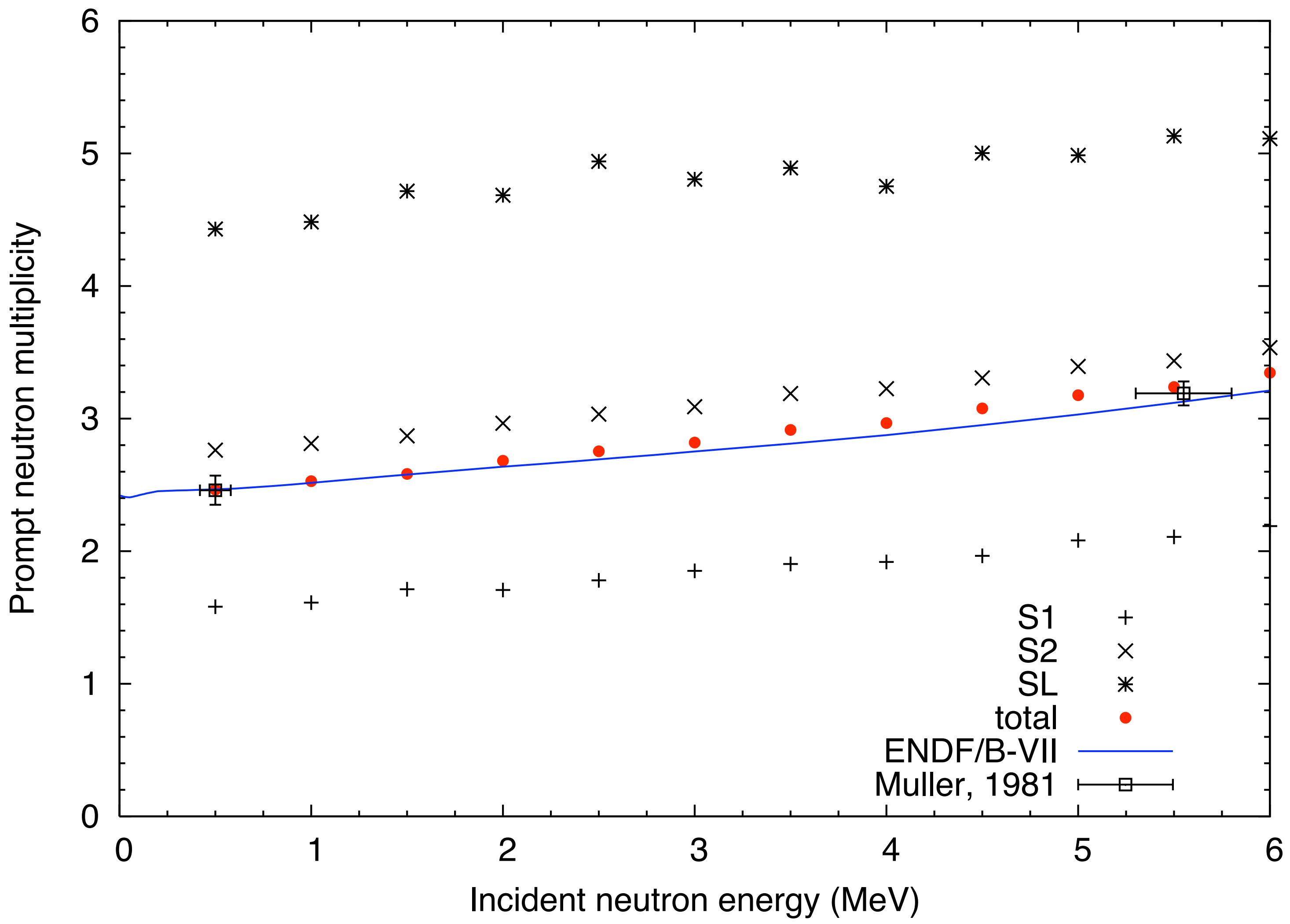
Evolution with incident neutron energy E_{inc}



Weight of symmetric mode (SL) increases with E_{inc}.

Calculated values in very good agreement with ENDF/B-VII up to 2 MeV, and slightly underestimate it above.

In quite good agreement with Müller data (1984) at 0.5 and 5.5 MeV.

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Ongoing & Future work

- Full implementation of Hauser-Feshbach decay calculations by incorporating the spin of the primary fragments
- Skyrme-Hartree-Fock predictions for the fission fragments yields at scission, their deformation, intrinsic excitation energy and spin distribution. (w/ L.Bonneau, CENBG, France).
- Sensitivity of results to model parameters: evaluation of errors on quantities important for applications (e.g., spectrum errors for Gen-IV reactor applications)
- Application to more cases: U, Pu, Cm, Fm... isotopes
- Multiple chance fission, pre-scission neutrons, scission neutrons (?), ...
- ...

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Thanks!

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