Current and future fission research at DANCE

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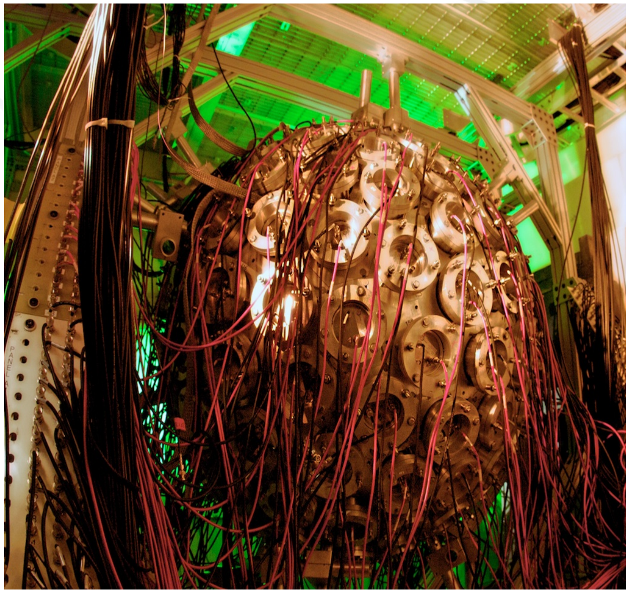
LA-UR-14-27016

Introduction – capture and fission at DANCE

- The Detector for Advanced Neutron Capture Experiments (DANCE) was developed for studies of neutron capture:
  - High precision cross sections
  - Photon strengths and level densities
  - Resonance J^{π} assignments
- Located at the Lujan Center at the LANSCE
- 160 x BaF2 crystals in 4π geometry
- Fast (6ns), high efficiency calorimeter for γ-rays
- Digital DAQ – 324 channels
- Recently, focus on neutron-induced fission:
  - Prompt fission gamma-ray (PFG) studies
  - Correlations between PFG and other fission observables
  - Cross sections



DANCE - 160 x BaF_2 gamma-ray calorimeter

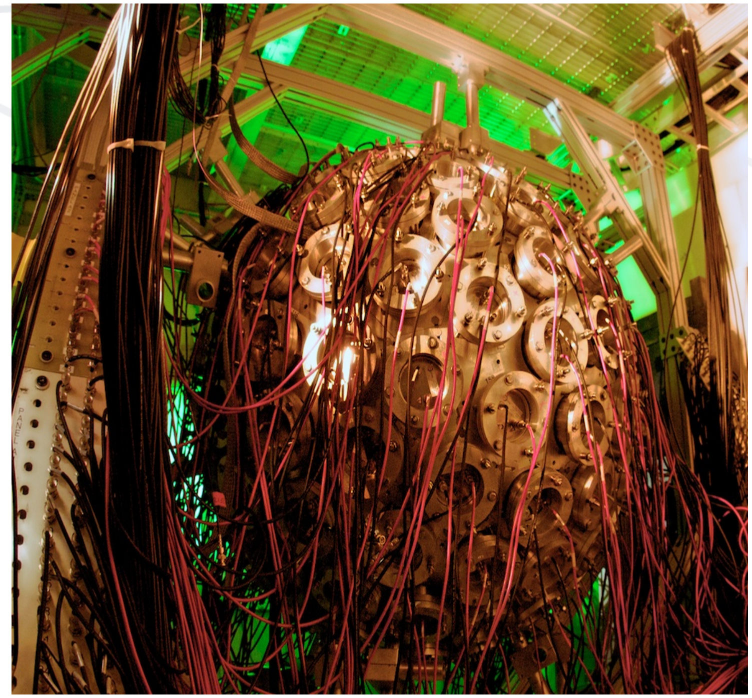
- Neutrons: 800 MeV p+W

- TOF: 20.24 m flight path

- Water moderator

Motivations

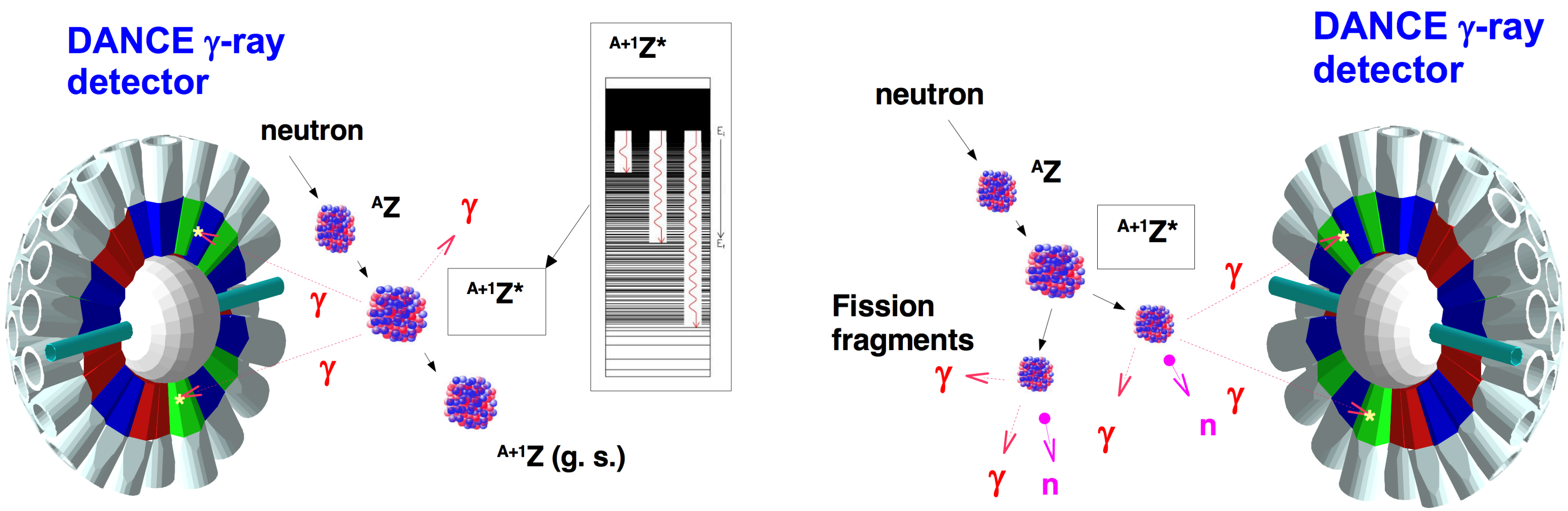
- Basic Nuclear Science
- Applications
- Nuclear Energy
- Stockpile Stewardship
- Non-proliferation
- Nuclear Forensics
- New High Precision Data on NC and NF



DANCE - 160 x BaF_2 gamma-ray calorimeter

Capture and fission on actinides

- Both capture and fission process occur



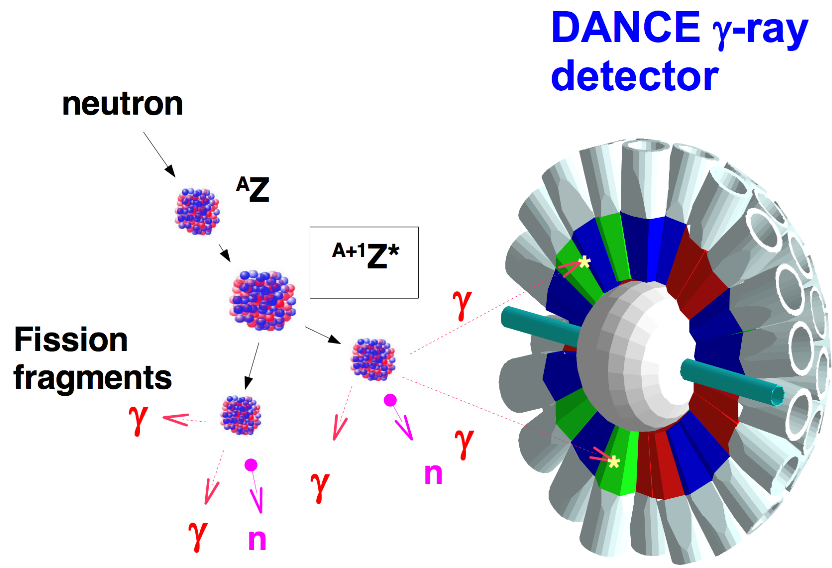
Capture
$\Sigma E\gamma$ = Q (6.35 MeV)
$M\gamma$ = narrow distribution

Fission
$\Sigma E\gamma$ = wide distribution
$M\gamma$ = wide distribution

Capture and fission on actinides

- Fission can be identified using additional fragments detectors

Parallel Plate Avalanche Counter



Fission

$\Sigma E\gamma$ = wide distribution

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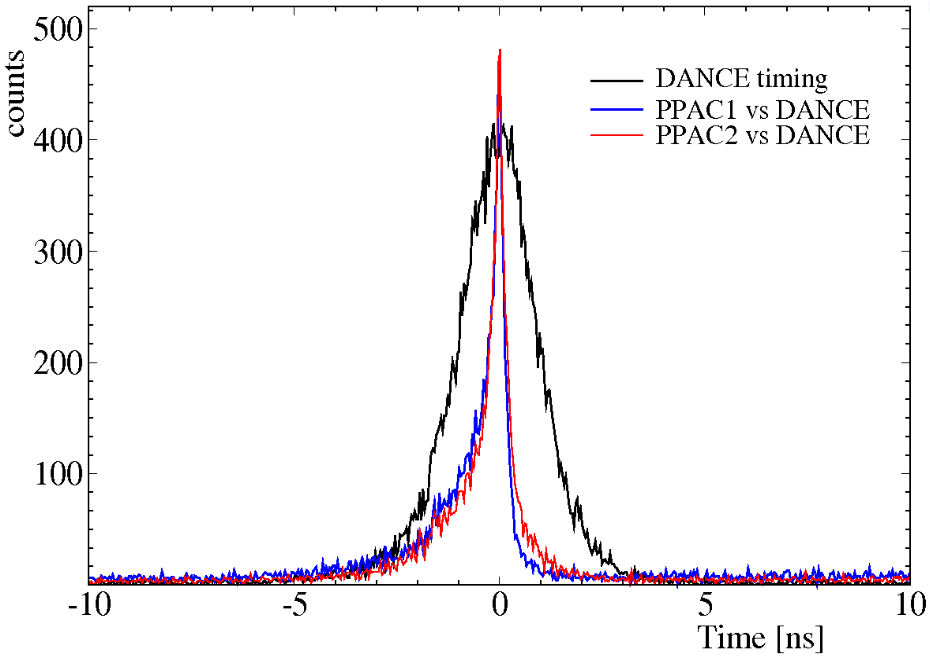
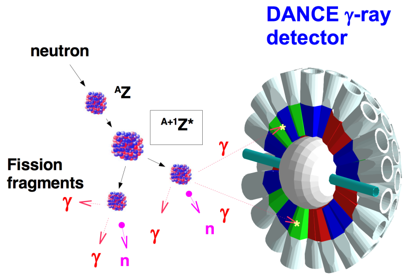




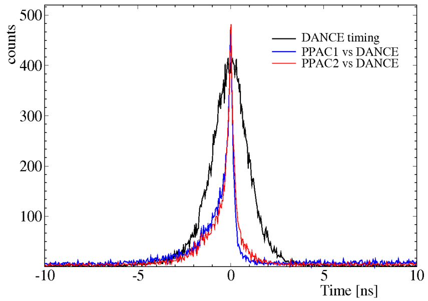
Fission
ΣEγ = wide distribution
Mγ = wide distribution

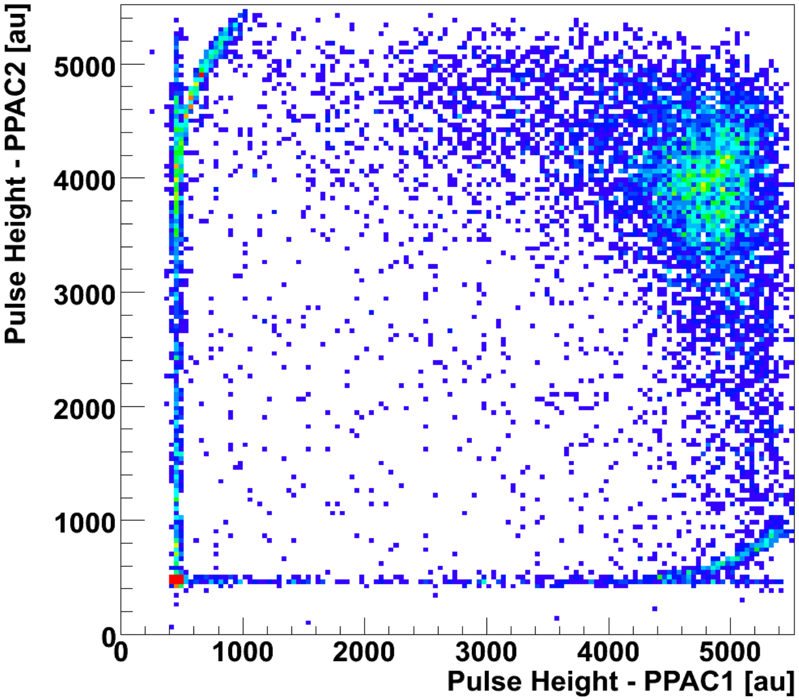
Excellent Timing

Capture and fission on actinides

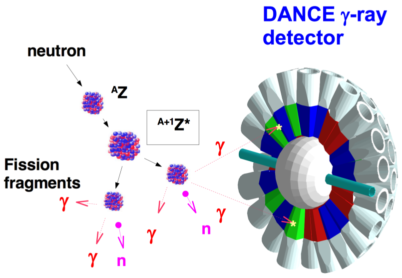
- Fission can be identified using additional fragments detectors

Parallel Plate Avalanche Counter





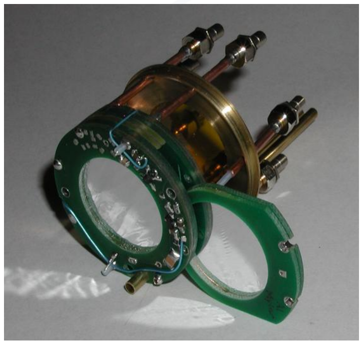
Coincidence between two sides of PPAC removes alpha particles



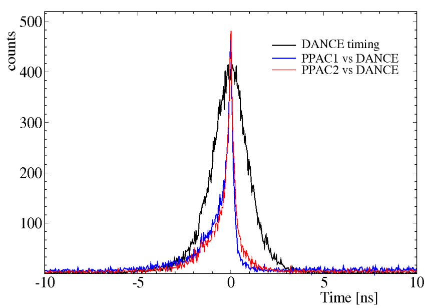
Fission
ΣEγ = wide distribution
Mγ = wide distribution

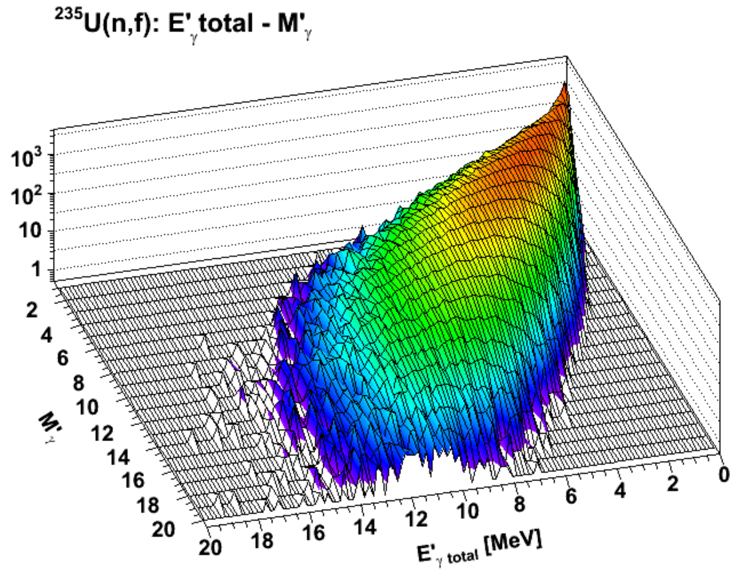
Capture a... ...s

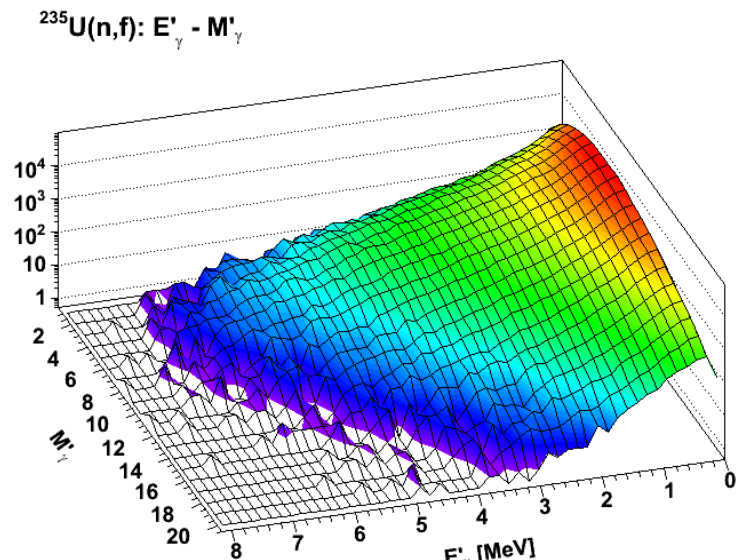
- Fission can be id... ...letectors

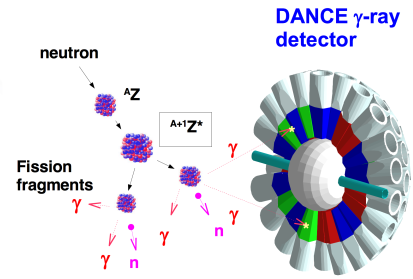


Parallel Plate Avalanche Counter









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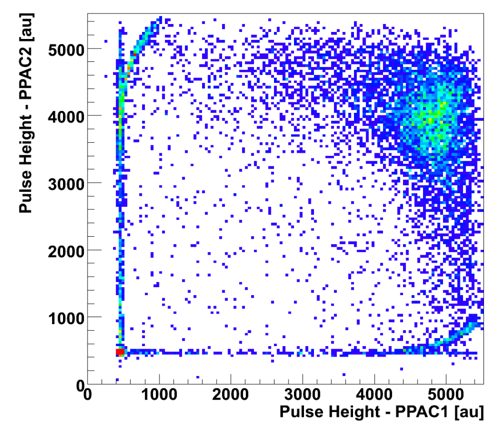


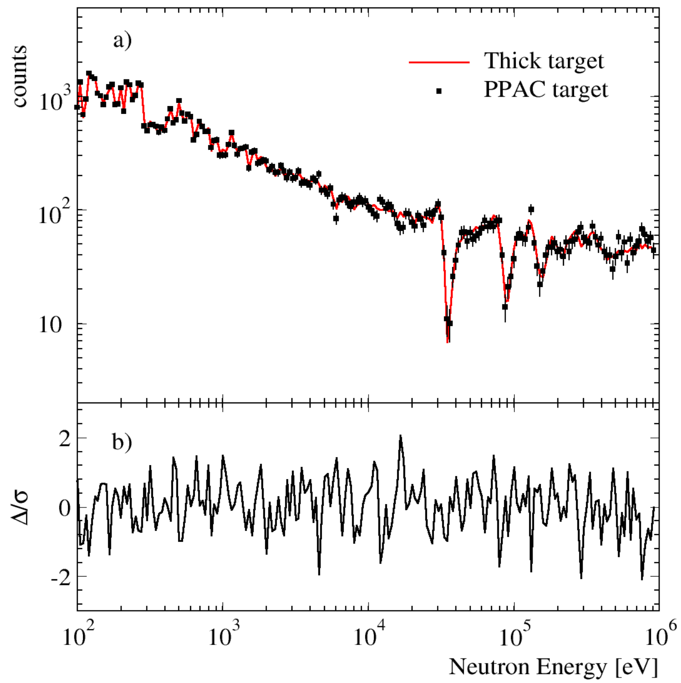
Correlated prompt-fission gamma ray spectra are measured in coicidence with PPAC (<6ns)

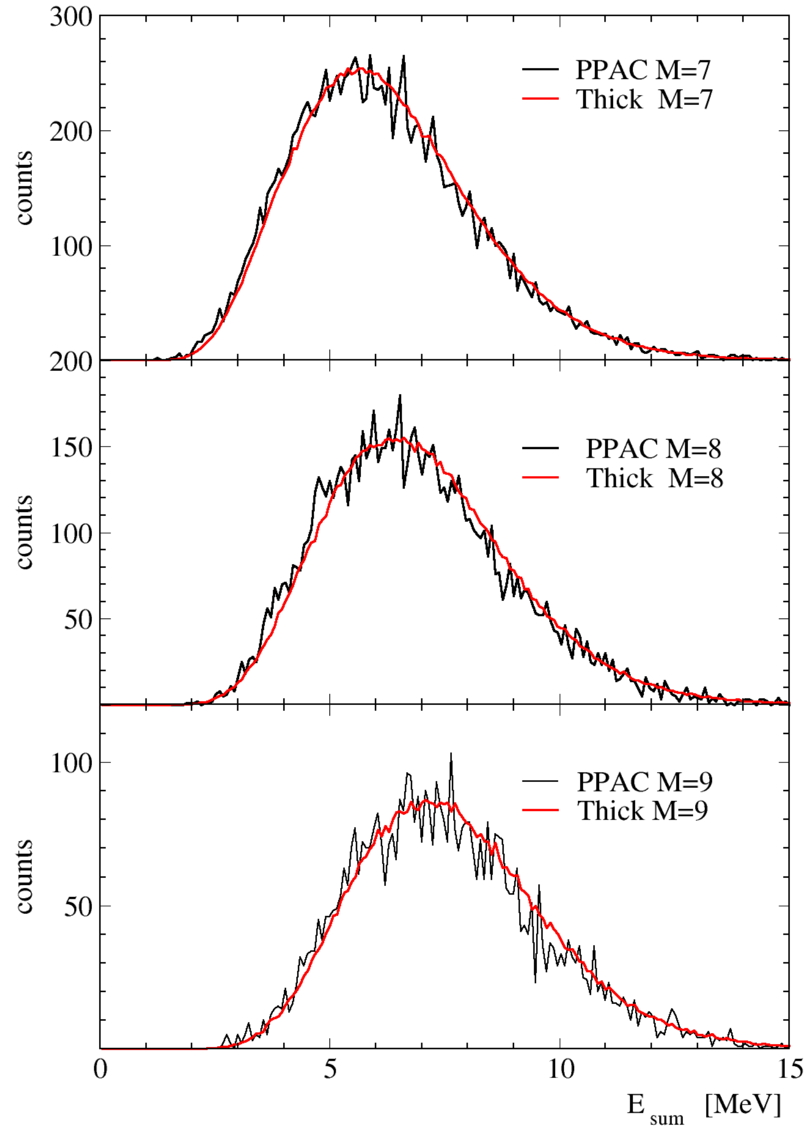
Research Programs

- A) High fidelity neutron capture measurements at DANCE
  – Five year long experimental program: U-234,235,236,238(n,g)
  – Reduce the uncertainties below 3%
  – Funded by DOE, Office of Science, Nuclear Physics
- B) Studies of prompt fission gamma-rays correlations with FF
  – Three years long experimental program: Cf-252, U-235
  – Funded by NA22, Office of Detection and Non-proliferation, DOE
- C) Short-lived Actinide Isomers - NEUANCE
  – Three year long, major R&D program
  – New capability at DANCE – 4π neutron detection
  – Funded by LDRD/DR (LANL), DOE

Capture XS: high precision U235 and Pu239

- PFG spectra obtained using PPAC tagging
- Very good understanding of PFG(Mγ)
- Thin/thick target comparisons – enabled high precision cross sections on U-235 and Pu-239





Capture XS: high precision U235 and Pu239

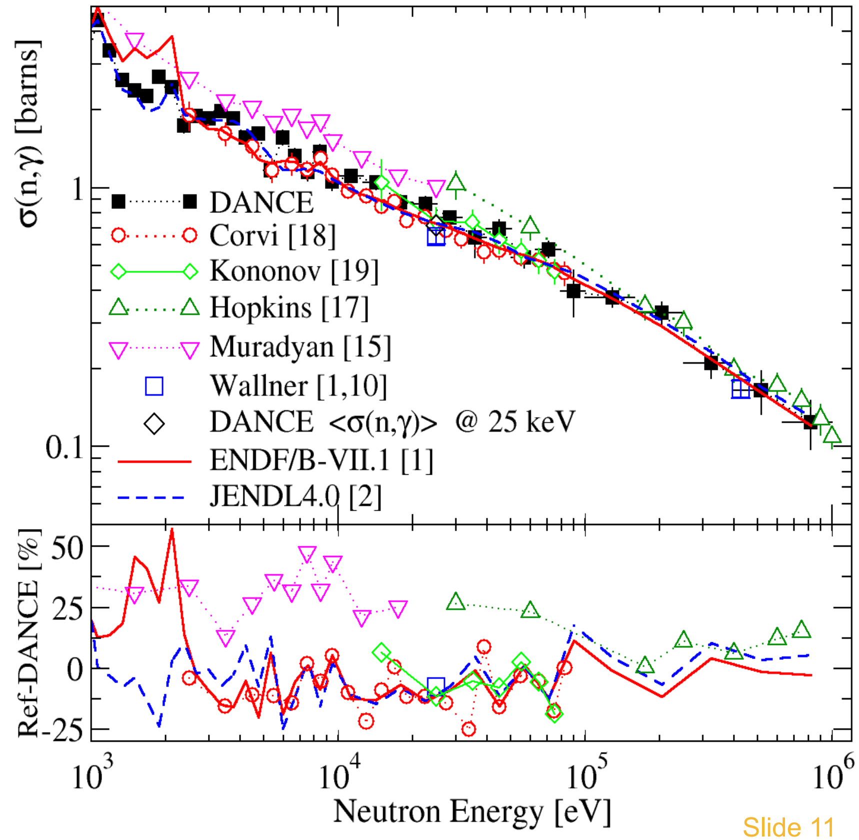
- Ratio method developed for $^{235}U(n,\gamma)$
- Precision <3% was achieved using simultaneous rate determination;
  - Rates of $^{235}U(n,\gamma)$ and $^{235}U(n,f)$
  - The same target → same neutron flux for both reactions
  - Parallel Plate Avalanche Counter for (n,f)

$$\sigma\left({}^{235}U_{n,g}\right) \propto \frac{R\left({}^{235}U_{ng}\right)}{R\left({}^{235}U_{nf}\right)} \sigma\left({}^{235}U_{n,f}\right)$$

M. Jandel et al., Phys Rev Lett 109, (2012)

- Successfully implemented for ^{239}Pu

S. Mosby et al., PRC 89, 034610



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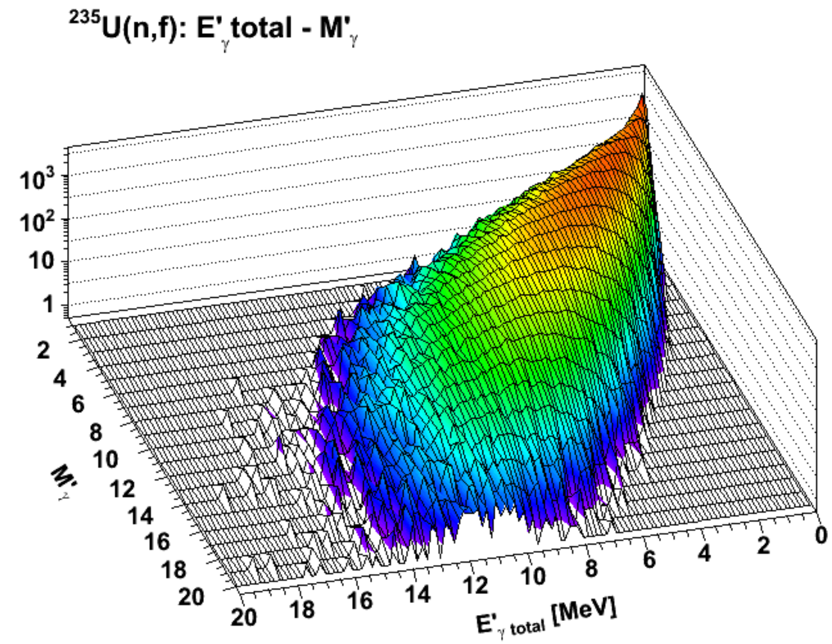
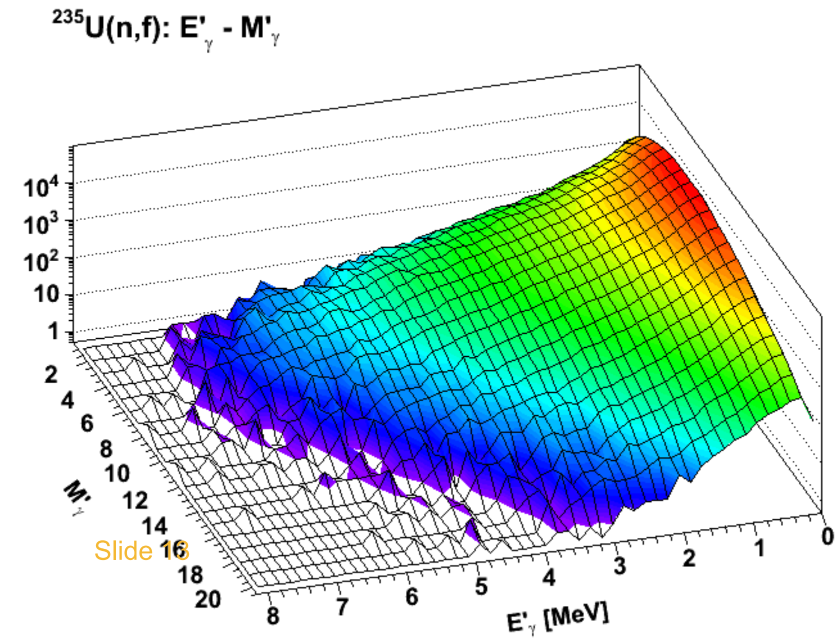
DANCE – efficient gamma-ray calorimeter

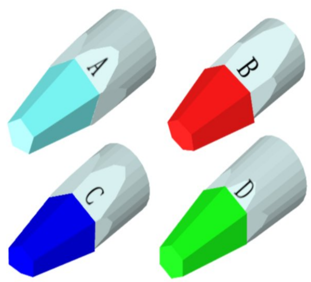
- With high efficiency and 4π solid angle DANCE is ideal for prompt-fission gamma-rays studies
- We measure correlated events of $M\gamma$, $E\gamma$ and $E_{\gamma tot}$
- Complicated analysis – how to obtain original spectra of PFG ?
- Cross talk, and pileup is an issue
- One needs a very precise model of the DANCE array
- Inverse method
- Forward method

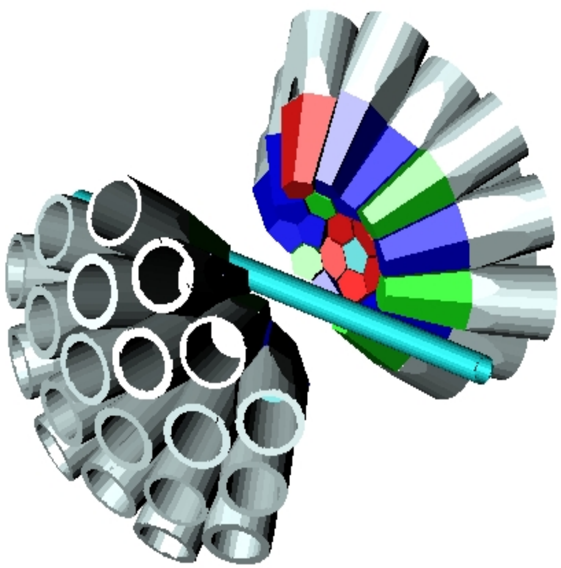


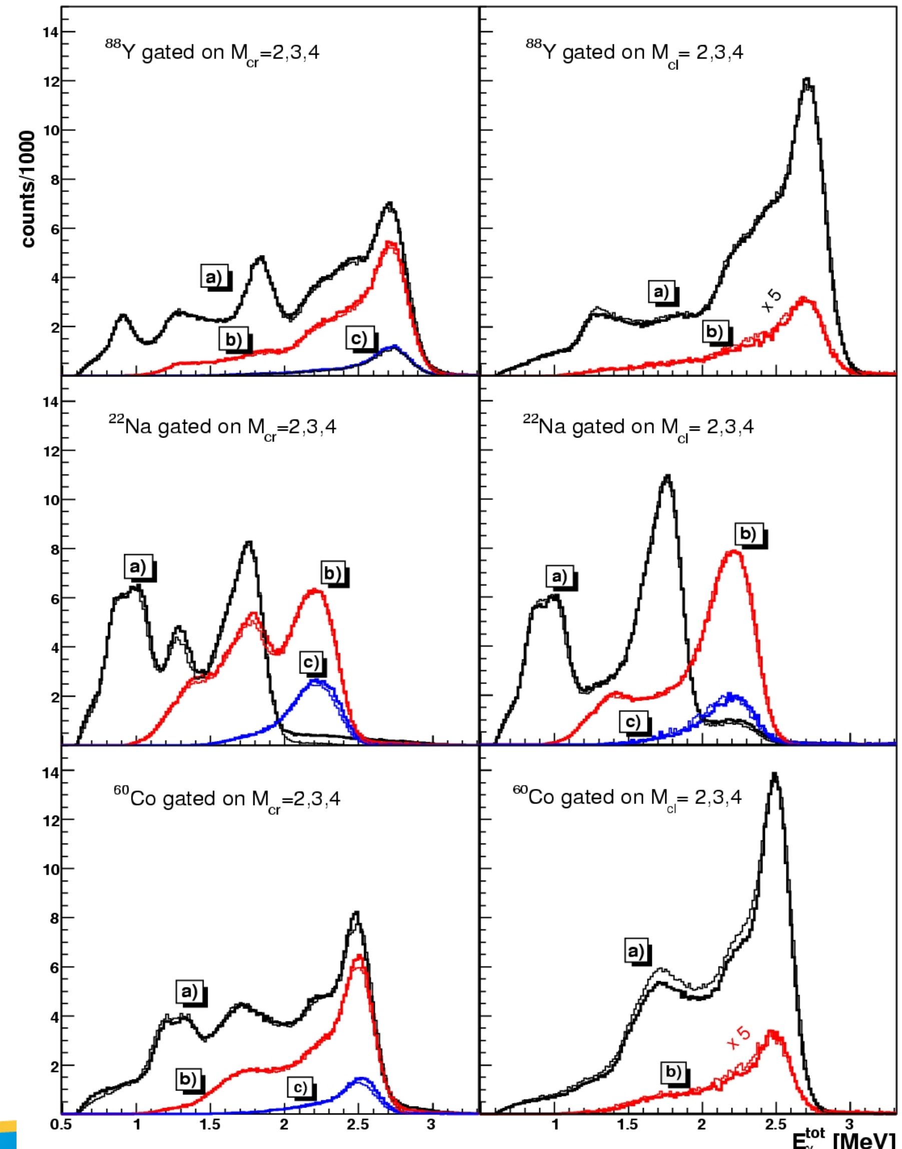


DANCE – Geant4 detector response

- Total γ-ray energy spectra gated on cluster and crystal multiplicity
  - Experiment (thick lines)
  - GEANT4 (thin lines)
  - M=2 (black)
  - M=3 (red)
  - M=4 (blue)
- ^{88}Y, ^{22}Na, ^{60}Co

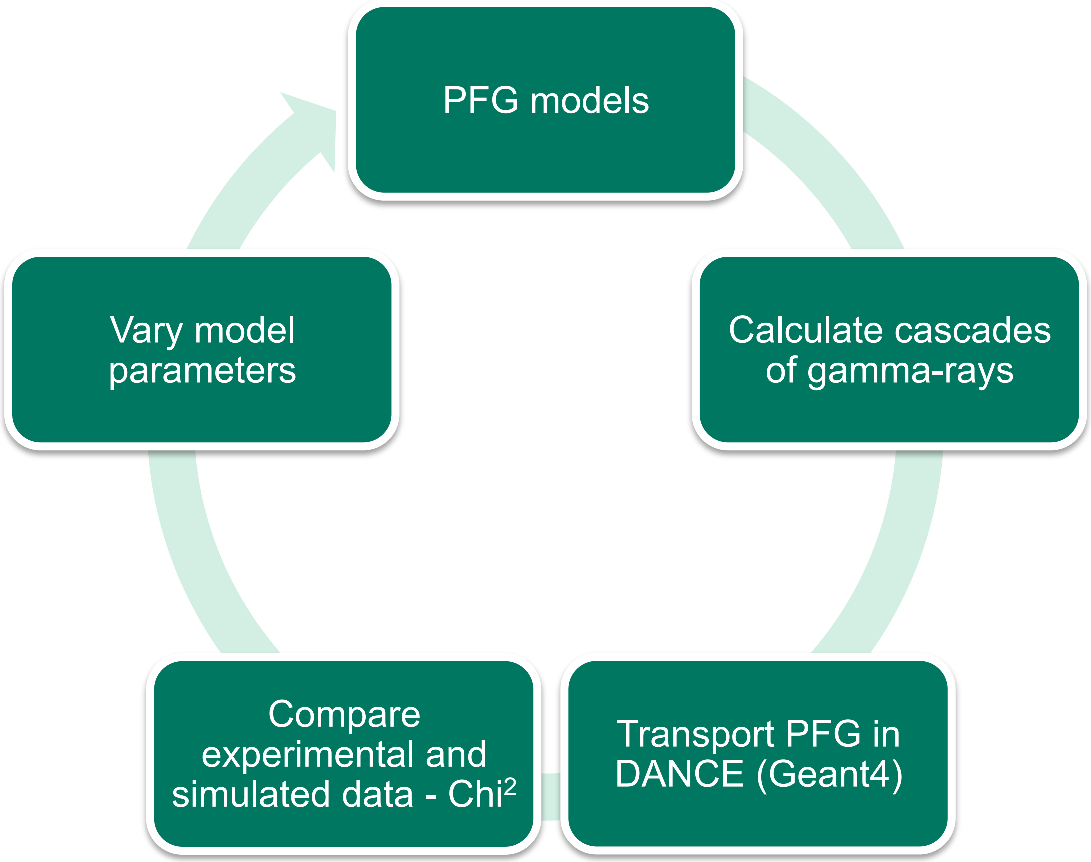






Deducing the real PFG emission properties including correlations

- Forward methods
- Models + Geant4 (event by event)
- Model PM – simple Monte Carlo PFG event generator
  - two pdf's for PFG multiplicity and $E_\gamma(M_\gamma)$
  - six free parameters
  - see J. Ullmann talk
- Detailed Statistical Model:
  - Monte Carlo model of fission (Stetcu, Talou)
  - Hauser-Feschbach evaporation of neutrons and PFG (CGM code, T. Kawano)
  - see I. Stetcu talk



Deducing the real PFG emission properties including correlations

- **Two component spectrum**
- Developed a parameterized model for γ-ray emission using Monte Carlo sampling and following pdfs – 6 free parameters :
  - PFG multiplicity
  - PFG energy from detailed balance +
  - Boltzmann approximation:

$$p(E_\gamma) = \frac{dN_\gamma}{dE} \propto E_\gamma^2 \sigma_\gamma(E_\gamma) \frac{\rho(E^*_{ini})}{\rho(E^*_{fin})},$$

$$\frac{\rho(E^*_{ini})}{\rho(E^*_{fin})} = e^{-E_\gamma/T},$$

$$\sigma_\gamma(E_\gamma) \propto \frac{(\Gamma_D E)^2}{(E_\gamma^2 - E_0^2)^2 + (\Gamma_D E_\gamma)^2},$$

$$p(M_{1,2}) = (2M_{1,2}+1)\, e^{-M_{1,2}(M_{1,2}+1)/2c_{1,2}^2}$$

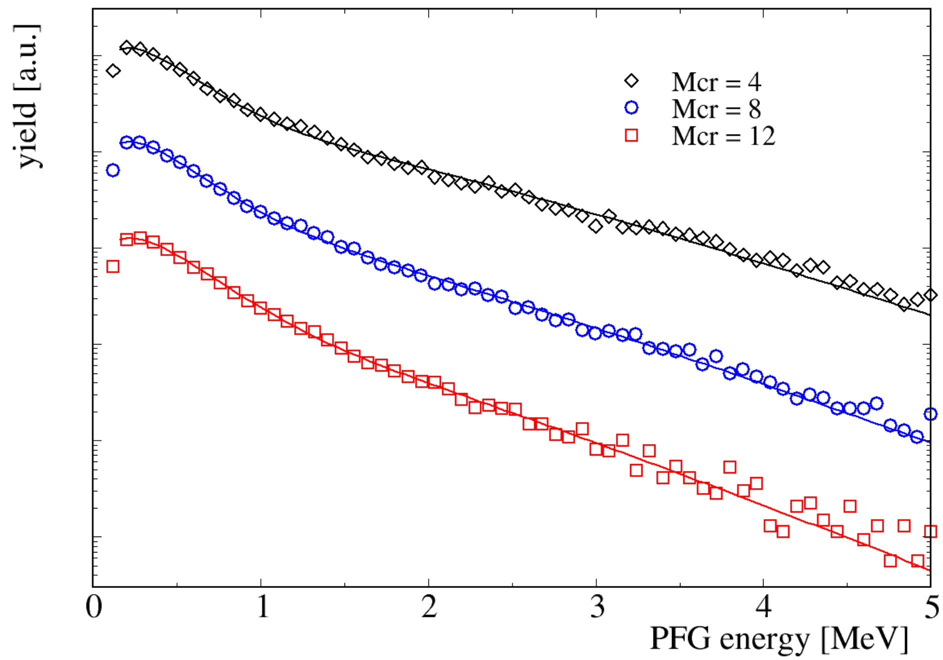
$$p_1(E_\gamma) \propto E_\gamma^2 e^{-t_1 E_\gamma}$$

$$p_2(E_\gamma) \propto E_\gamma^3 e^{-t_2 E_\gamma}$$

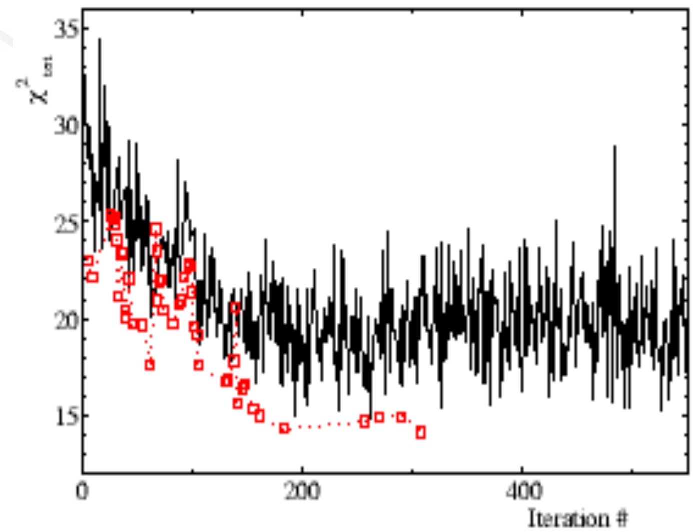
$$M_\gamma = M_1 + M_2$$

$$t_{1,2} = a_{1,2} + b_{1,2} M_\gamma$$

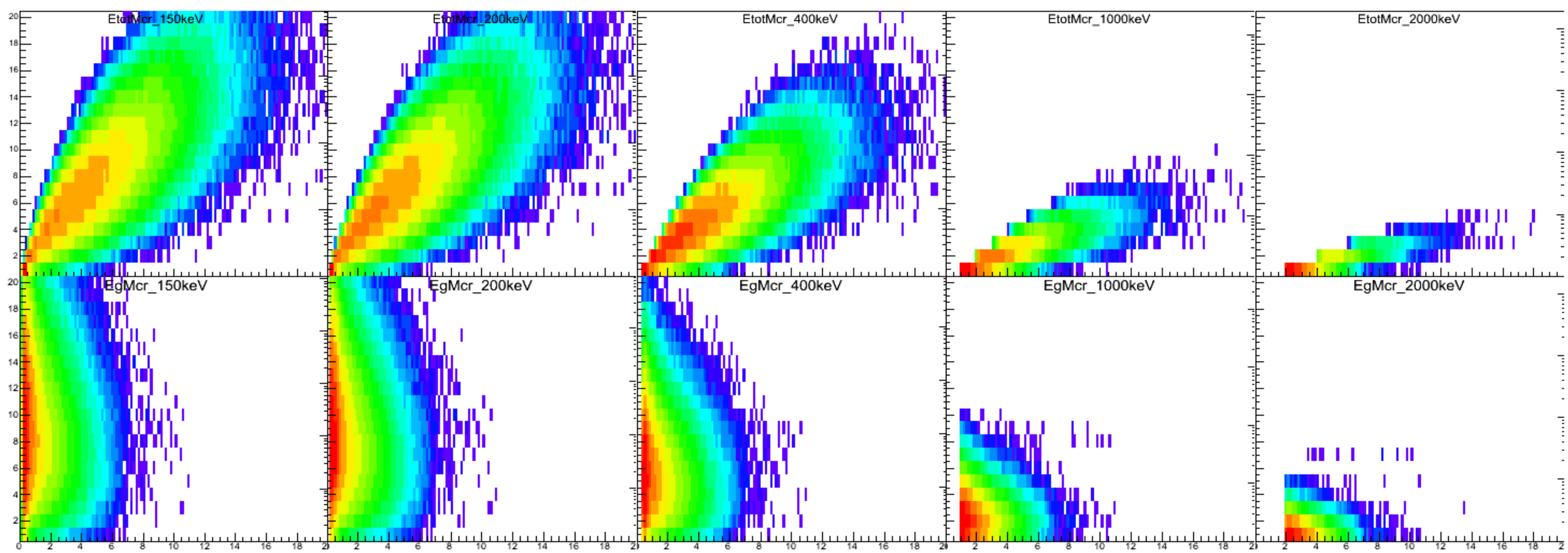
6 free parameters : $a_{1,2}, b_{1,2}, c_{1,2}$



Deducing the real PFG emission properties including correlations



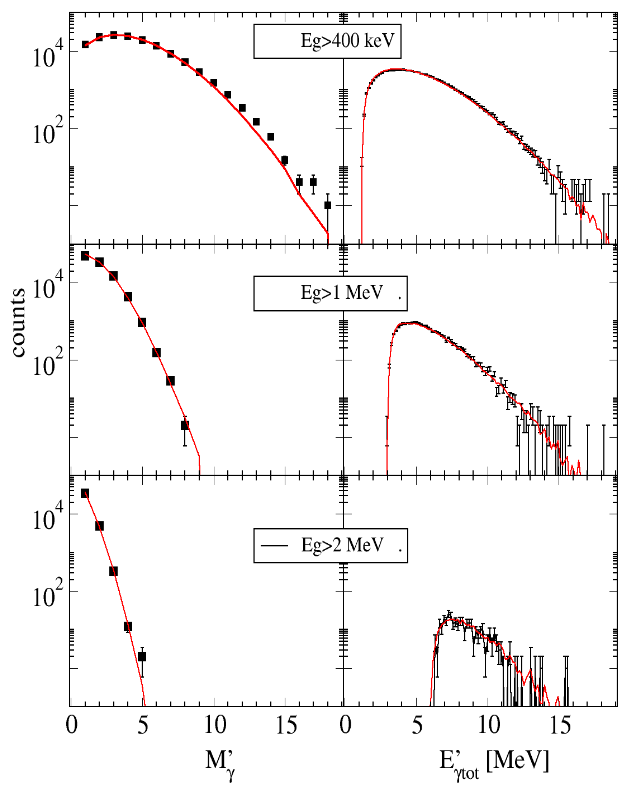
- Simulated annealing used to fit 6 parameters to data
- Energy of the system calculated from metric: $E = \Sigma\, \chi^2$
- $\Sigma\, \chi^2$: 125 x 20 x 2 x 4 = experimental values compared to simulated
- Experimental data are normalized to number of fission triggers
- Step accepted depending on the change in energy of the system
  - dE>0 accept if y<exp(-dE/T)
  - dE<0 accept
- T_0 determined from the first step

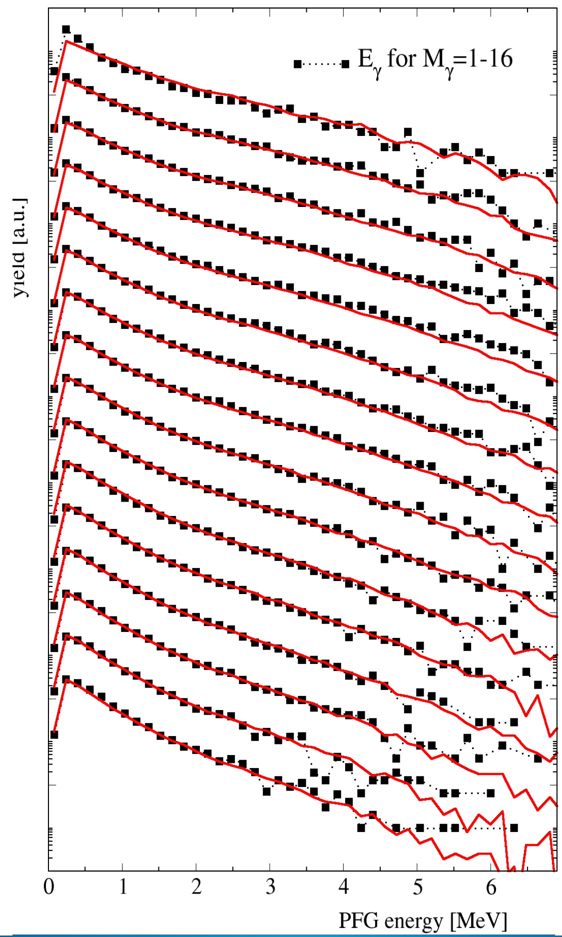


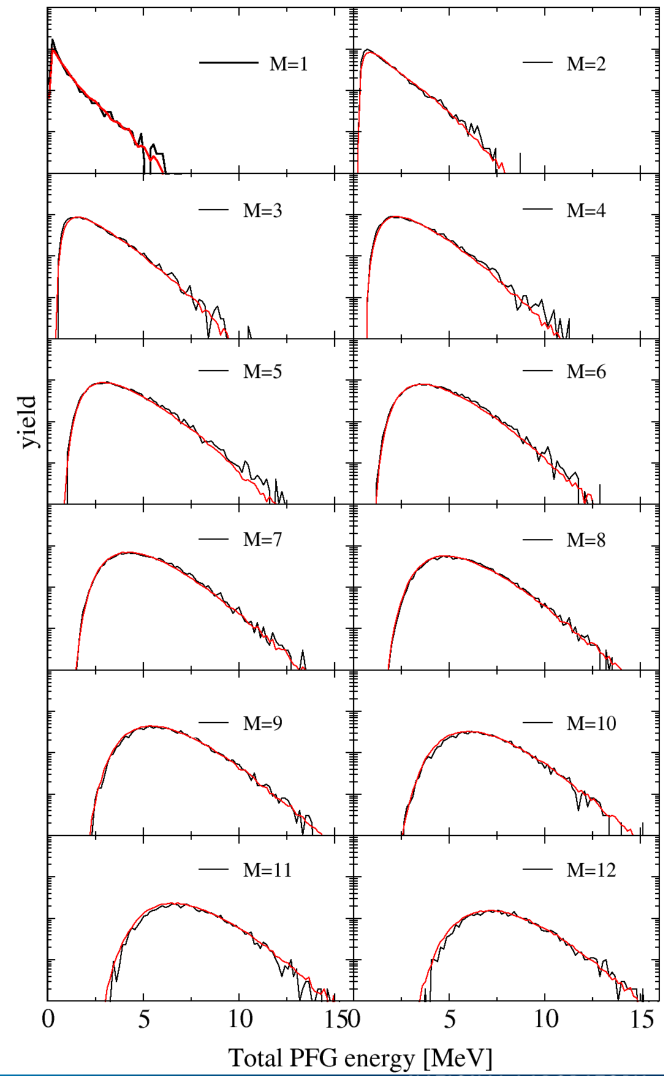
Deduced PFG for U-235(n,f)

M. Jandel et al., to be published in Physics Procedia, conf. proceedings of GAMMA-2, Sremski Karlovci, Serbia, 2013

- Excellent agreement obtained using PM
- Only 1 normalization constant and many differential spectra are reproduced !!







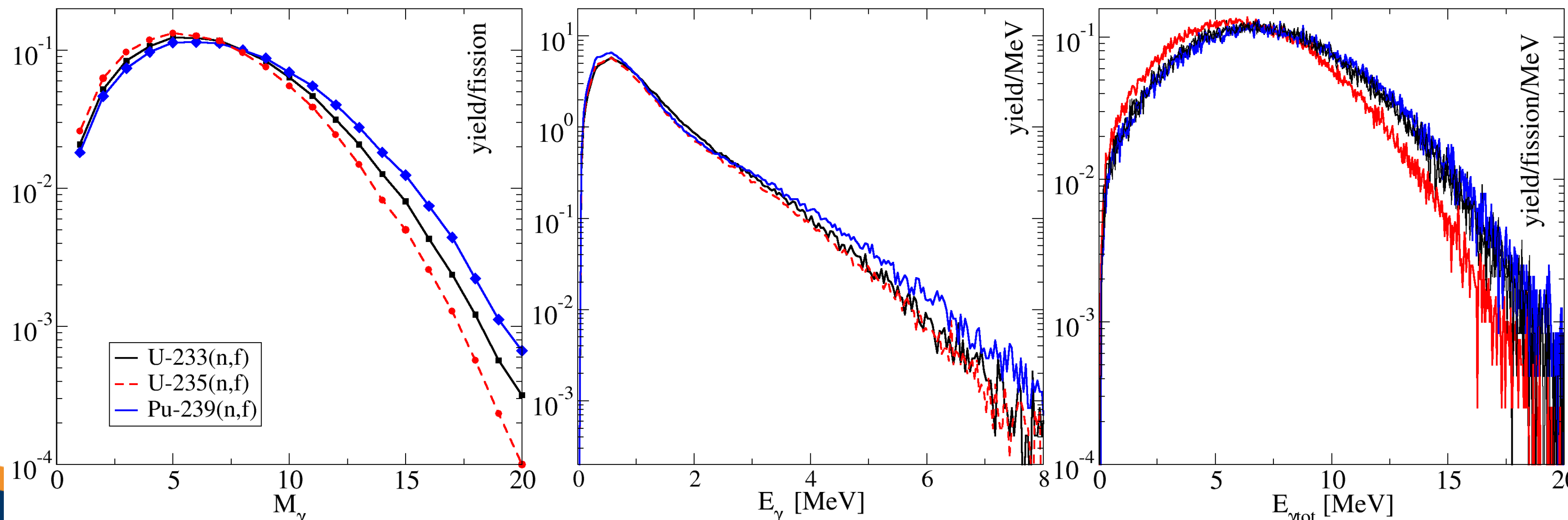
Deduced PFG for U-235(n,f)

- Excellent agreement obtained using PM
- Correlation between Eg, Mg

M. Jandel et al., to be published in Physics Procedia, conf. proceedings of GAMMA-2, Sremski Karlovci, Serbia, 2013

	Mg	sig	Eg	sig	Eg,tot	sig
^{235}U	6.31	3.02	1.025	0.8100	6.480	3.0700
^{233}U	6.76	3.15	1.077	0.8300	7.240	3.3200
^{239}Pu	7.21	3.42	1.036	0.8800	7.430	3.4300
^{242m}Am	7.14(5)	3.45(4)	0.999(5)	0.88(1)	7.13(6)	3.32(3)
^{252}Cf	8.11(7)	3.77(4)	0.891(9)	0.807(9)	7.22(6)	3.33(3)

	c_1	c_2	a_1	b_1	a_2	b_2
^{235}U	6.2	2.06	3.610	0.0453	1.620	0.0458
^{233}U	6.53	2.22	3.376	0.0449	1.575	0.0461
^{239}Pu	7.11	2.14	3.618	0.0454	1.403	0.0438
^{242m}Am	7.17(5)	2.02(2)	3.80(3)	0.0467(3)	1.371(5)	0.0450(7)
^{252}Cf	7.73(8)	2.57(3)	5.03(6)	0.0098(2)	1.65(2)	0.0406(7)



Deduced PFG for U-235(n,f) – a comment on inverse method solutions

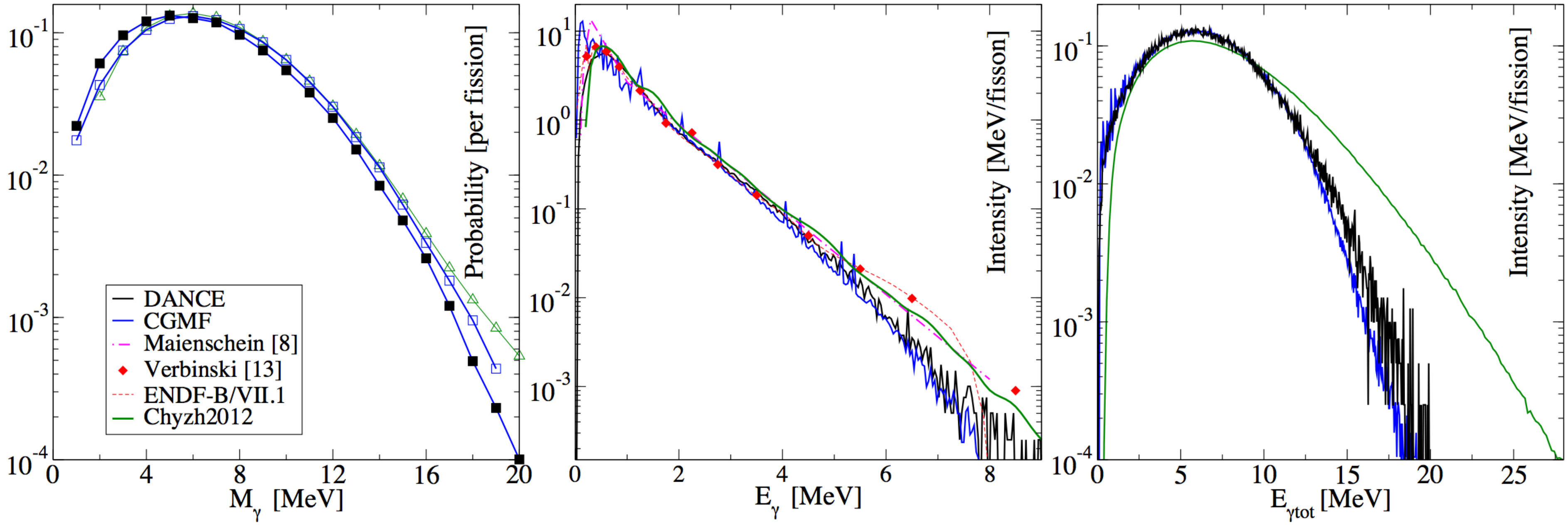


FIG. 17. Properties of PFG emission in neutron induced fission of U-235 deduced from DANCE experimental data using parametrized PM and CGMF models, respectively. Multiplicity M_γ, energy E_γ and total energy $E_{\gamma tot}$ distributions are shown from left to right, respectively. Black full symbols and lines show results deduced by the optimization procedure of parametrized model described in Section III A. Blue empty squares and lines show results of detailed fission modeling using CGMF model described in III B with α_I=1.3. Data on E_γ from [13] and [8, 14] are shown using red markers and magenta dashed-dotted line, respectively.

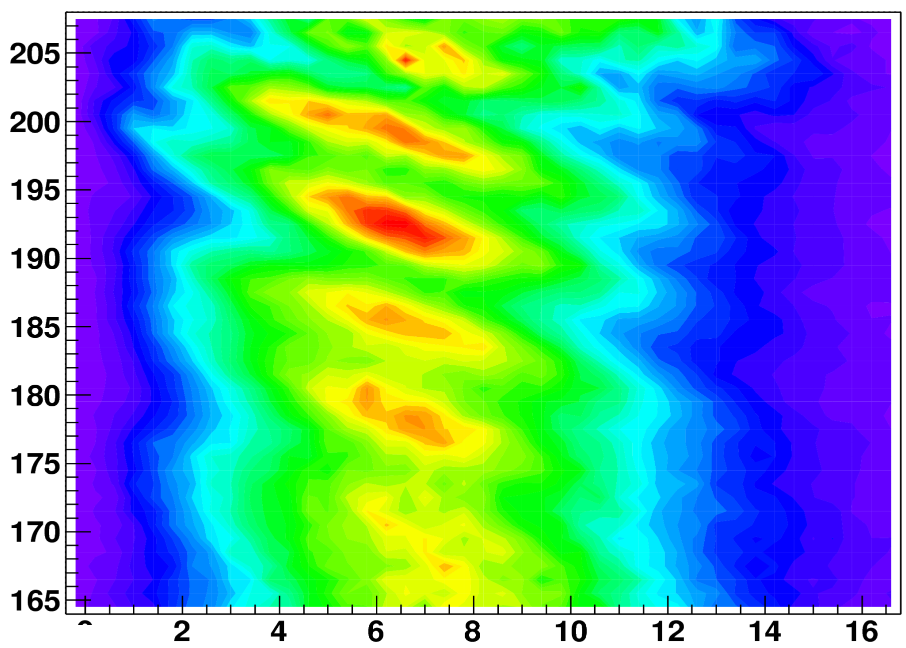
1D deconvolution - A. Chyzh et al., Phys. Rev. C **87**, 034620
!! If spectral intensity does not change with Mg – total energy is not reproduced well !!

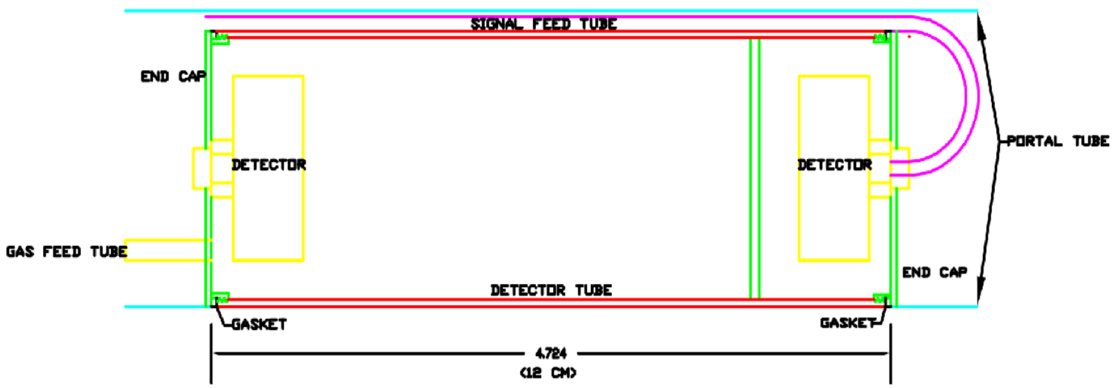
DANCE – efficient gamma-ray calorimeter

- Benchmarking the evaporation and fission codes – CGM(F) (P. Talou, I. Stetcu, T. Kawano)
- Tuning parameters of fission modeling in CGMF
  - Spin distributions
    - *I. Stetcu, T. Kawano, P. Talou, M. Jandel, Phys. Rev. C 90, 024617*
    - *I. Stetcu, T. Kawano, P. Talou, M. Jandel, Phys. Rev. C 88, 044603*
  - Averages and variances of PFG distributions
- Improving transport codes
- MCNP6 development – de-excitation modules (gamma/neutrons in correlation)

DANCE – FF + PFG measurements

- Next step – adding measurements of kinetic energies and masses of fission fragments with PFG
- We will use 2 Si detectors for Cf-252 FF measurement at DANCE (next week)
- Benchmarking the evaporation and fission codes – CGMF (P. Talou, I. Stetcu, T. Kawano)
- MCNP6 development – de-excitation modules (gamma/neutrons in correlation)





Al can designed for two Si detectors. (by postdoc C. Walker)

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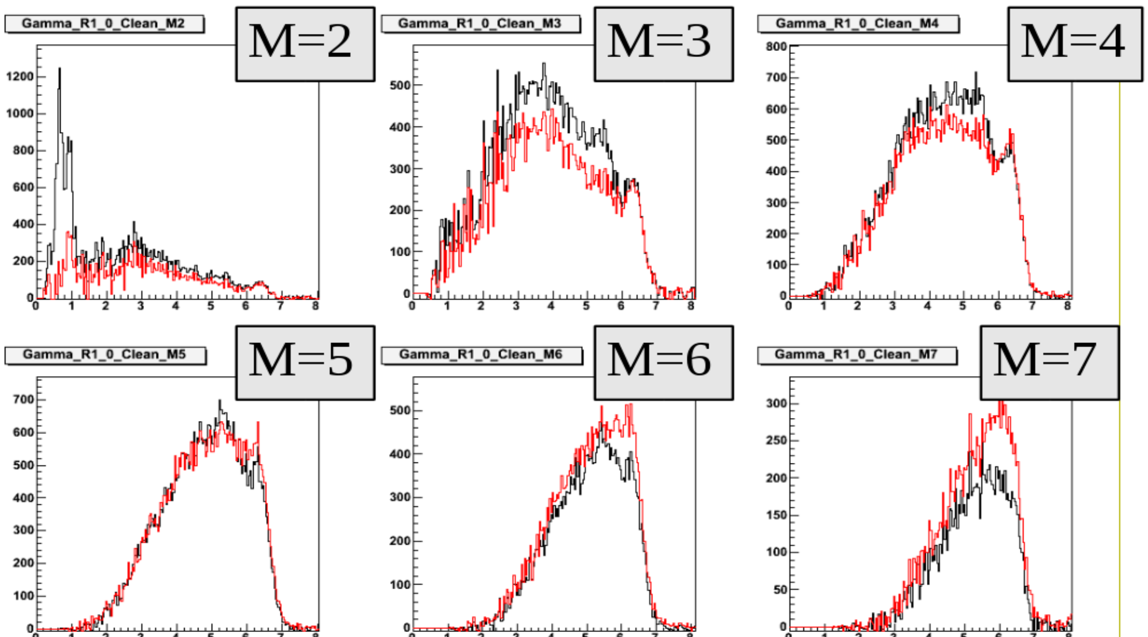
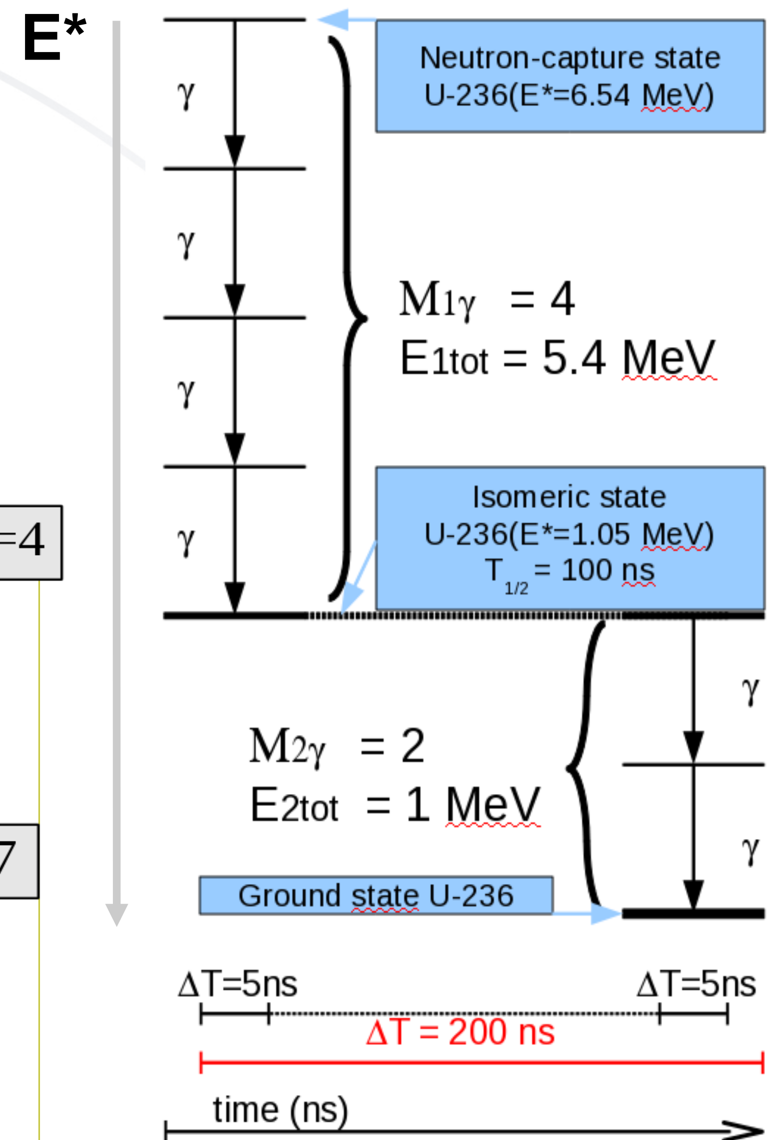
Isomeric states after U235+n

- During analysis of ^{235}U(n,γ) cross section we have found structure in the total gamma-ray energy E_{tot} spectra

M. Jandel et al., Phys Rev Lett 109, (2012)

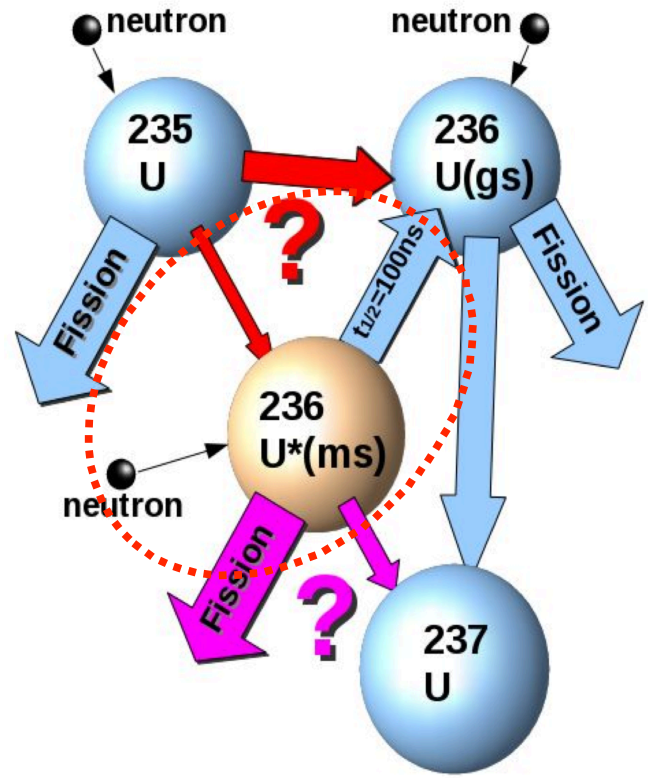
- E_{tot} variations with ΔT and number of gamma-rays detected in a ΔT window





Isomeric states after U235+n

- In high neutron fluence the secondary reactions can occur
- $^{236}U^*$: 1024 keV (4-) $T_{1/2}$ = 100 ns
- $^{236}U^*$: 678 keV (1-) $T_{1/2}$ = 3.7 ns



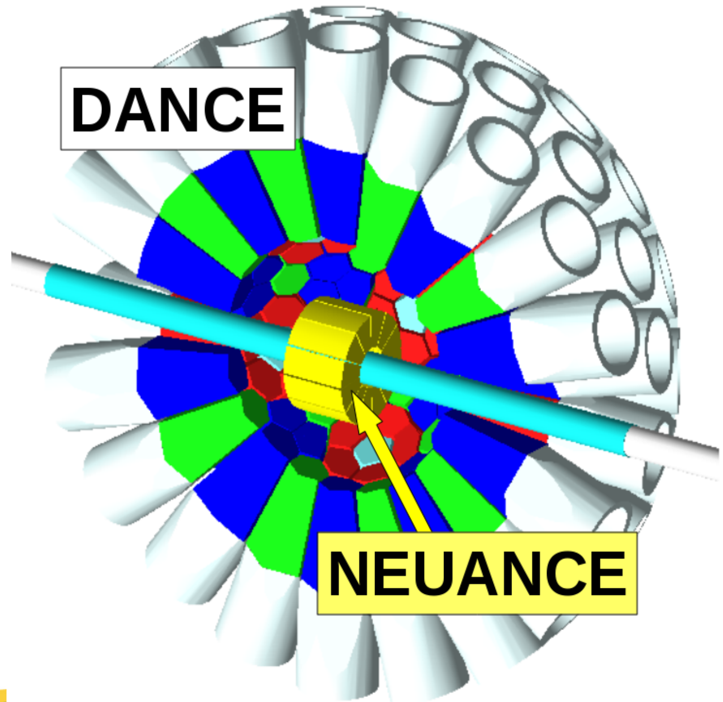
- What is the population of these states after ^{235}U+n ?
- What are the n-reaction cross sections on these states ?

NEUANCE - NEUtron Array at daNCE

- We need to improve counting statistics on fission and capture of U235
- For all gamma multiplicities !
- This is very difficult with FF detectors because of thin targets

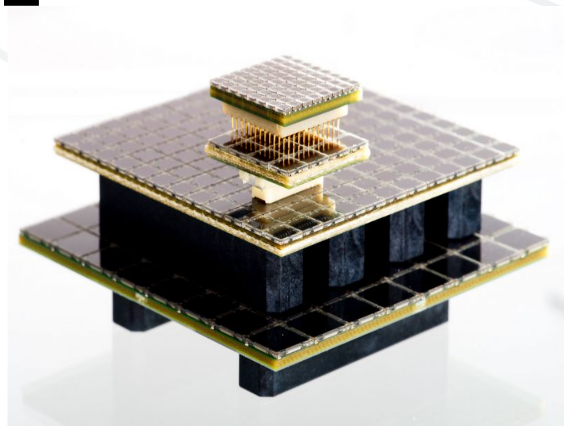
- What is the population of these states after ^{235}U+n ?

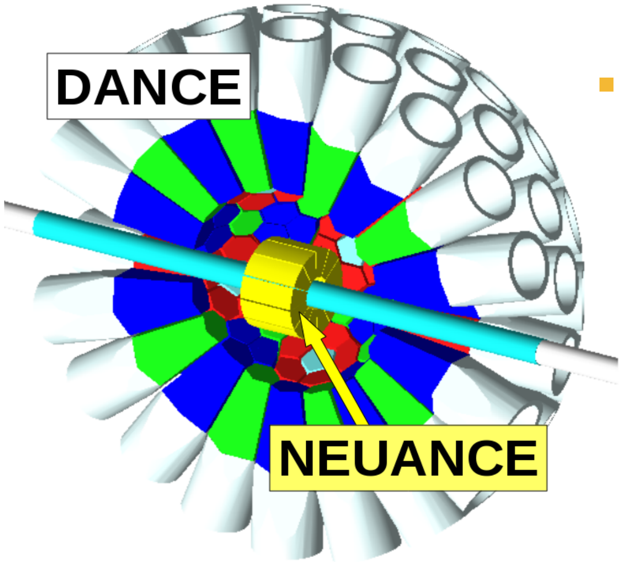
- NEUANCE: 8-12 segments of liquid scintillators in the center of DANCE
- NEUANCE will be sensitive only to neutrons above 200 keV --> only from fission



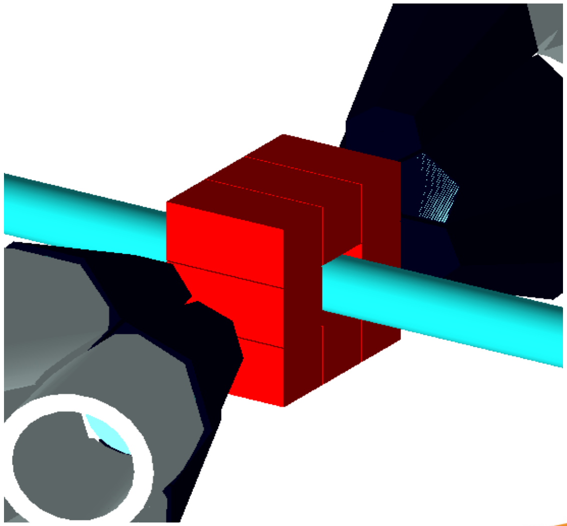
NEUANCE - NEUtron Array at daNCE

- Challanges in NEUANCE design
  - Small cavity (17 cm diameter) - need small PMTs or alternative SiPM
  - Loss of 6LiH shell - larger backgrounds
  - Close geometry - pileups, pulse shape discrimination efficiency





- NEUANCE - 12 or 8 segments of liquid scintillators
  - Geant4 and MCNP-Polimi simulations

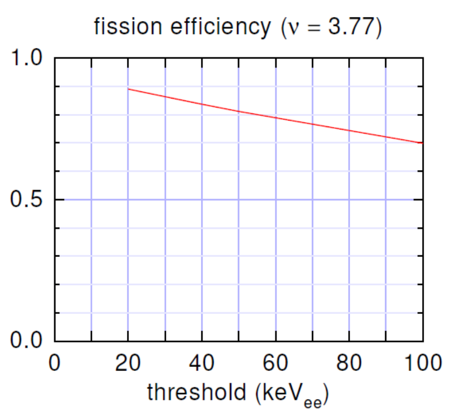


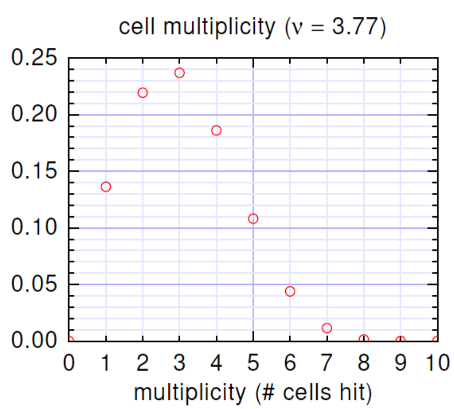
NEUANCE - NEUtron Array at daNCE

- MCNP-Polimi: NEUANCE - 12 or 8 segments of liquid scintillators
- thanks to T. Taddeucci

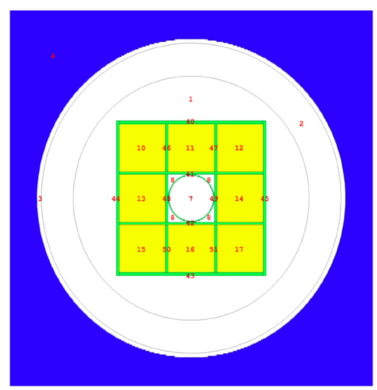
Detection efficiency for fission events is much higher

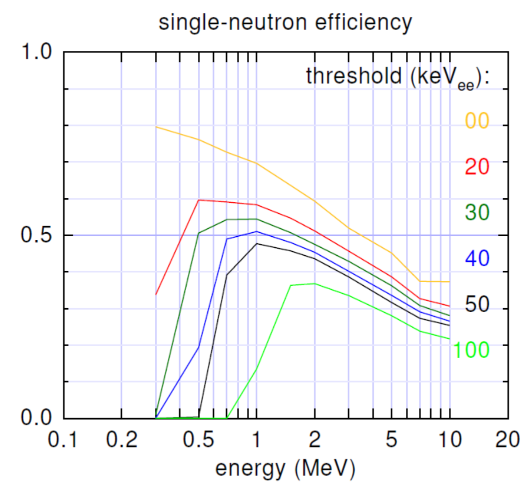
Yet to do: TOF windowing and pileup corrections





MNCPX-PoliMi was used to calculate the efficiency of a square detector array

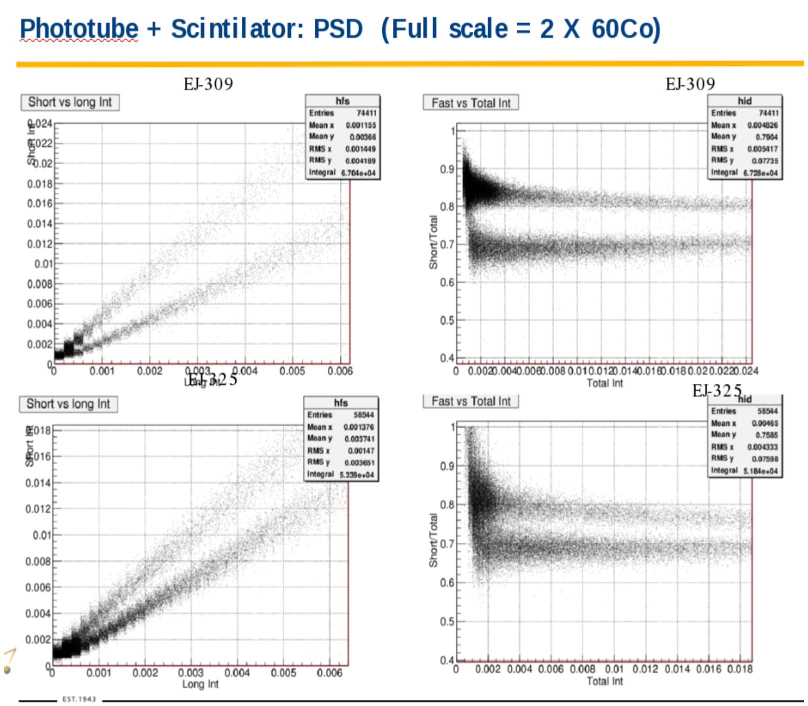




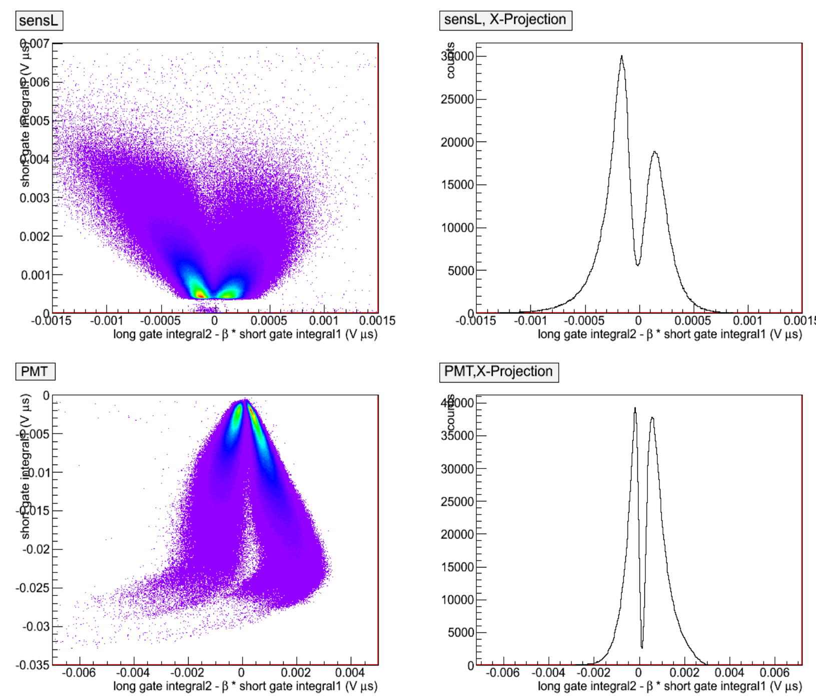
NEUANCE - NEUtron Array at daNCE

- Detector tests are under way - prototype cells
- Hammamatsu PMT vs SiPM - PSD efficiency tests

Liquid Scintillator + PMT

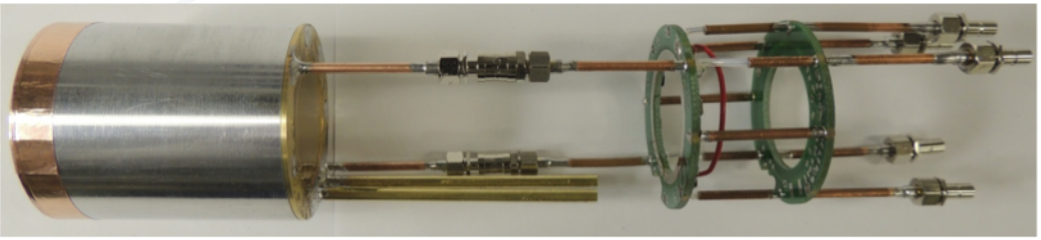


Stilbene + SiPM(6x6mm)

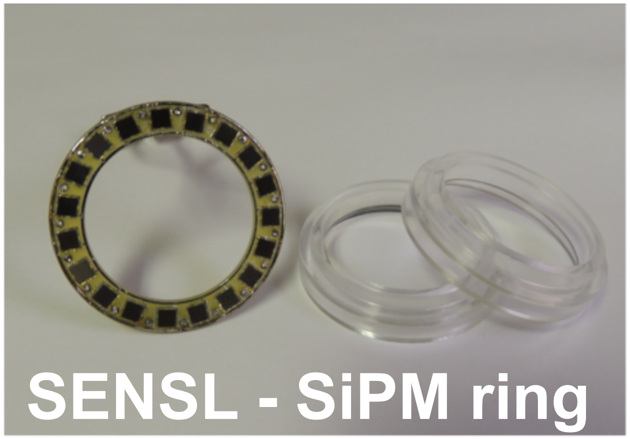


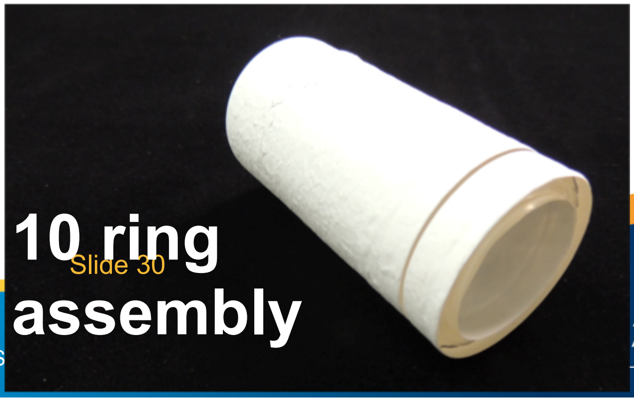
Fission fragment detectors R&D

- A) Multifoil PPACs



- B) Thin scintillator foils - multifoil design allows to put many foils per 1mg/cm2 in beam
  - Thin sc foils 10x between the rings
  - Acrylic rings are painted from inside by sc paint
  - Light collected at the end by SiPM ring
  - Initial tests with Cf-252 are promising
  - design/work by G. Rusev





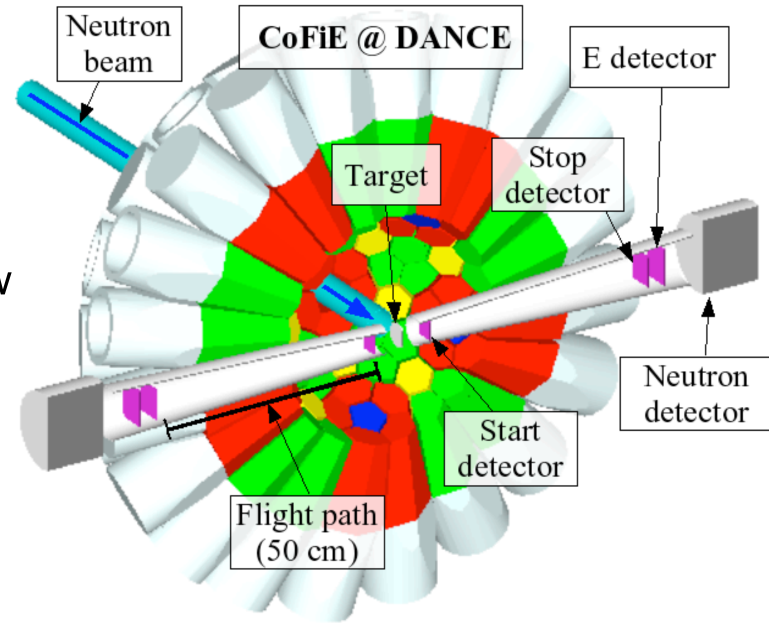
New data acquisition for DANCE

- 14 bit 500 MHz digitizers – arriving next week !
- 160 BaF2 channels + 32 x NEUANCE with PSD + auxiliary det (Si, TFS)
- FPGA onboard zero suppression signal processing
- Asynchronous data streams

- Significant investment/ development
- New hardware will arrive soon
- Next beam cycle will be used to implement it, in parallel with existing DAQ

Summary

- Very exciting times for DANCE
- Well funded for next four years and new opportunities will open up with all upgrades and new detection capabilities – NEUANCE, FF detectors
- Cross sections: U, actinides
- Fission properties: can we have CoFiE @ DANCE: complete measurements of prompt neutrons and gammas and fission fragments in full correlation: **with NEUANCE we probably can !**
- Fundamental studies, de-excitation physics
- Applied physics: reactor heat, delayed gamma-rays



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- X-division: M . Chadwick