Capture and Fission with DANCE and NEUANCE

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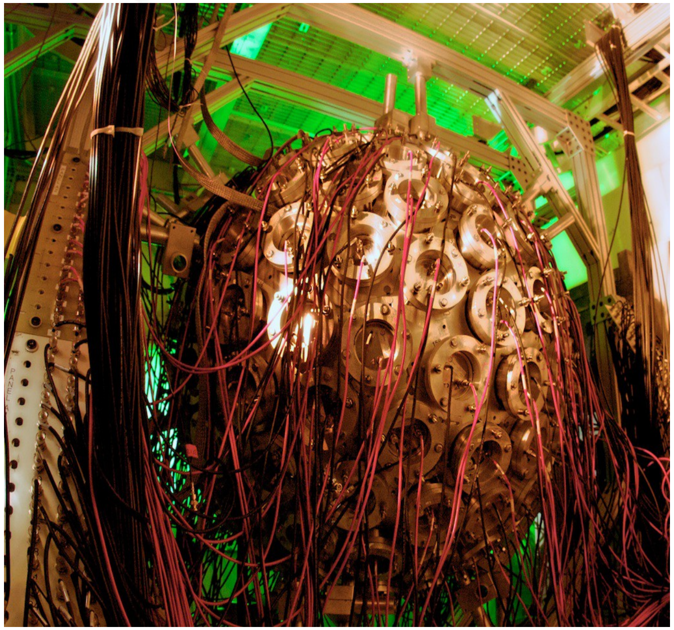
P(ND)^2-2, Oct 14-17, 2014, Bruyeres-le-Chatel, France

Nuclear data measurements at DANCE

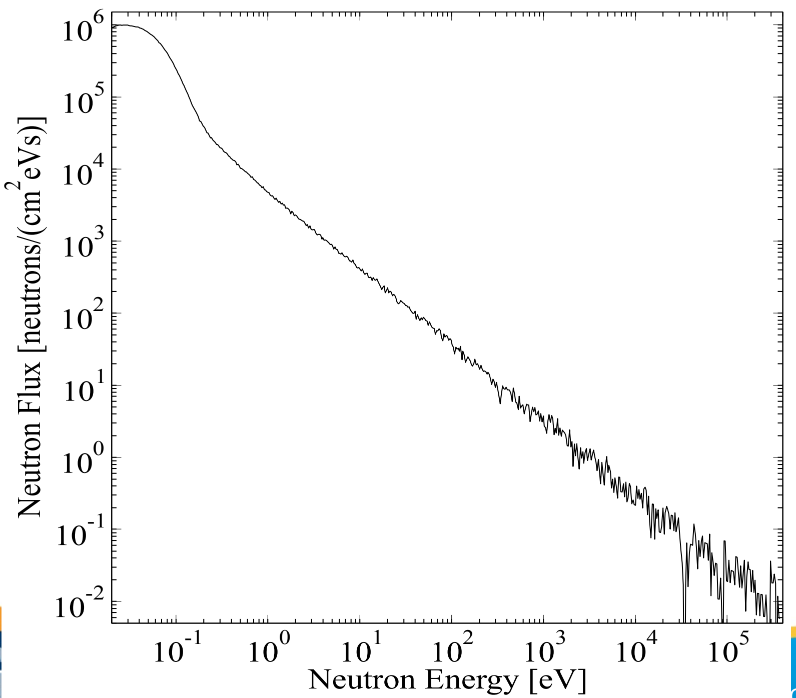
- Neutron capture and induced fission
- Detector for Advanced Neutron Capture Experiments
  - Cross sections
  - photon strengths, level densities
  - Resonance J^{π} assignments
  - Fission gamma rays
- Basic Nuclear Science
- Applications
  - Nuclear Energy, stockpile stewardship, non-proliferation, nuclear forensics

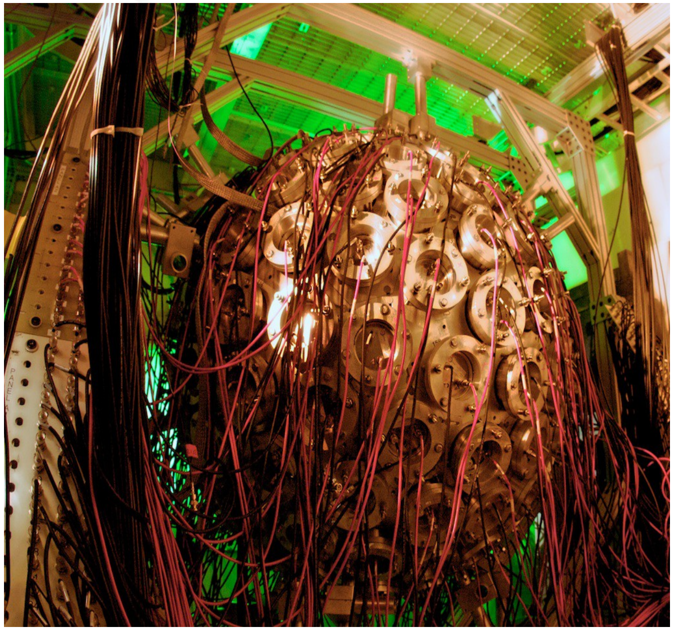


DANCE - 160 x BaF_2 gamma-ray calorimeter

Nuclear data measurements at DANCE

- Time-of-flight – 20 m flight path
- Lujan Center – water moderated 20 Hz neutron source from 800 MeV p+W
- Neutron flux – Maxwellian + 1/E
- Ideal for resonances and up to 10 keV

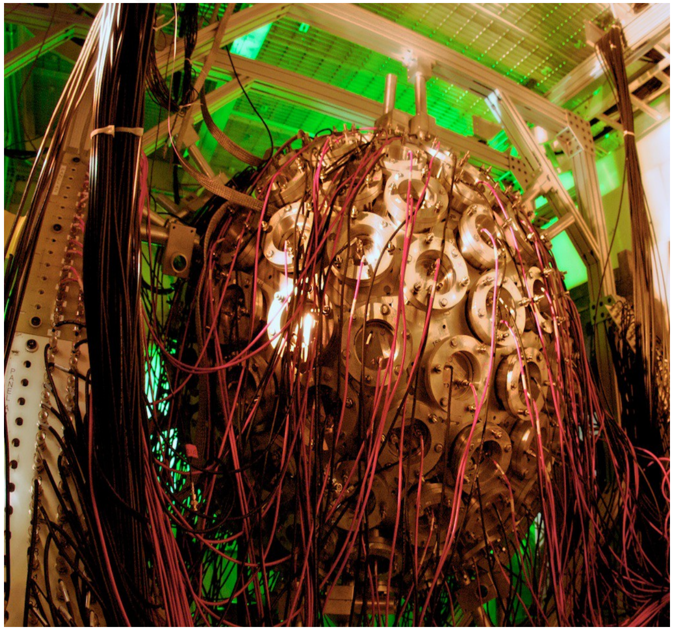




DANCE - 160 x BaF_2 gamma-ray calorimeter

Nuclear data measurements at DANCE

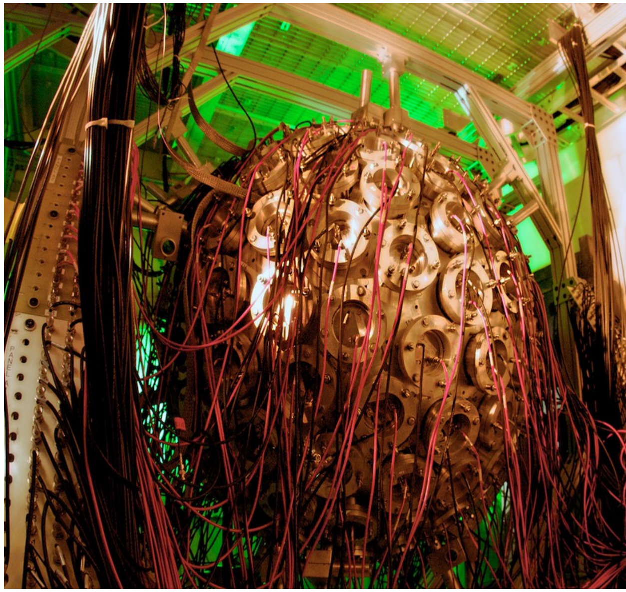
- Cross sections actinides: Np-237, Am-241, U-235, U-238, Pu-239
- Nuclear structure/resonances: Gd, Mo, Dy – lead by G. Mitchell, M. Krticka, and P. Koehler
- Applications: Cd (Rusev), Lu (Roig), Ir, Tm, As isotopes
- Fission gamma-rays, parametrization, Hauser-Feshbach models: Pu-239, U-235, Am-242m, U-233, Cf-252
- Many LLNL lead measurements on actinides to study PFG using deconvolutions (A. Chyzh, C. Y. Wu)



DANCE - 160 x BaF_2 gamma-ray calorimeter

DANCE capabilities

- Large solid angle and granularity
- 160 x BaF2 crystals in 4π geometry
- Fast (6ns - dT), high efficiency calorimeter for γ-rays
- Digital DAQ – 324 channels
  - Transition to 14bit 500 MS/s CAEN DAQ
  - Better resolution – 50 x more data !
- Design of new auxiliary detectors to fit in DANCE
  - Neutrons, fission fragments, gamma-ray (spectroscopy)
- 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

Current 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) Short-lived Actinide Isomers - NEUANCE
  - Three year long, major R&D program
  - New capability at DANCE – 4π neutron detection
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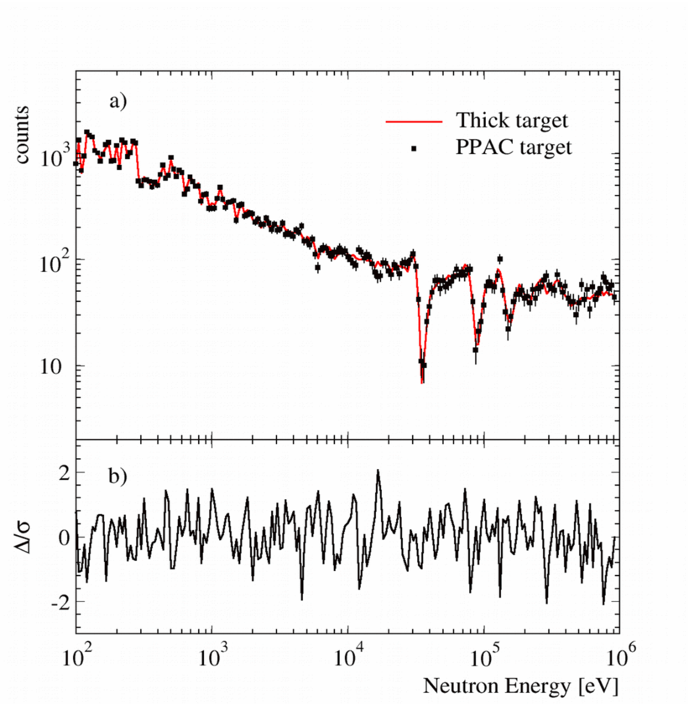
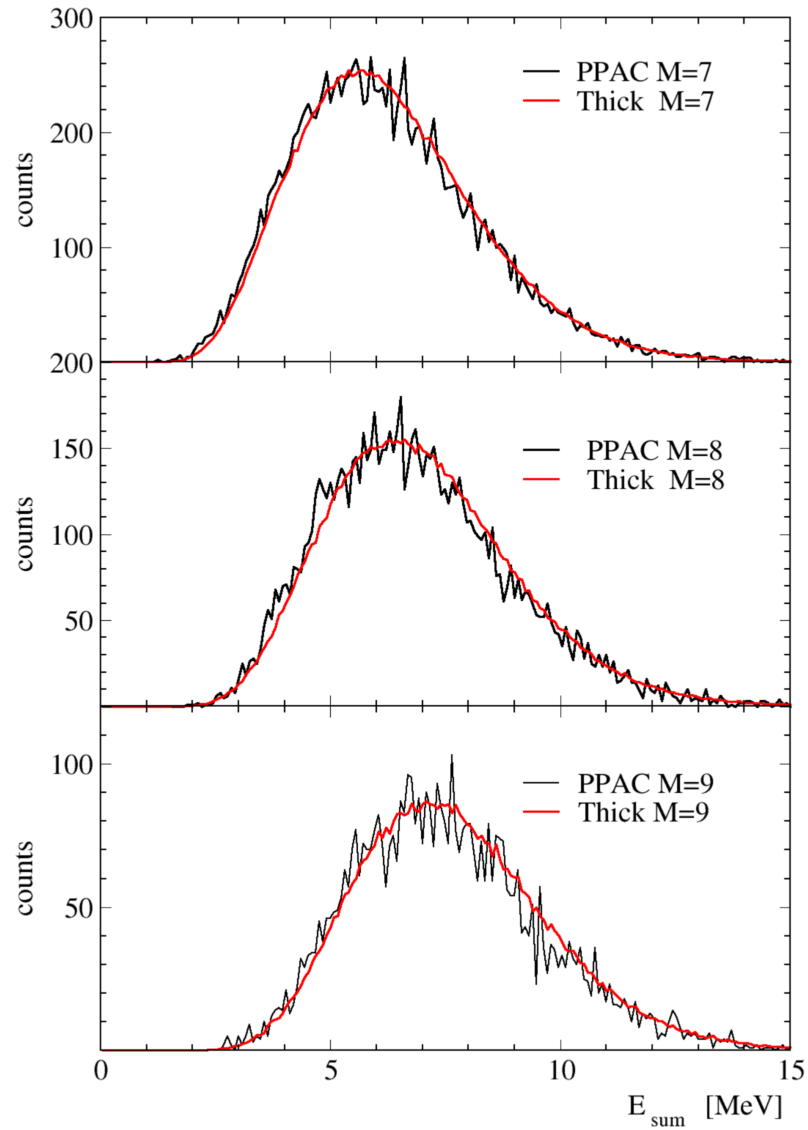
Capture XS: high precision U235 and Pu239

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





Capture XS: high precision U235 and Pu239

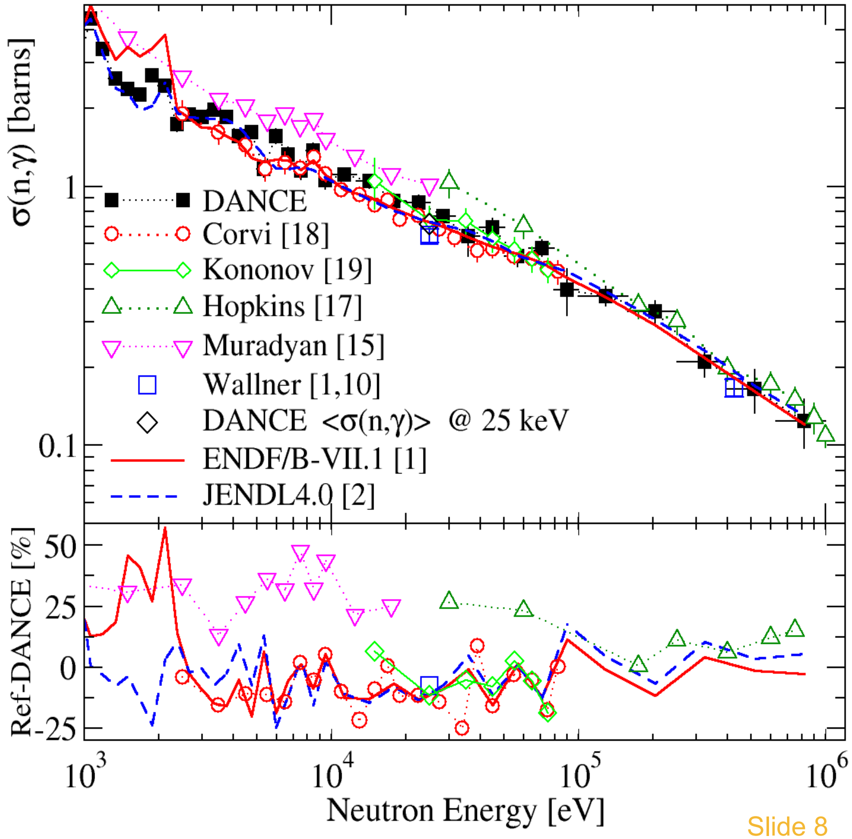
- Ratio method developed for $^{235}U(n,\gamma)$
- Precision <3% was achieved using simultaneous rate determination;
  - Rates of $^{235}U(n,\gamma)$ and $^{235}U(n,f)$
  - The same target → same neutron flux for both reactions
  - Parallel Plate Avalanche Counter for (n,f)

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

- Successfully implemented for ^{239}Pu

S. Mosby et al., PRC 89, 034610

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



Future Capture XS: U236 and U238 mixed targets

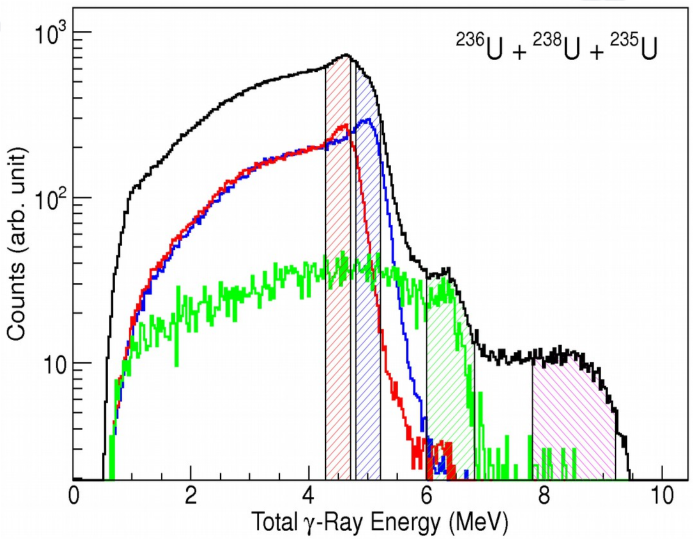
- Can Ratio method be applied for ^{236}U and other isotopes ?

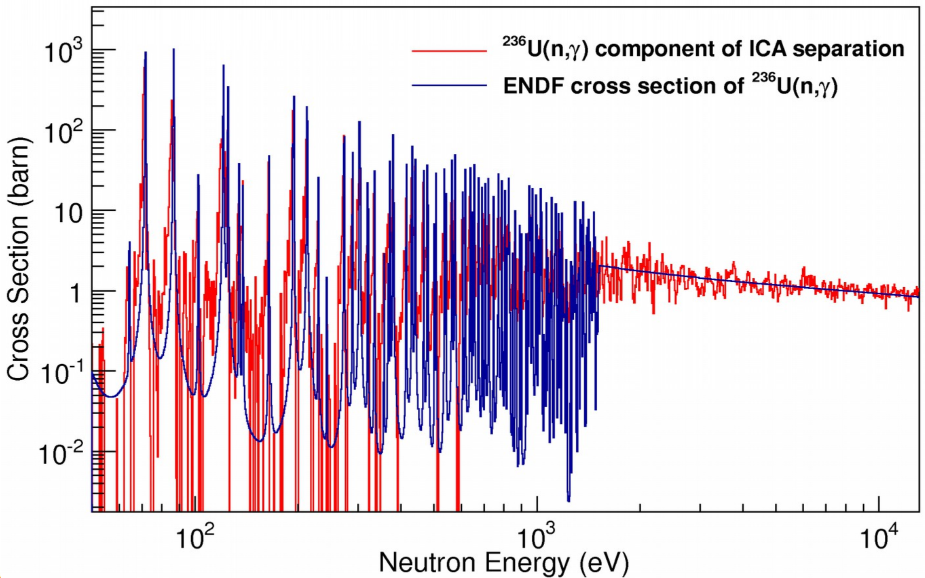
$$\sigma\left(^{236}U_{n,g}\right) \propto \left(\frac{R\left(^{235}U_{ng}\right) + R\left(^{236}U_{ng}\right)}{R\left(^{235}U_{n,f}\right)} - \frac{R\left(^{235}U_{ng}\right)}{R\left(^{235}U_{n,f}\right)} \right) \sigma\left(^{235}U_{n,f}\right)$$

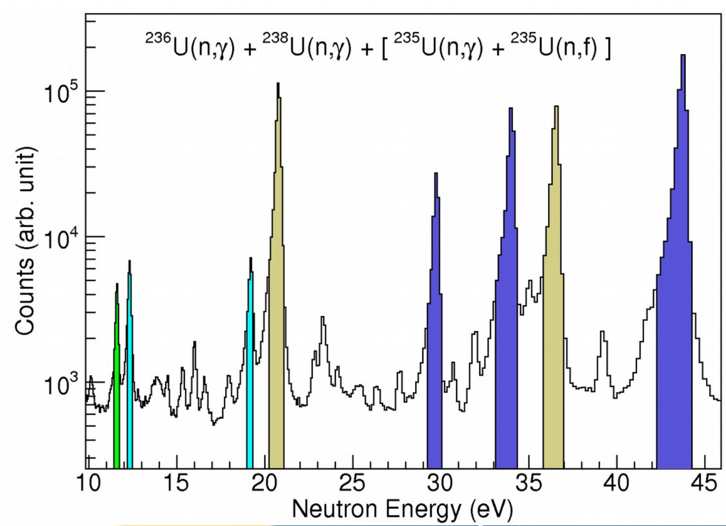
- New measurements with mixed targets to cancel out n flux:
  - ^{236}U+^{235}U (Nov 2013)
  - ^{238}U+^{235}U (Fall, 2014)

Capture XS: U236 and U238 – applied math

- Independent Component Analysis
  - work in progress by B. Baramsai
  - Promising (spins/parities assignment)
- Last year measurements
  - U-235+U-236+U-238 mixed target
  - We need additional data – planned this year





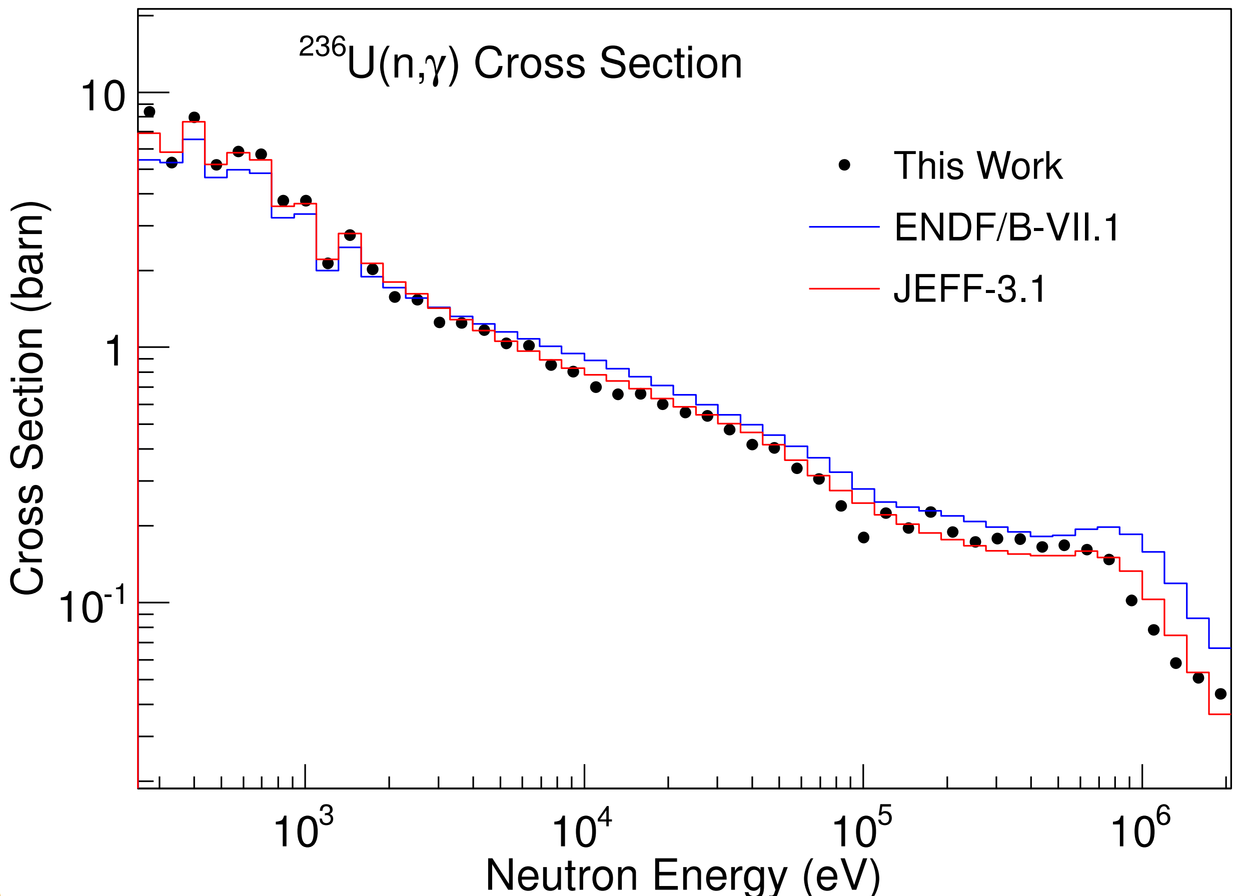


U-236 Capture XS: U236 / U235 from independent measurements

- Can Ratio method be applied to developed for ^{236}U(n,g) and other isotopes ?

$$\sigma\left({}^{236}U_{n,g}\right) \propto \left(\frac{R\left({}^{236}U_{ng}\right)}{R\left({}^{235}U_{n,f}\right)}\right)\sigma\left({}^{235}U_{n,f}\right)$$

Results of region of two independent measurements on thick U-236 and U-235 foils are promising



U238 Capture XS: U238 / U235 from independent measurements

- Can Ratio method be applied to developed for $^{236}U(n,g)$ and other isotopes ?

$$\sigma\left({}^{238}U_{n,g}\right) \propto \left(\frac{R\left({}^{238}U_{ng}\right)}{R\left({}^{235}U_{n,f}\right)}\right)\sigma\left({}^{235}U_{n,f}\right)$$

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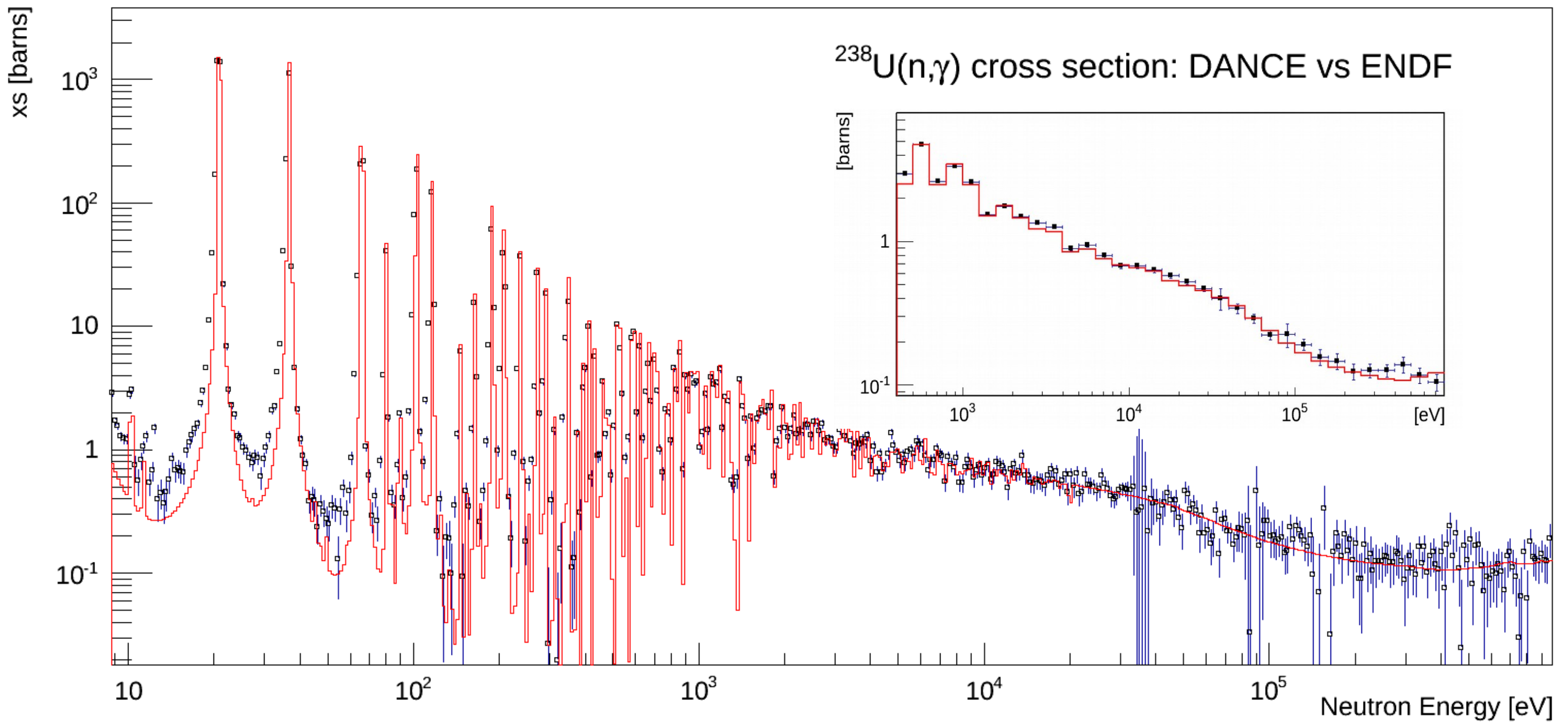
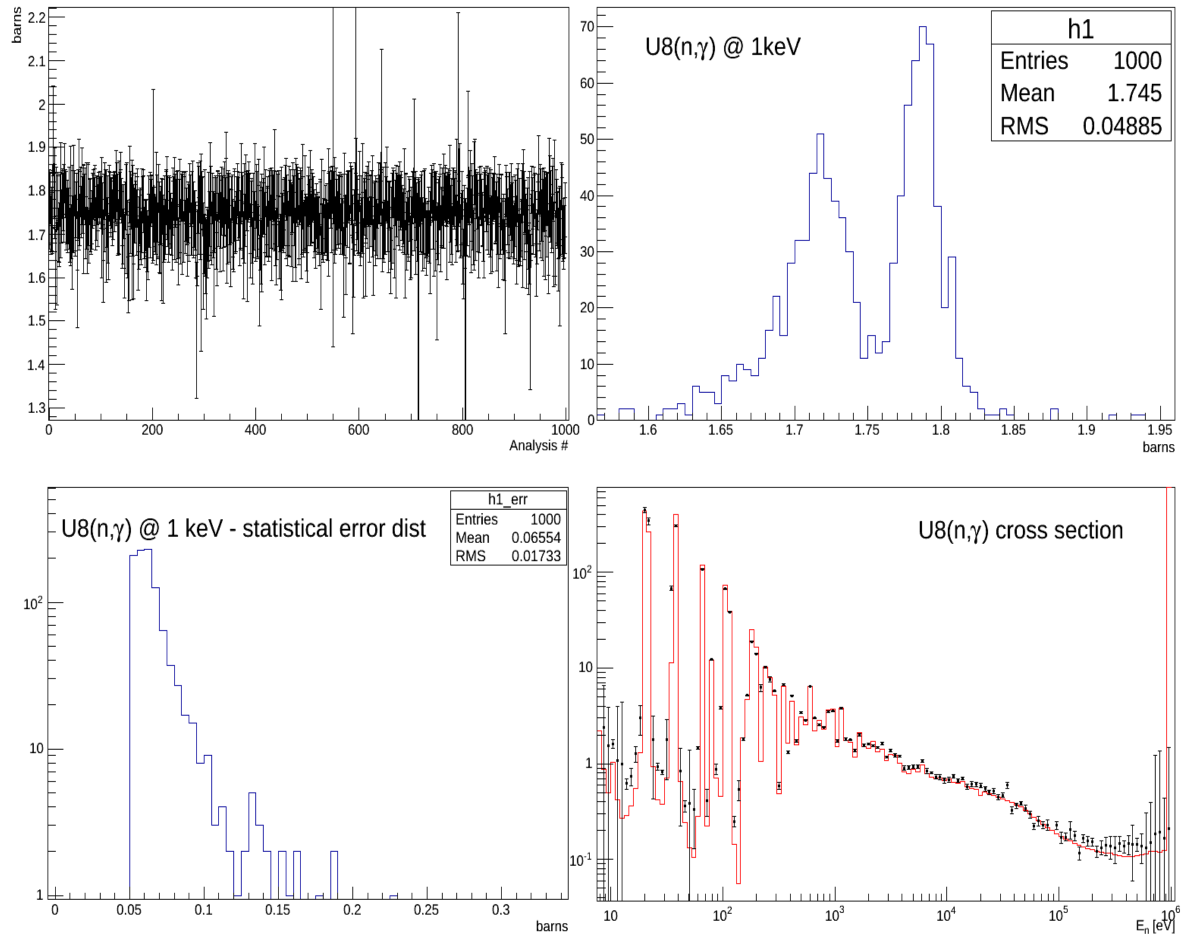


Capture XS: uncertainties – Monte Carlo

- Many Sources:
  - Detector set-up, reference nuclear data, analysis, data reduction
- Data Reduction
  - What happens if 1000 people analyze the same dataset ?
  - Sample over all parameters of data reduction using Monte-Carlo

Capture XS: U238 - uncertainties – Monte Carlo

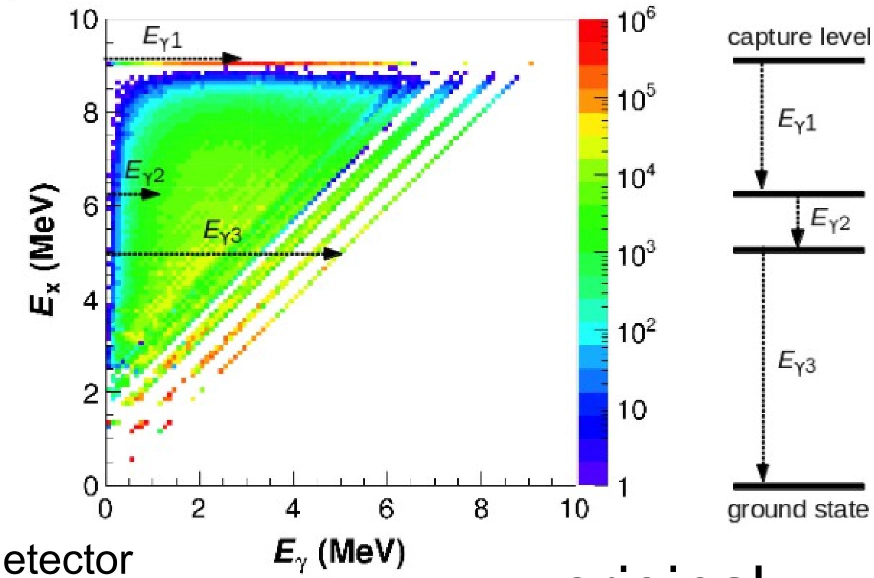
- Gates: M=(p(M1),p(M2)), E1=(p(Q1),p(Q2)), E2=(p(B1),p(B2))
- P is a distribution to sample from (Gaussian, uniform)
- U238 – En=1 keV
- 1.745 (0.05) barns
- Average statistical error ~ 0.066
- Systematical/analysis error ~ 0.05



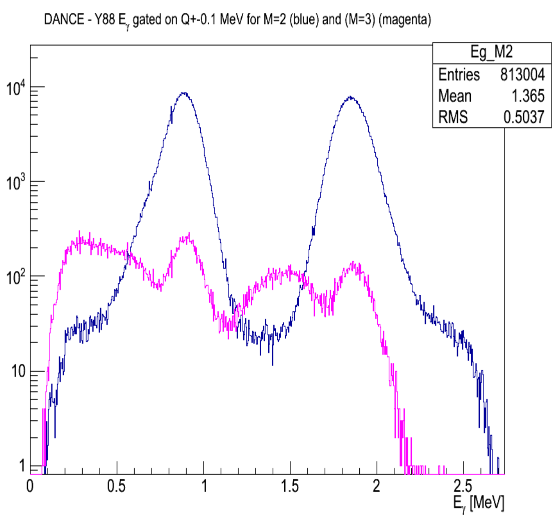
Future developments – capture gamma

- Capture gamma-rays correlated data
  - Suggestions for the correlated gamma-ray data library
  - Multidimensional decomposition of gamma-cascades

Rusev et al. , Phys. Rev. C **88** , 057602 (2013)



measured



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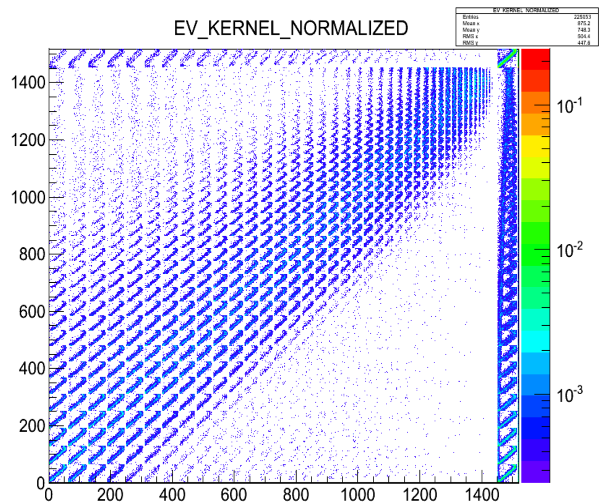
Response of detector with correlations



x

original

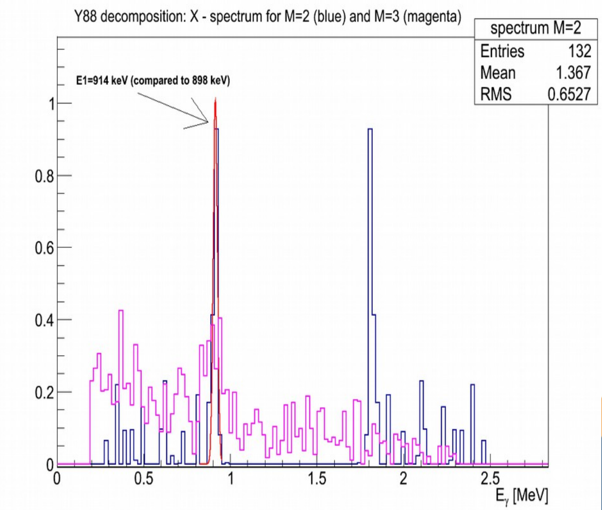


Illustration 1: Results of the decomposition for M=2 (blue) and M=3(magenta)

Research Programs

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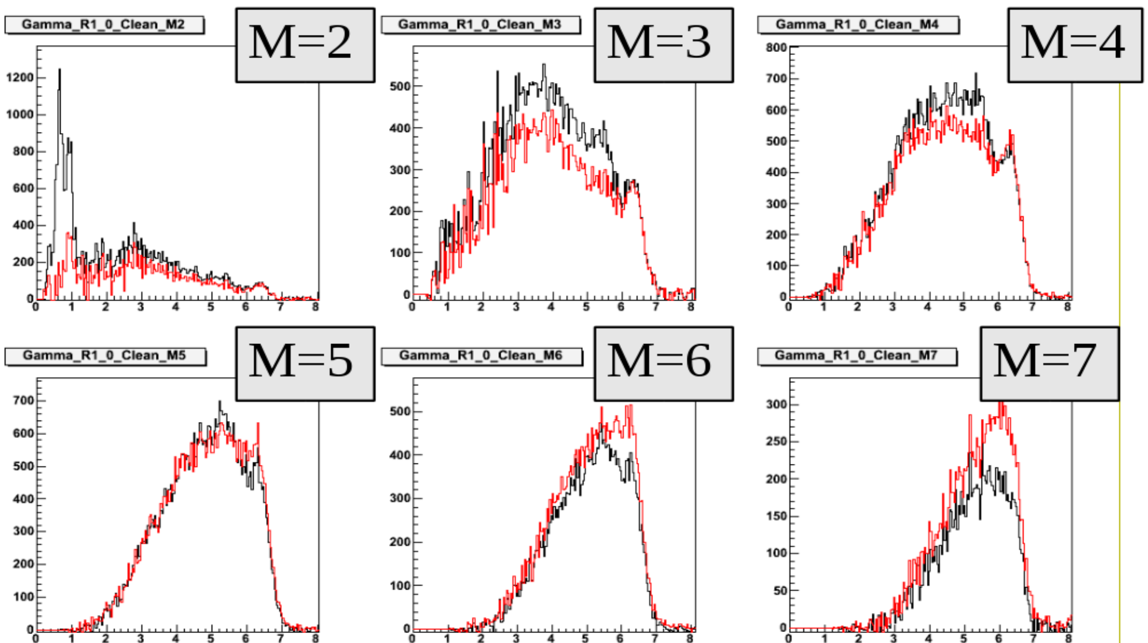
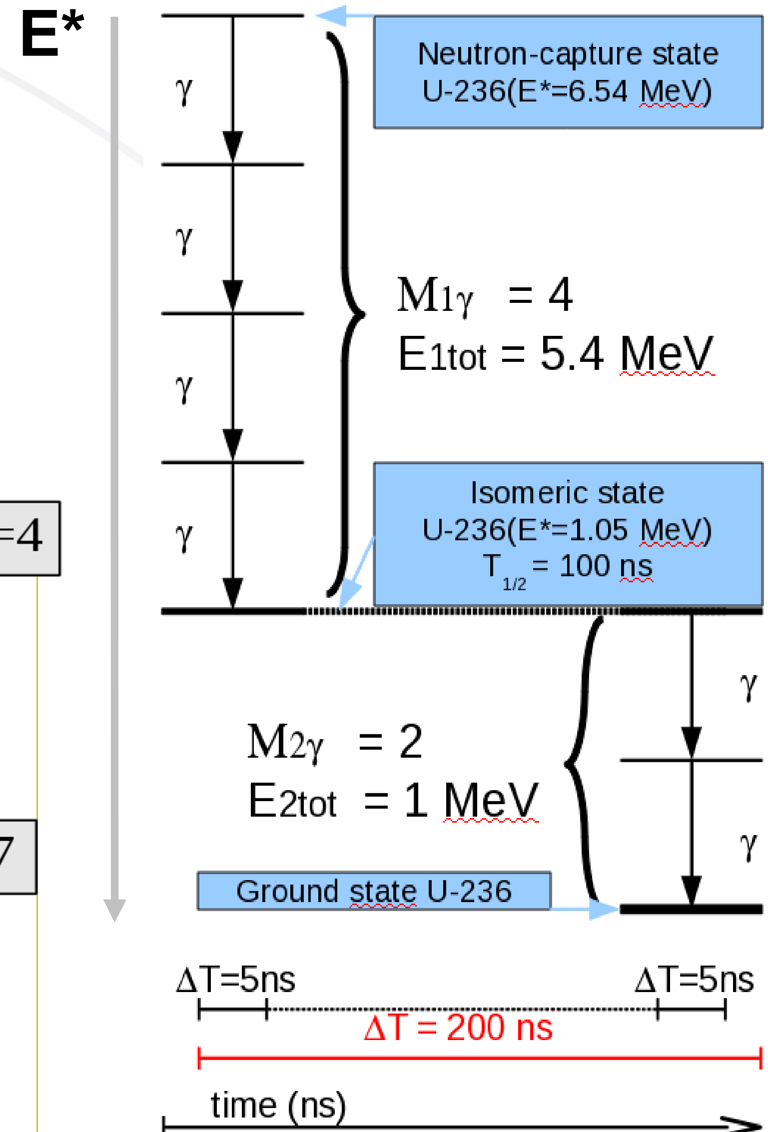
Isomeric states after U235+n

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

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

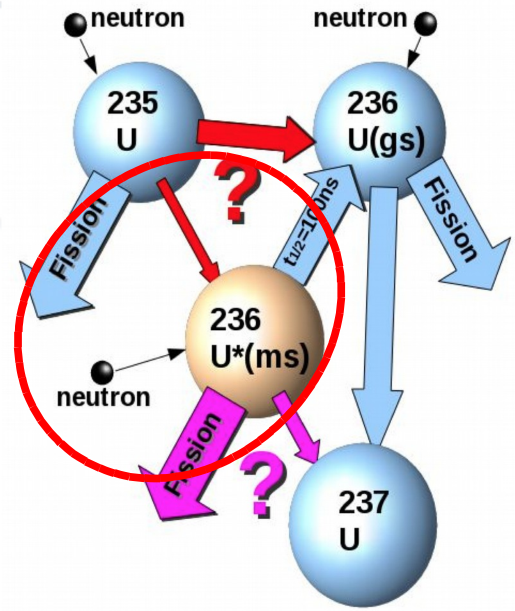
- E_{tot} variations for different number M of gamma-rays detected in a dT window



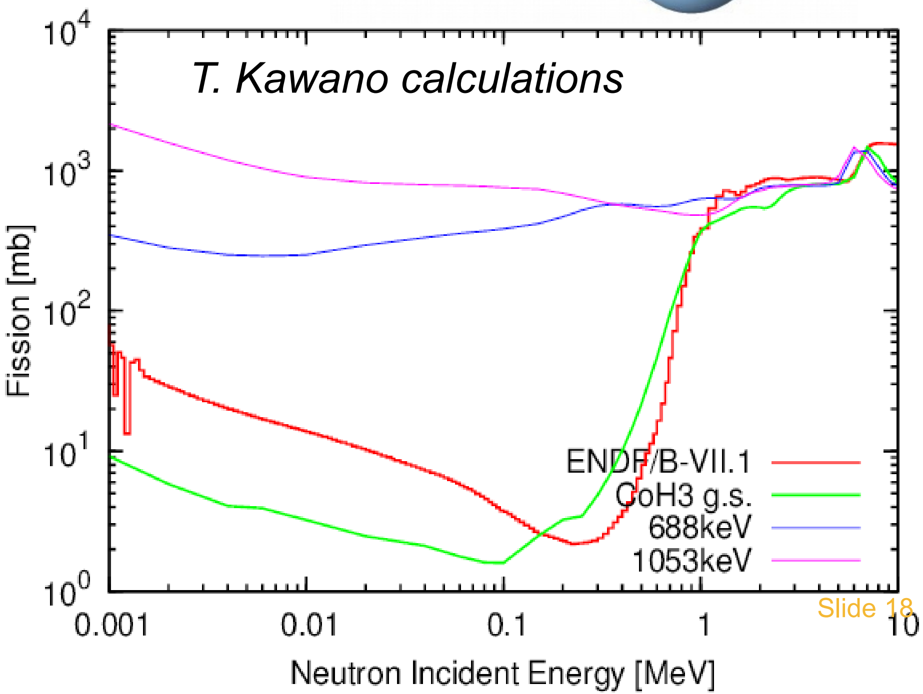


Isomeric states after U235+n

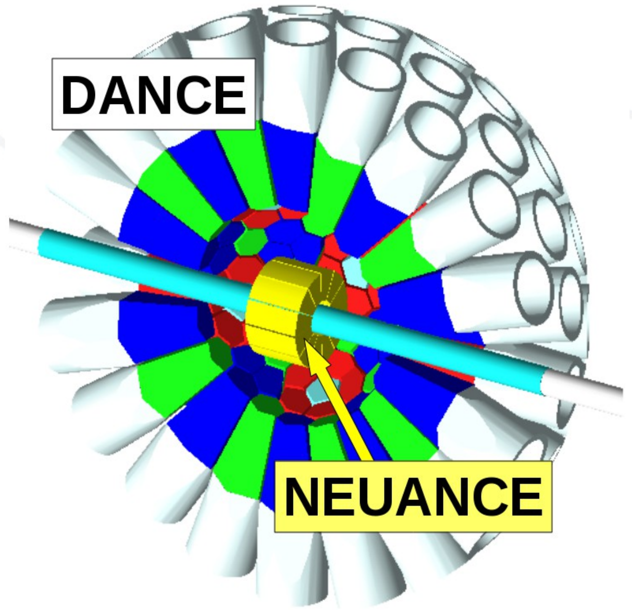
- In high neutron fluence the secondary reactions can occur
- $^{236}U^{*}$: 1024 keV (4-) $T_{1/2}$ = 100 ns
- $^{236}U^{*}$: 678 keV (1-) $T_{1/2}$ = 3.7 ns



- 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

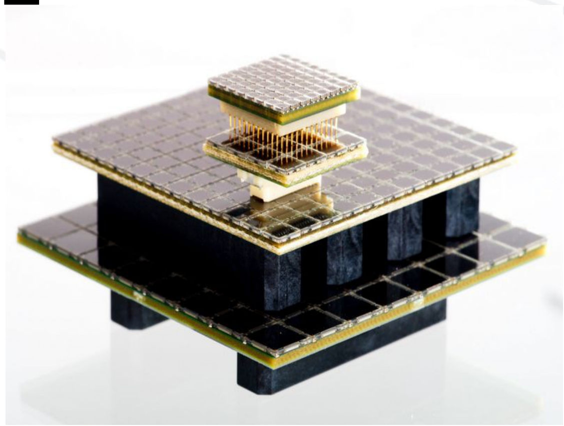


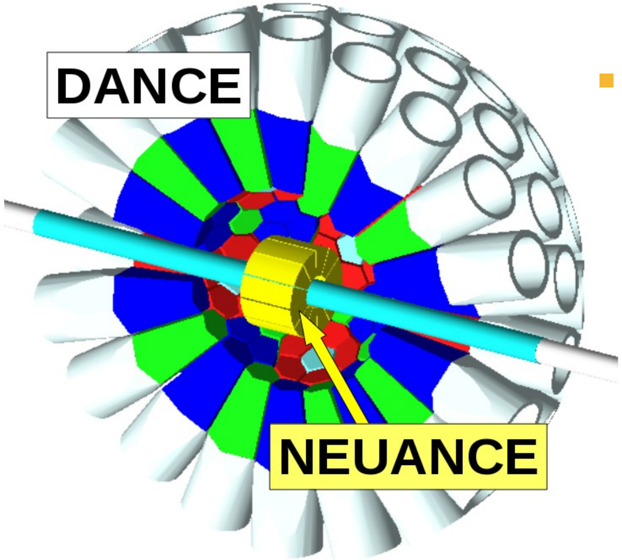
- We need to improve counting statistics on fission and capture of U-235
- For all gamma multiplicities !
- This is very difficult with FF detectors because of thin targets

- NEUANCE: 32 segments of liquid scintillators in the center of DANCE
- NEUANCE will be sensitive only to neutrons above 200 keV --> only from fission
- Construction is in progress – first tests at DANCE in January 2015

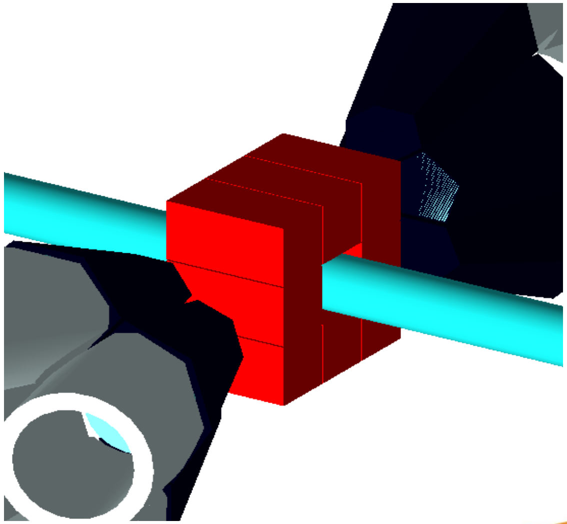
NEUANCE - NEUtron Array at daNCE

- Challenges 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



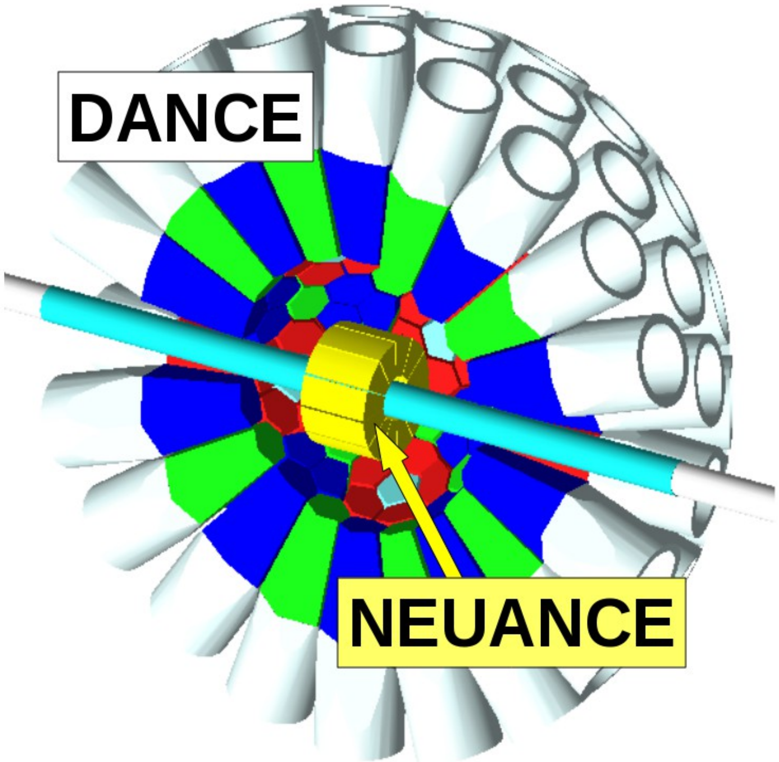


- NEUANCE - 12 or 8 segments of liquid scintillators
  - Geant4 and MCNP-Polimi simulations



NEW CORRELATED DATA with NEUANCE

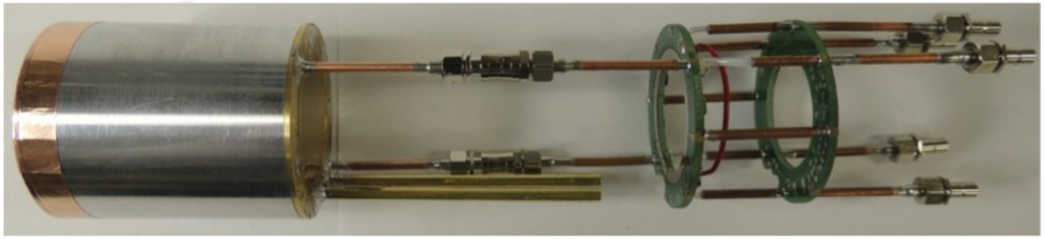
- Time dependent capture and fission gamma-rays. Large statistics and full correlations
- Improved cross sections using NEUANCE as a veto/tagging detector
- Fission neutrons correlations
- Fission neutrons vs fission gamma-rays
- Fission fragment detectors
  - Correlations with A, Z, KE
  - This brings us to next research program



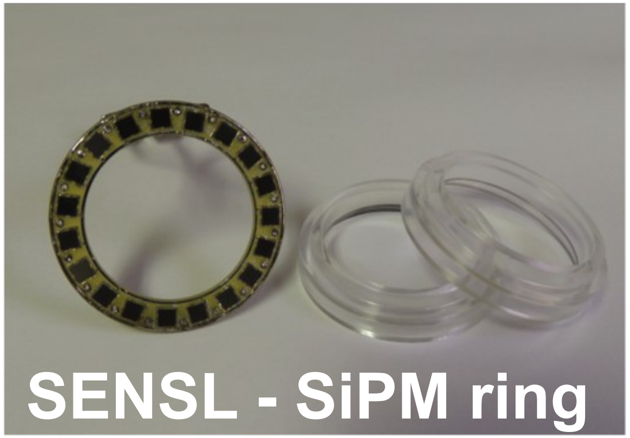
Future outlook

Fission fragment detectors R&D

- A) Multi-foil PPACs



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



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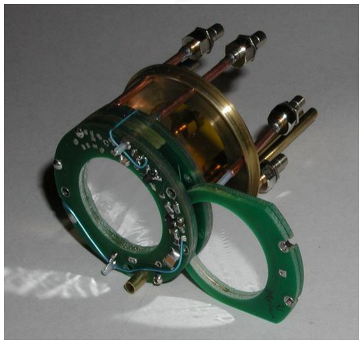
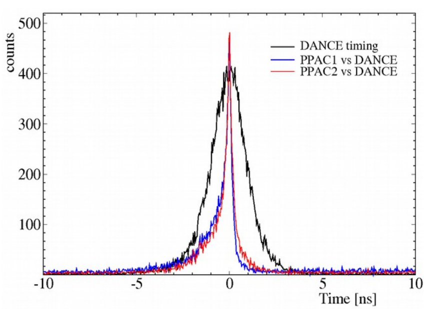
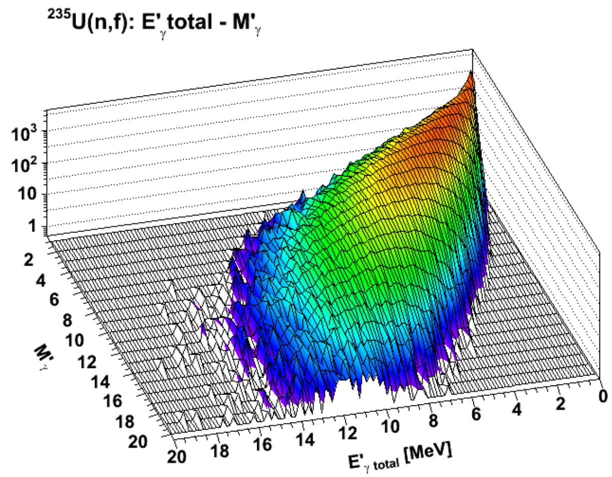
Capture and fission on actinides

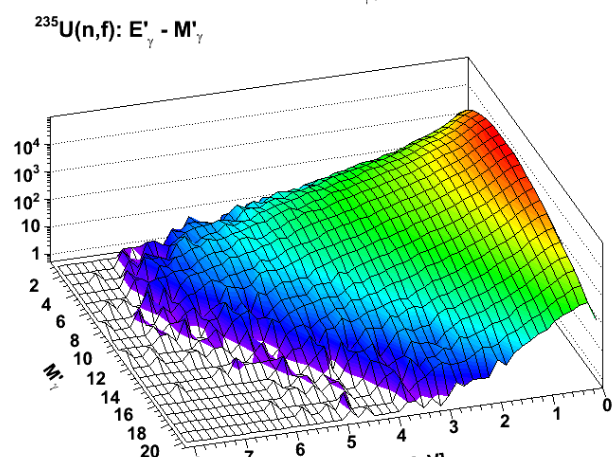
- Fission can be identified using additional fragments detectors

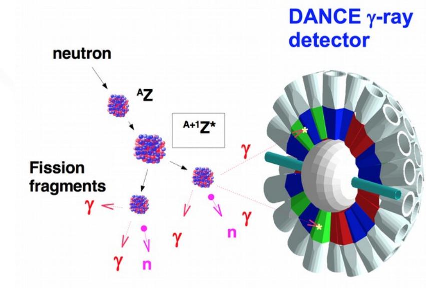


Parallel Plate Avalanche Counter

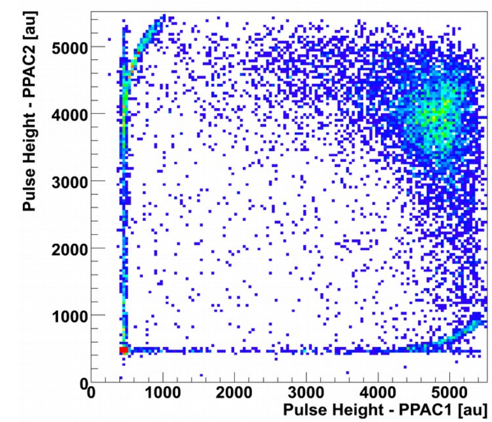








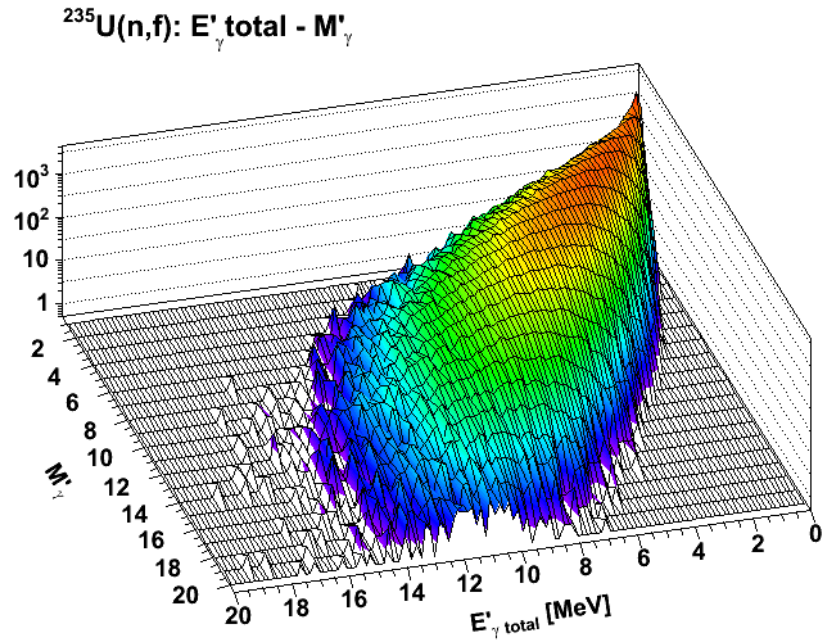
Fission
$\Sigma E\gamma$ = wide distribution
$M\gamma$ = wide distribution

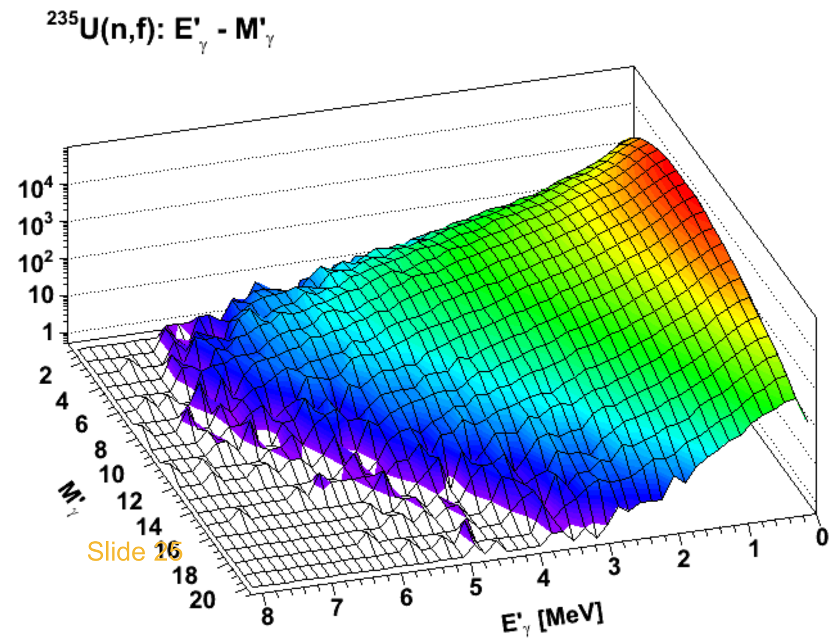


Correlated prompt-fission gamma ray spectra are measured in coicidence with PPAC (<6ns)

DANCE – efficient gamma-ray calorimeter

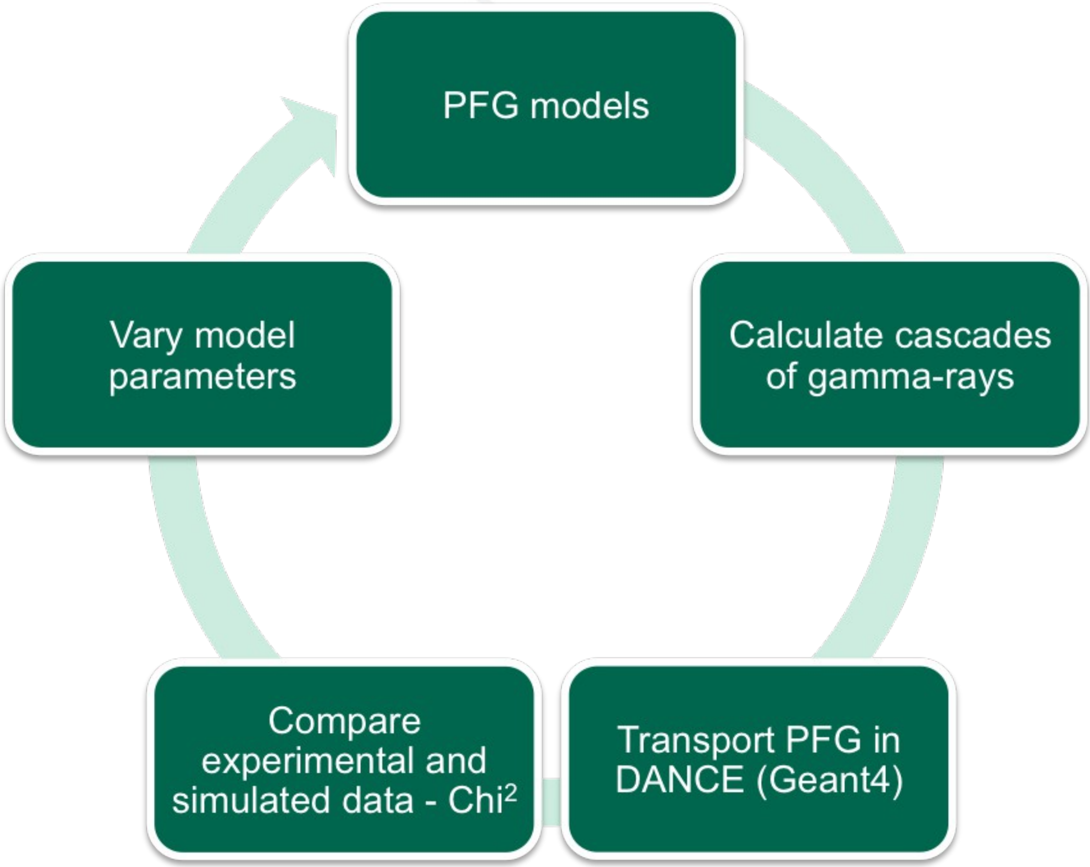
- With high efficiency and 4π solid angle DANCE is ideal for prompt-fission gamma-rays studies
- We measure correlated events of $M\gamma$, $E\gamma$ and $E_{\gamma tot}$
- Complicated analysis – how to obtain original spectra of PFG ?
- Cross talk, and pileup is an issue
- One needs a very precise model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





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(M(
  - 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

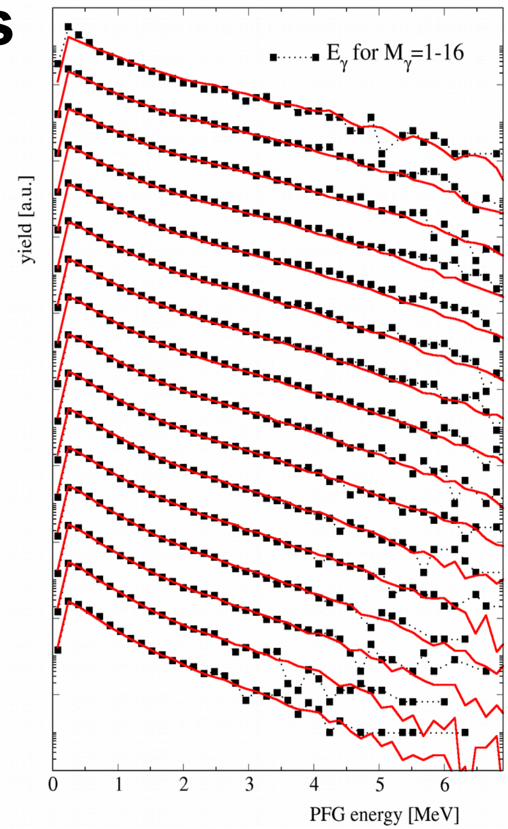


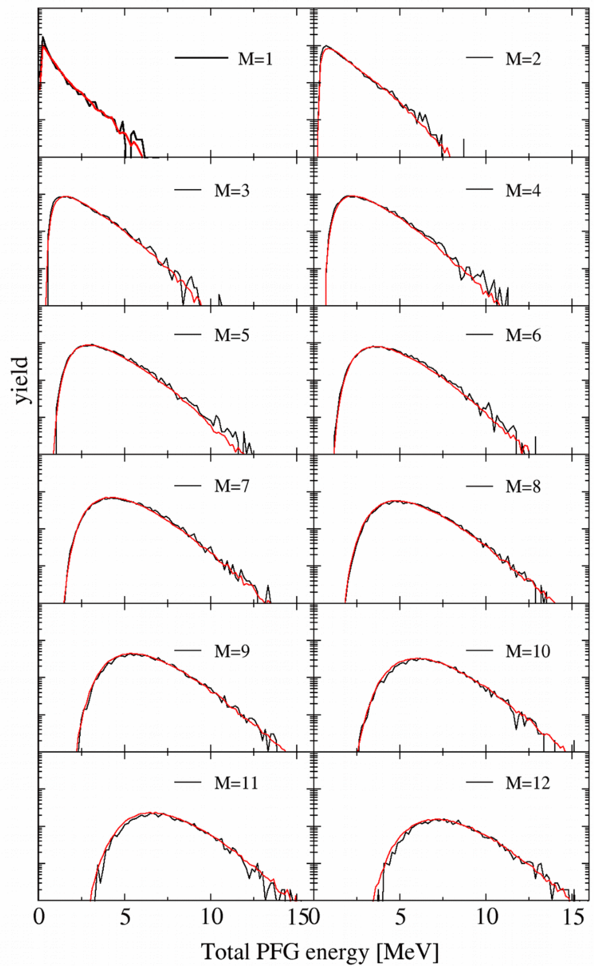
CGMF code development for MCNP6

- 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)

Deducing the real PFG emission properties including correlations

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





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

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

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

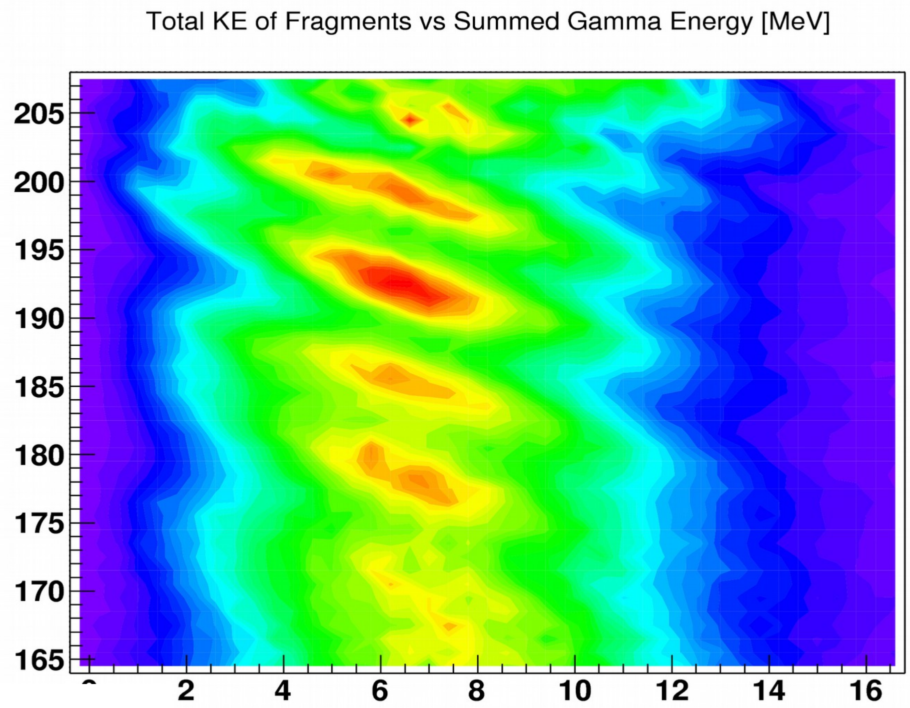
$$M_\gamma = M_1 + M_2$$

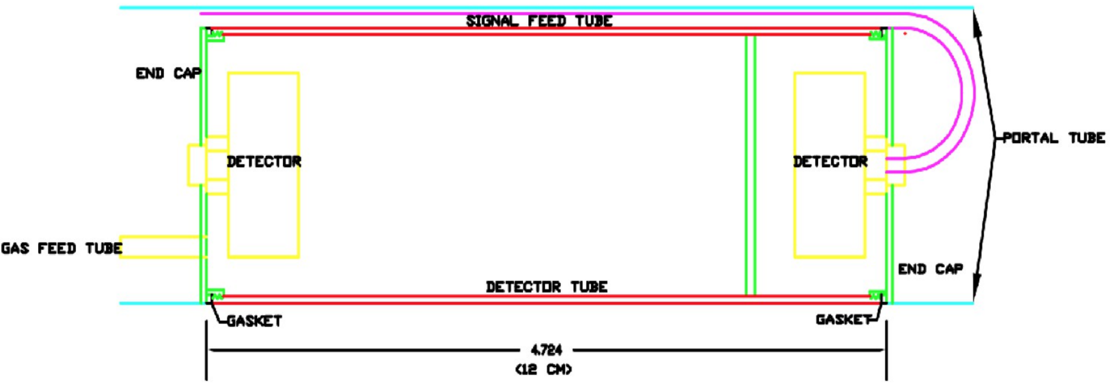
$$t_{1,2} = a_{1,2} + b_{1,2} M_\gamma$$

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

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 (this year)
- Benchmarking the evaporation and fission codes – CGMF (P. Talou, I. Stetcu, T. Kawano)
- MCNP6 development – de-excitation modules (gamma/neutrons in correlation)



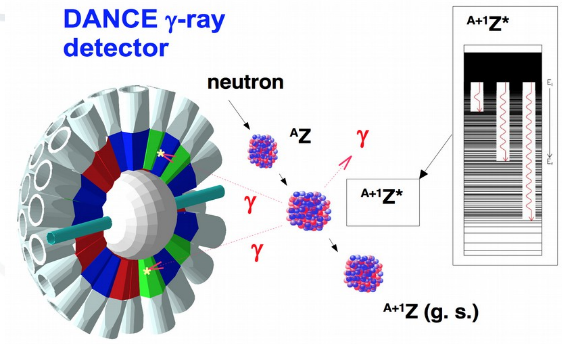


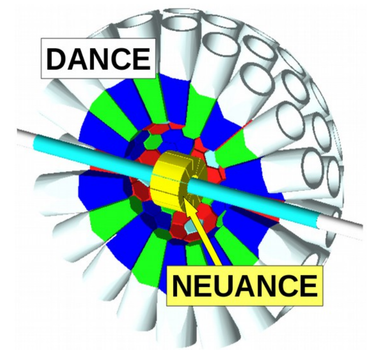
Al container designed for two Si detectors.

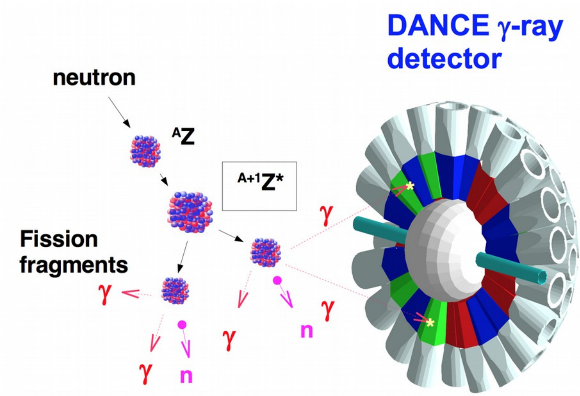
(by postdoc C. Walker)

FUTURE

- Capture cross sections on U-234, U-236, U-238
  - ABSOLUTE cross section
  - Mixed targets and thin very well characterized targets
  - Developed methodologies will be used for other samples of interest
- New detector capabilities
  - NEUANCE + FISSION FRAGMENT Detectors (Spider/ ionization chambers or …)
  - Fully correlated data PFG, PFN and FF
  - Better fission models
  - Move DANCE to WNR
  - Or redesign Lujan target for brighter flux at 100keV





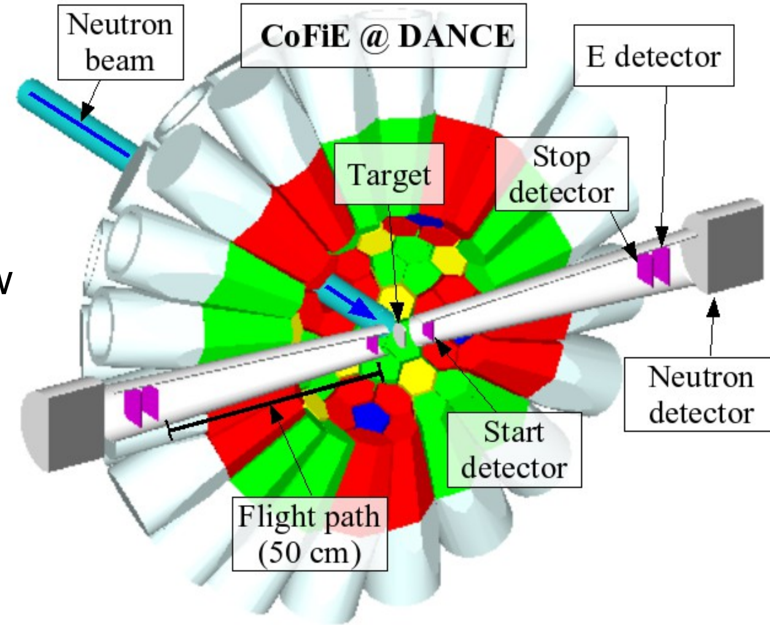


Future outlook

- FUTURE PLANS:
- Reduce uncertainties of cross section data above 1 keV for all actinides
  - Understand systematic uncertainties
  - Sample composition, scattering corrections etc …
- New moderator designs at Lujan center or WNR to improve/increase neutron flux >10 keV and make proton bunch narrower (<few ns)
- Important for many aspects of the measurements (not only at DANCE):
  - Actinide isomers
  - Cross sections in fast region (reactors)
  - Delayed gamma-rays from capture and fission in fast region

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



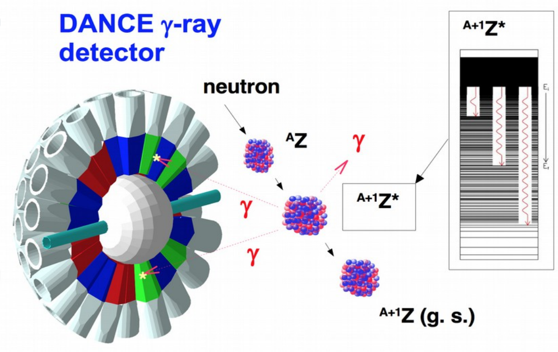
Acknowledgements

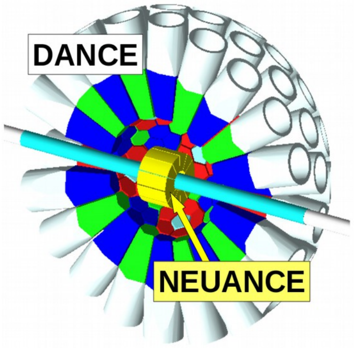
- C-division: B. Baramsai, G. Rusev, T. A. Bredeweg, M. M. Fowler, C. Walker, J. B. Wilhelmy, D. J. Vieira
- LANSCE-NS (P-27) – A. Couture, S. Mosby, J. L. Ullmann, T. N. Taddeucci, J. O'Donnell, R. C. Haight
- T-division: A. Hayes, P. Talou, T. Kawano, I. Stetcu
- X-division: M . Chadwick

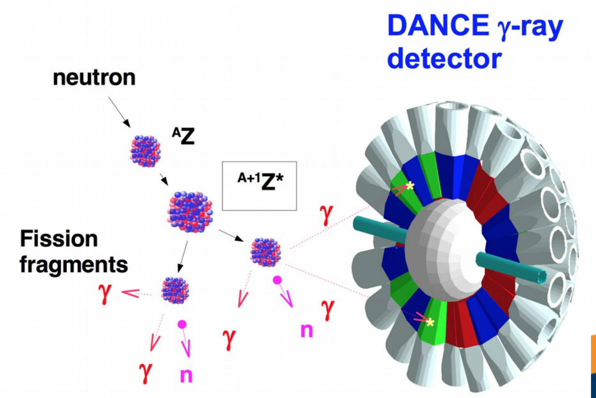
Additional slides

Summary

- Capture cross sections on U-236, U-238
  - Ratio approach from independent measurements
  - Monte-Carlo error propagation
- New detector capabilities
  - NEUANCE
  - Fission fragment detectors: thin film scintillators, Si detectors
  - Upgrade of data acquisition
- New capabilities for fission experiments
  - Under development
  - Theoretical work also







Deducing the real PFG emission properties including correlations

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

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

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

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

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

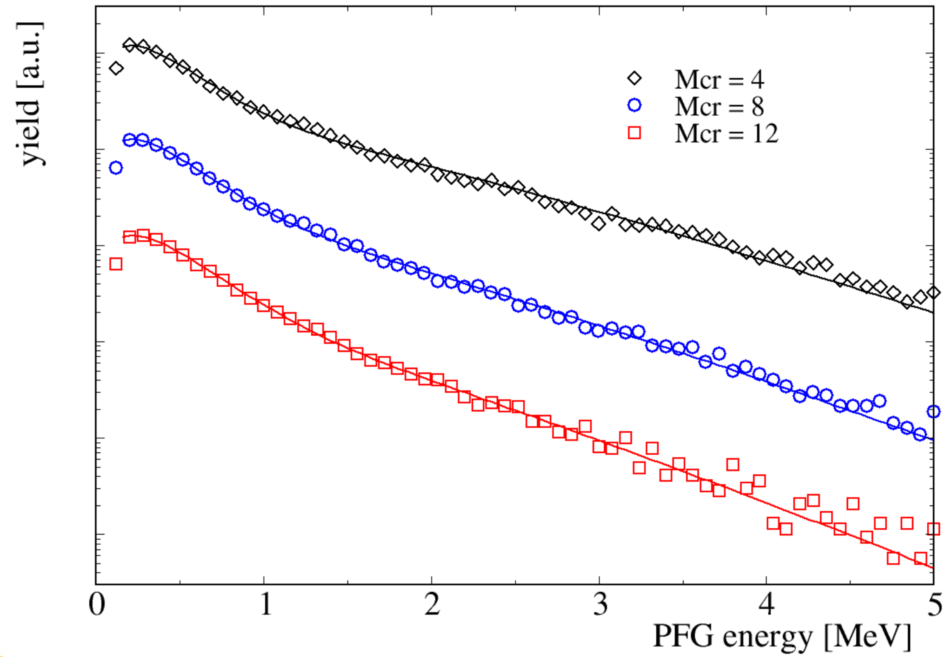
$$p_1(E_\gamma) \propto E_\gamma^2 e^{-t_1 E_\gamma}$$

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

$$M_\gamma = M_1 + M_2$$

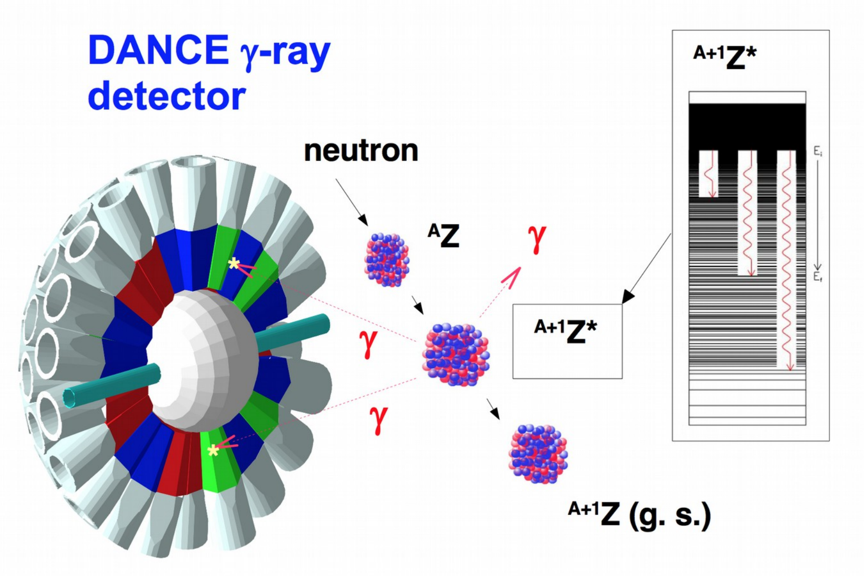
$$t_{1,2} = a_{1,2} + b_{1,2} M_\gamma$$

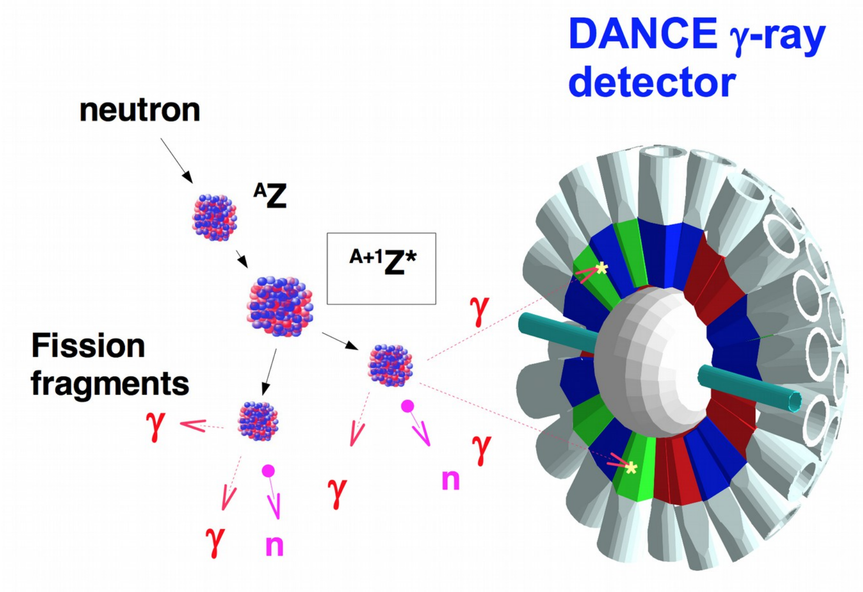
$$6\; free parameters: a_{1,2}, b_{1,2}, c_{1,2}$$



Capture and fission on actinides

- Both capture and fission process occur



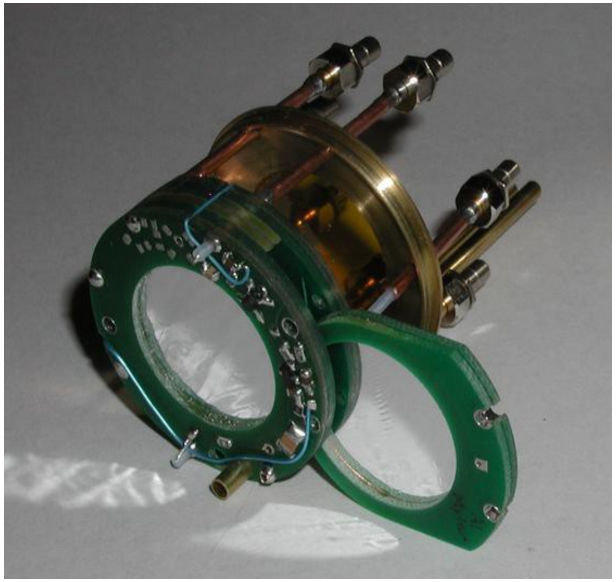


Capture
$\Sigma E\gamma$ = Q (6.35 MeV)
$M\gamma$ = narrow distribution

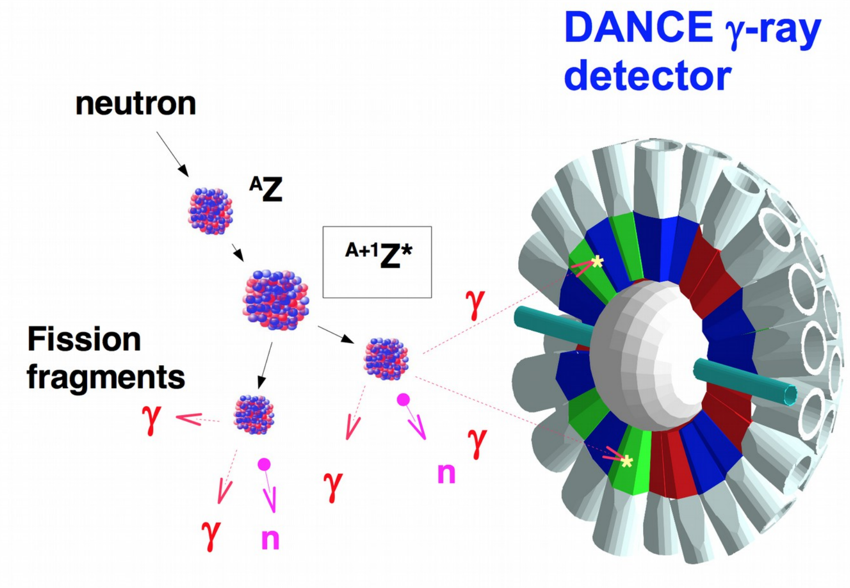
Fission
$\Sigma E\gamma$ = wide distribution
$M\gamma$ = wide distribution

Capture and fission on actinides

- Fission can be identified using additional fragments detectors



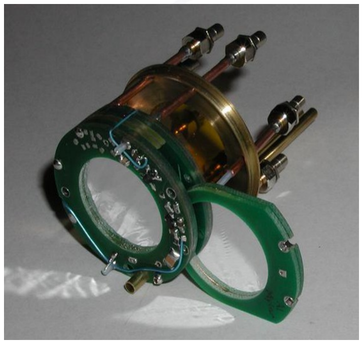
Parallel Plate Avalanche Counter



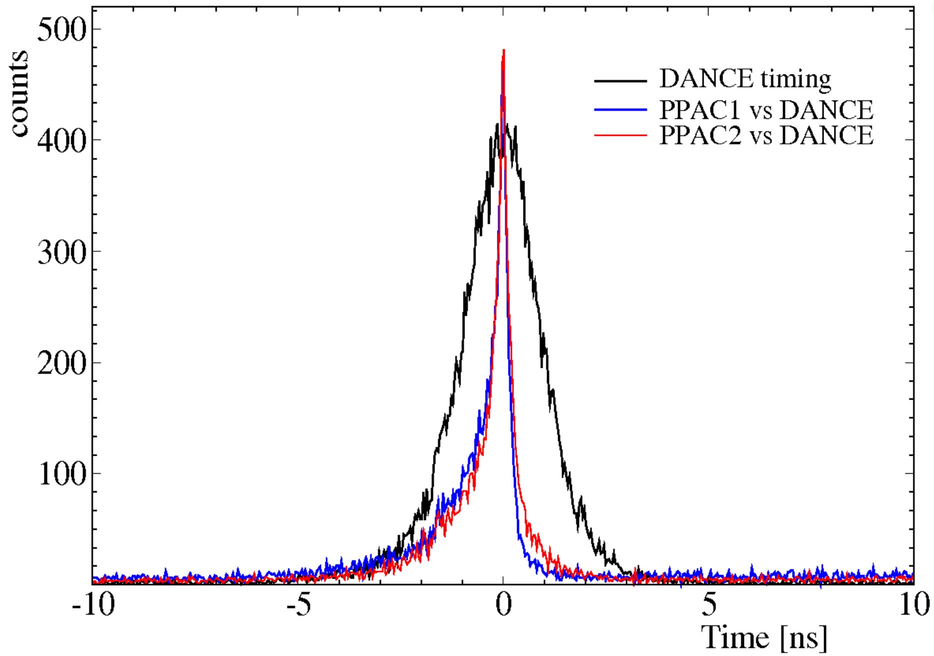
Fission
$\Sigma E\gamma$ = wide distribution
$M\gamma$ = wide distribution

Capture and fission on actinides

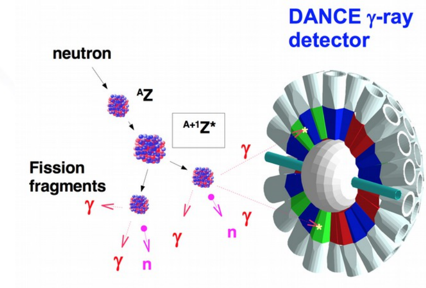
- Fission can be identified using additional fragments detectors



Parallel Plate Avalanche Counter



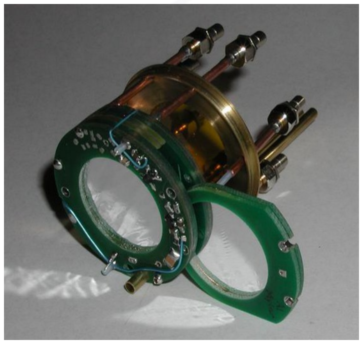
Excellent Timing



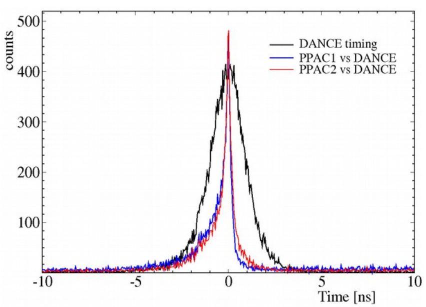
Fission
$\Sigma E\gamma$ = wide distribution
$M\gamma$ = wide distribution

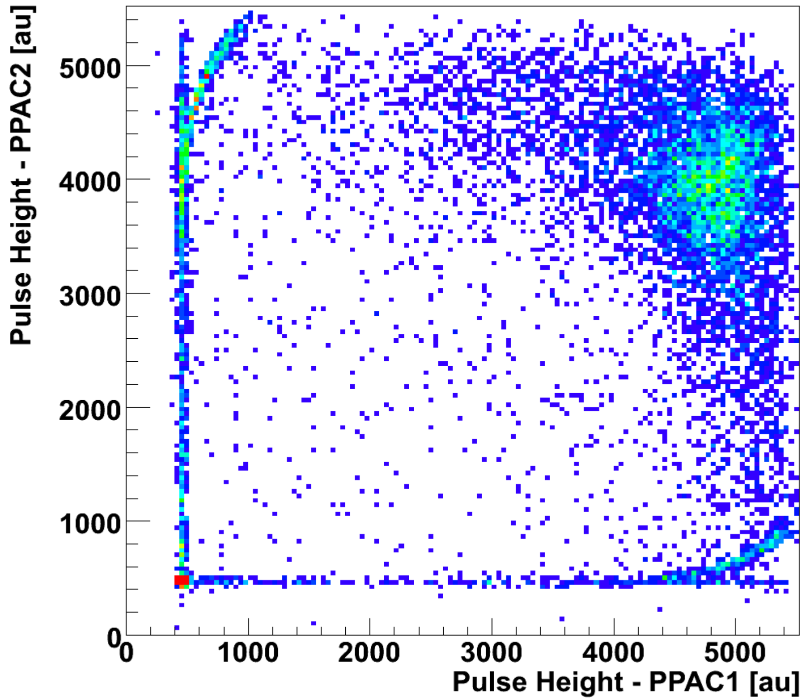
Capture and fission on actinides

- Fission can be identified using additional fragments detectors

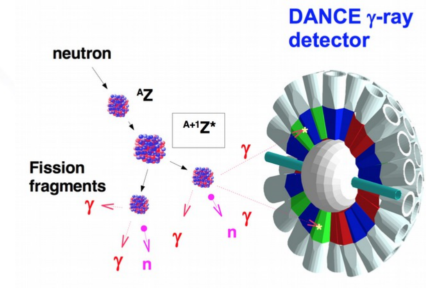


Parallel Plate Avalanche Counter





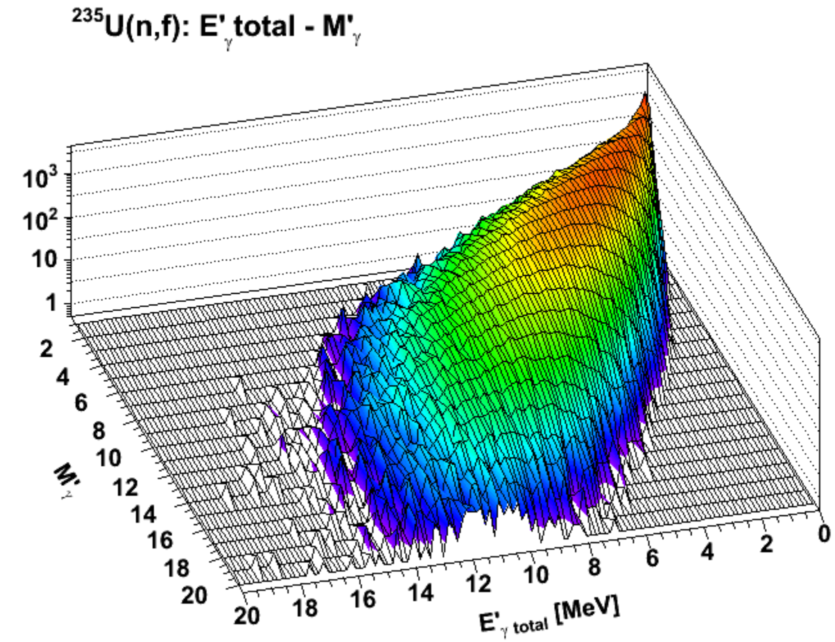
Coincidence between two sides of PPAC removes alpha particles

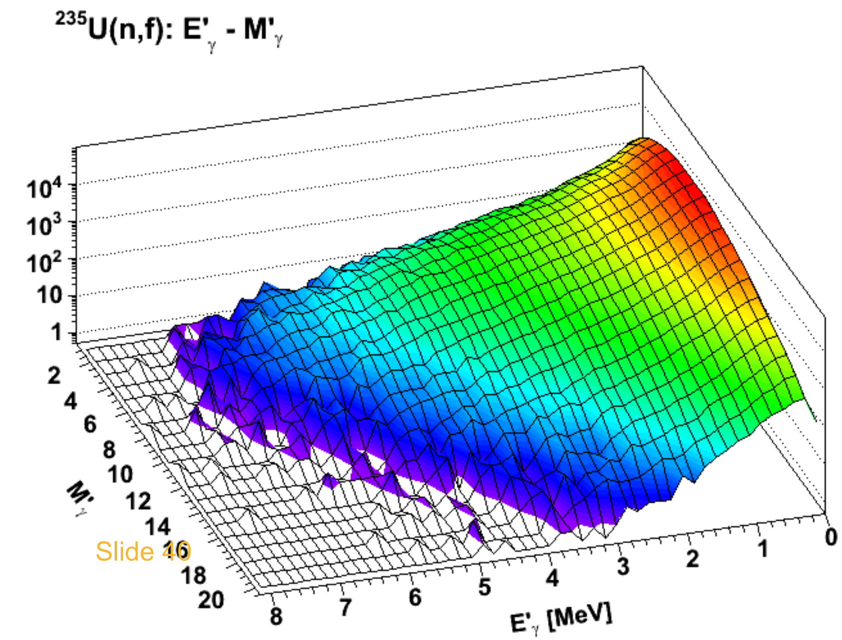


Fission
$\Sigma E\gamma$ = wide distribution
$M\gamma$ = wide distribution

DANCE – efficient gamma-ray calorimeter

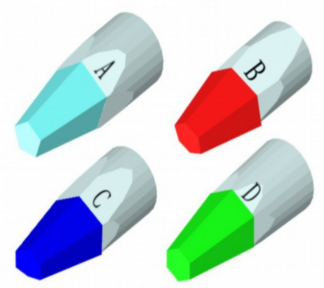
- With high efficiency and 4π solid angle DANCE is ideal for prompt-fission gamma-rays studies
- We measure correlated events of Mγ, Eγ and $E_{\gamma tot}$
- Complicated analysis – how to obtain original spectra of PFG ?
- Cross talk, and pileup is an issue
- One needs a very precise model of the DANCE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

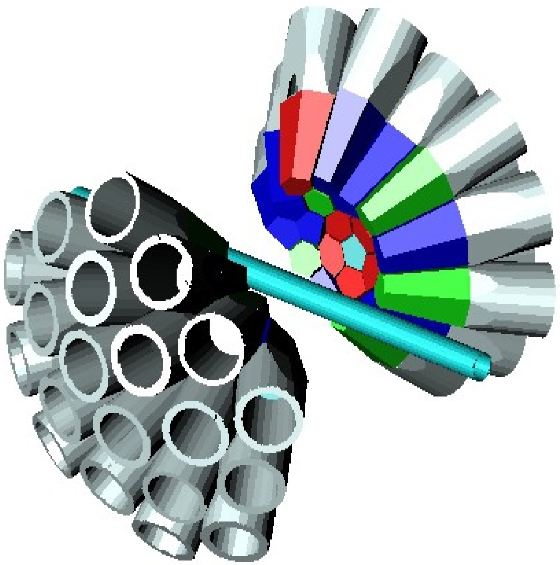


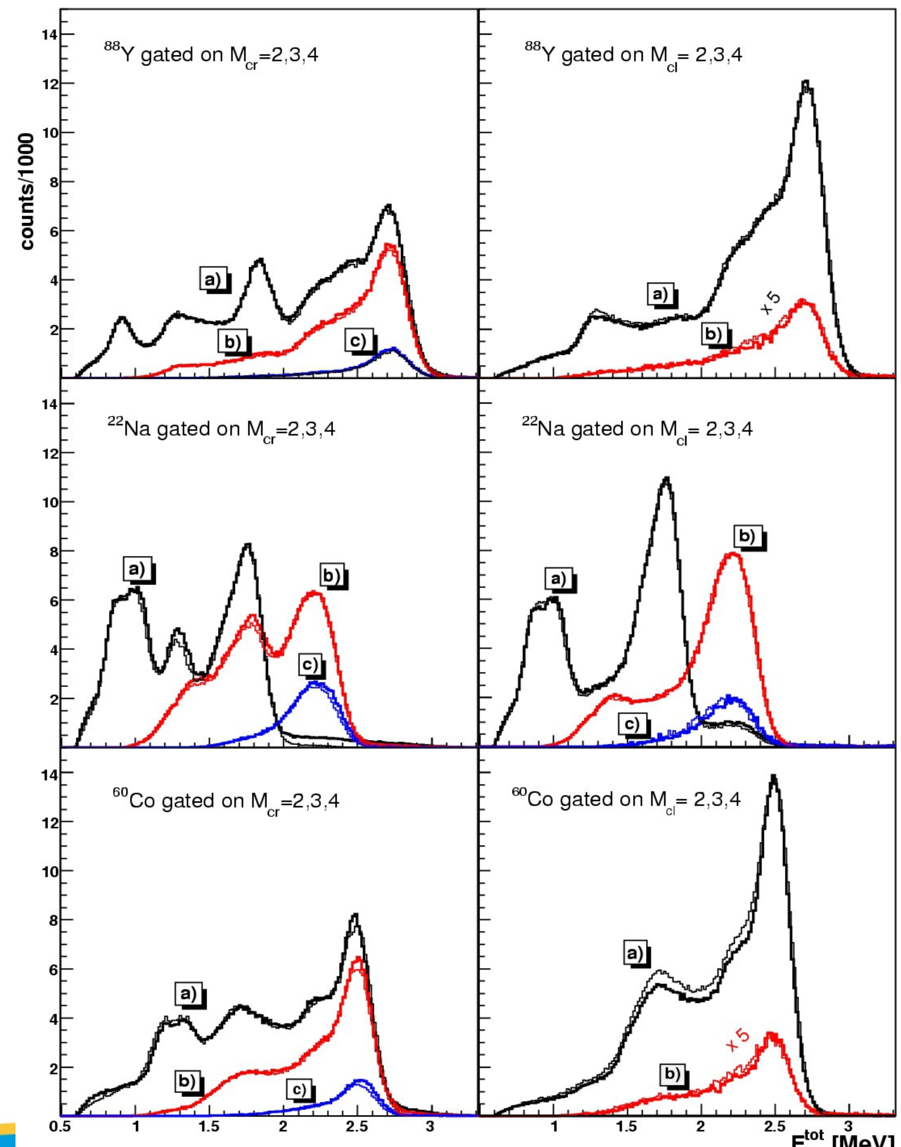


DANCE – Geant4 detector response

- 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

- **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:

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

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

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

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

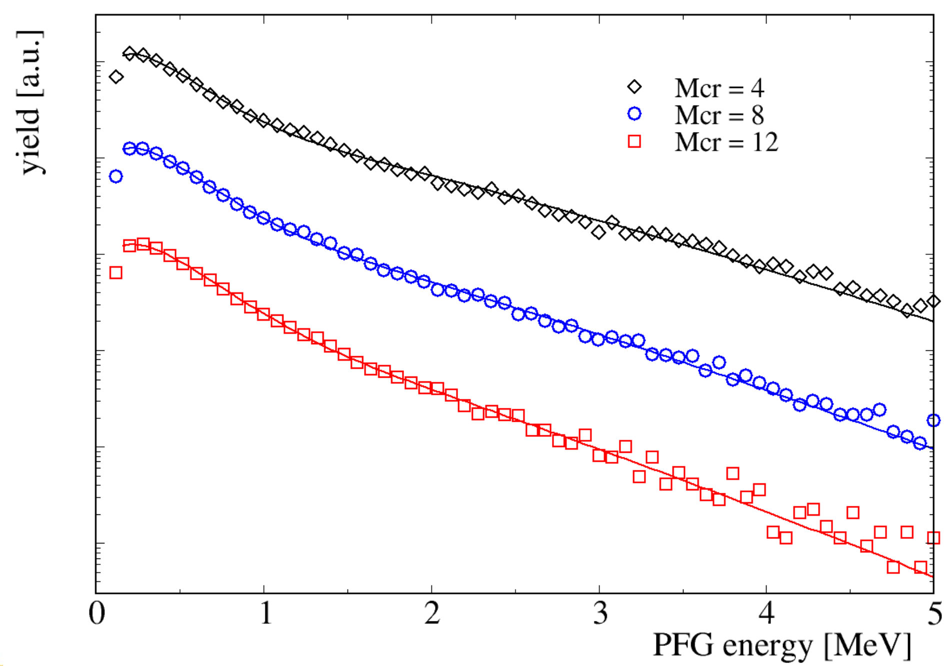
$$p_1(E_\gamma) \propto E_\gamma^2 e^{-t_1 E_\gamma}$$

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

$$M_\gamma = M_1 + M_2$$

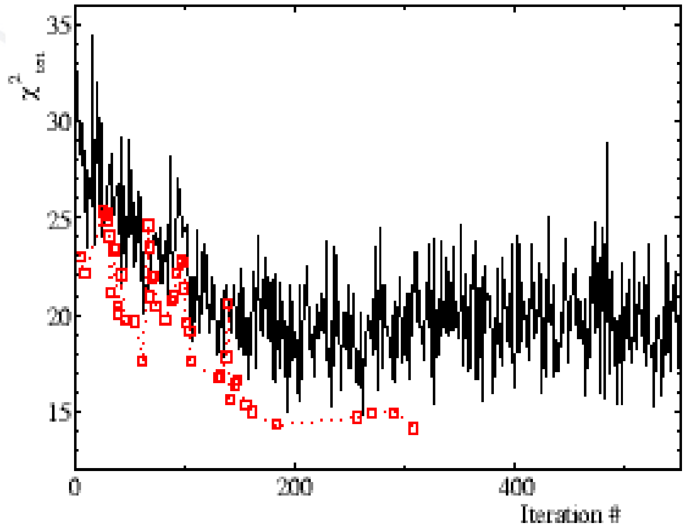
$$t_{1,2} = a_{1,2} + b_{1,2} M_\gamma$$

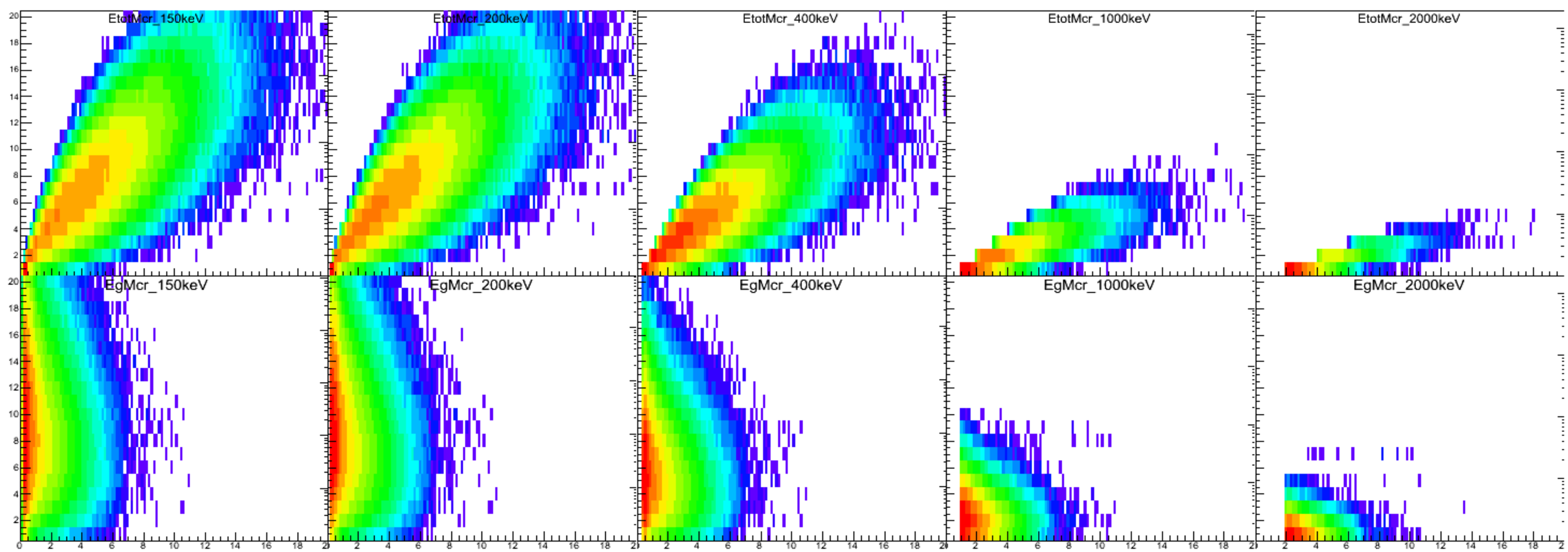
6 *free parameters*: $a_{1,2},\, b_{1,2},\, c_{1,2}$



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

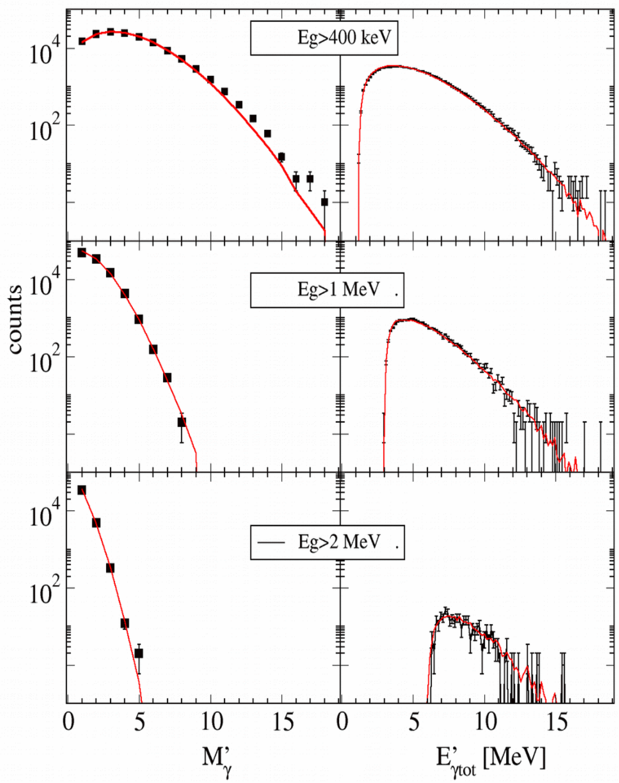


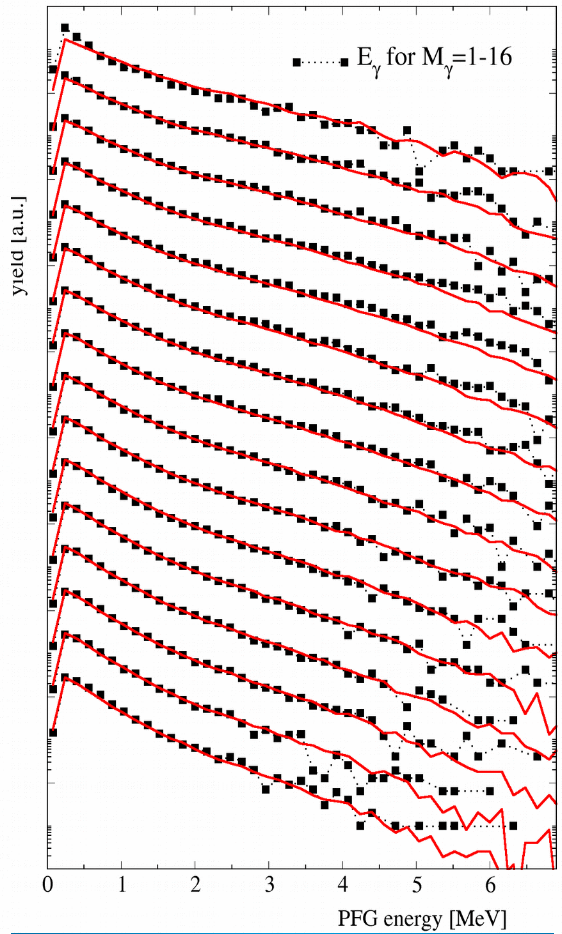


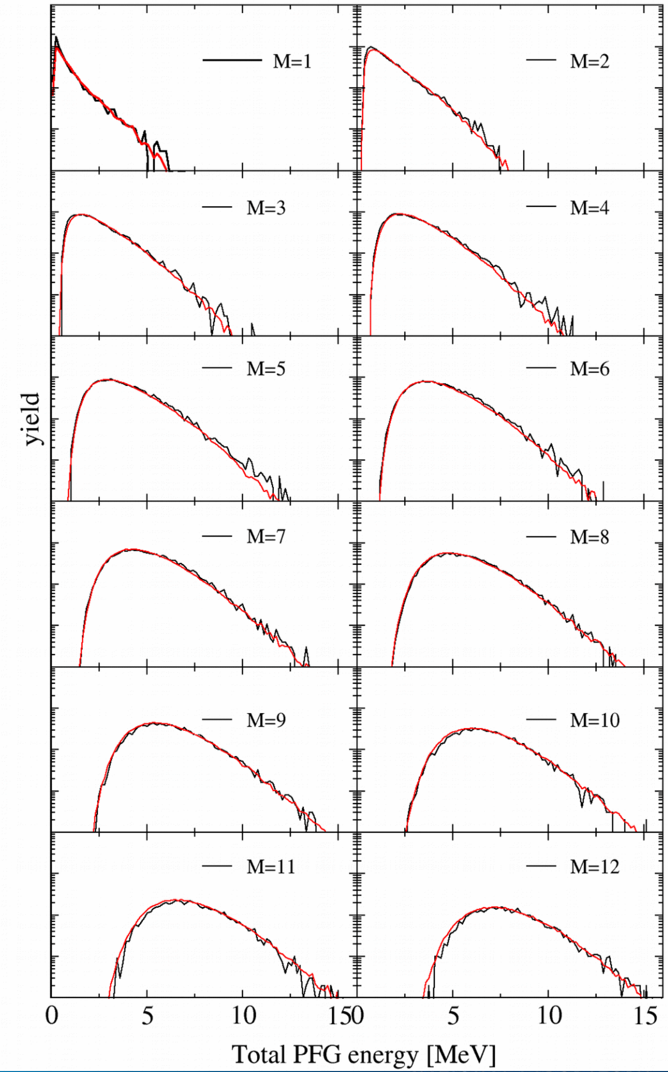
M. Jandel et al., to be published in Physics Procedia, conf. proceedings of GAMMA-2, Sremski Karlovci, Serbia, 2013

Deduced PFG for U-235(n,f)

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







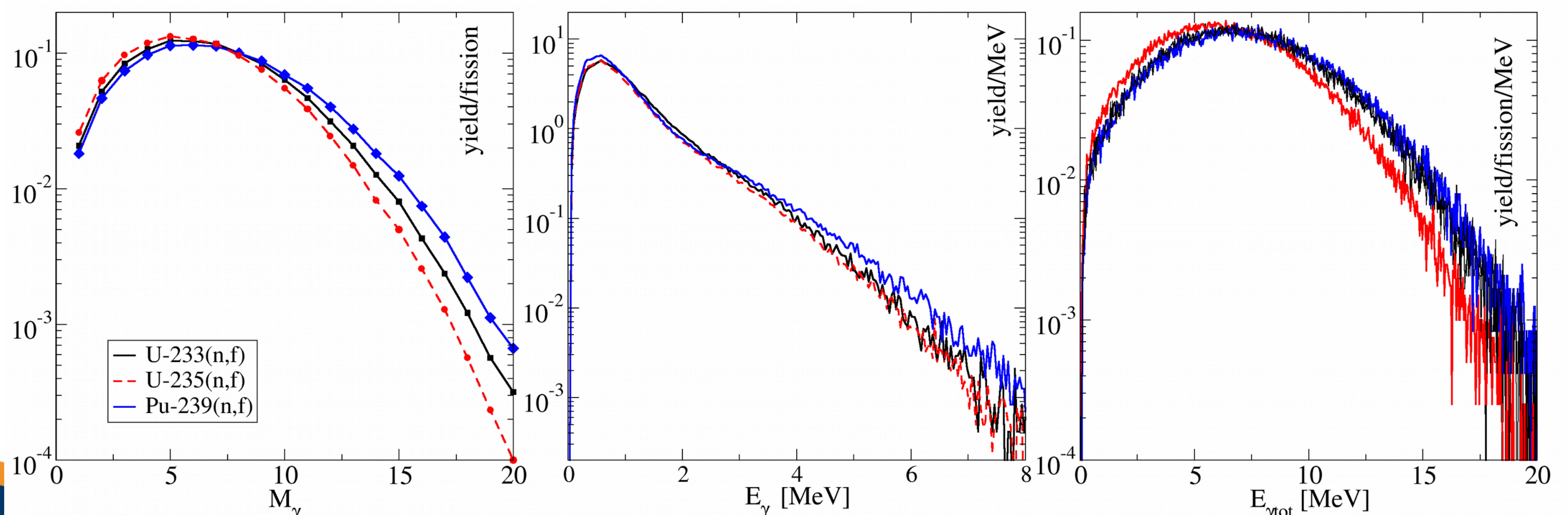
Deduced PFG for U-235(n,f)

- 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)

6 freeparameters:$a_{1,2}, b_{1,2},$



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

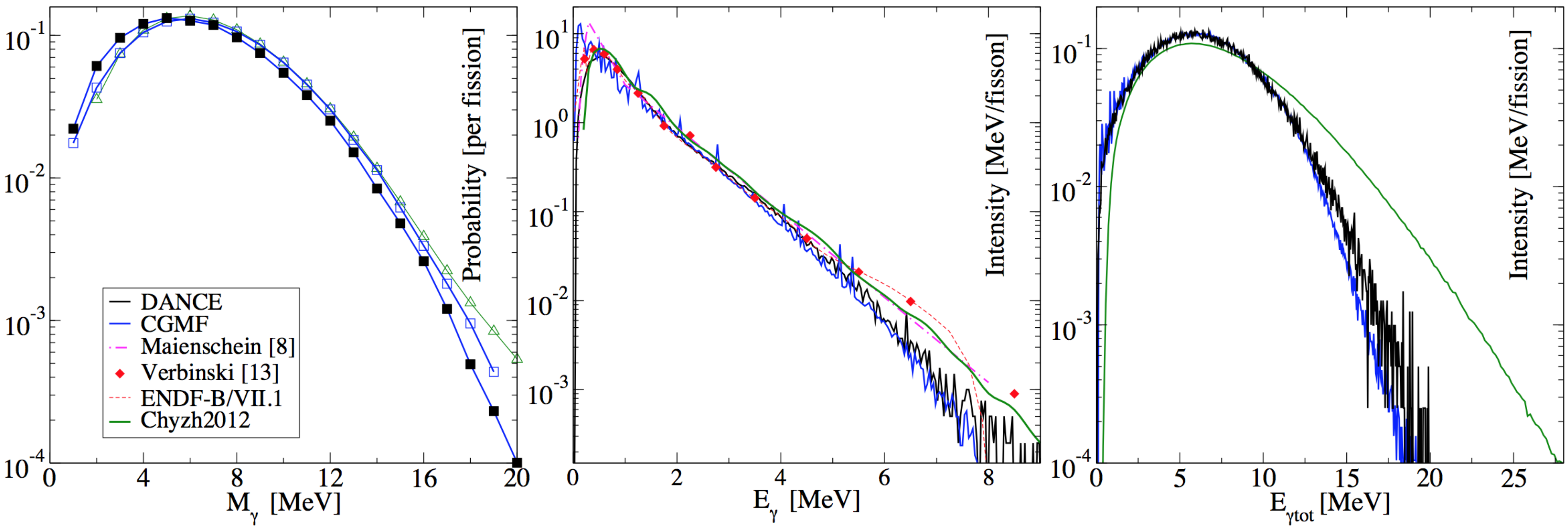


FIG. 17. Properties of PFG emission in neutron induced fission of U-235 deduced from DANCE experimental data using parametrized PM and CGMF models, respectively. Multiplicity M_γ, energy E_γ and total energy $E_{\gamma tot}$ distributions are shown from left to right, respectively. Black full symbols 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.

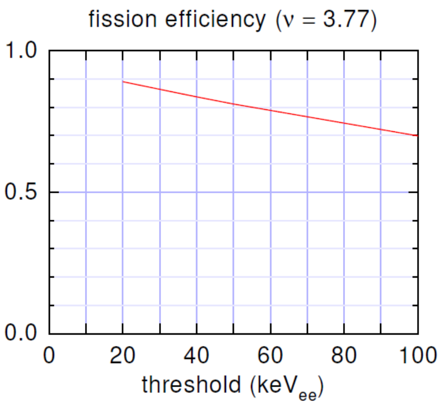
1D deconvolution - A. Chyzh et al., Phys. Rev. C **87**, 034620
!! If spectral intensity does not change with Mg – total energy is not reproduced well !!

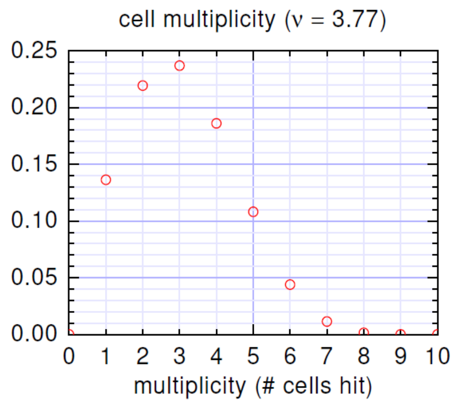
NEUANCE - NEUtron Array at daNCE

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

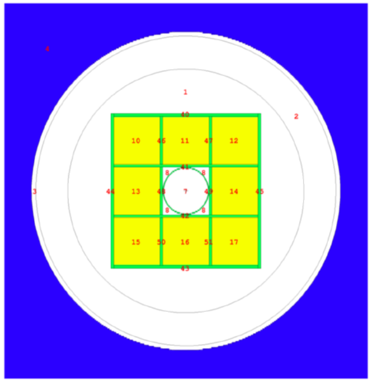
Detection efficiency for fission events is much higher

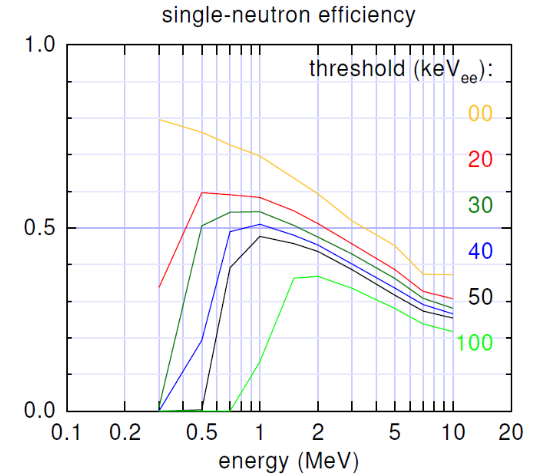
Yet to do: TOF windowing and pileup corrections





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

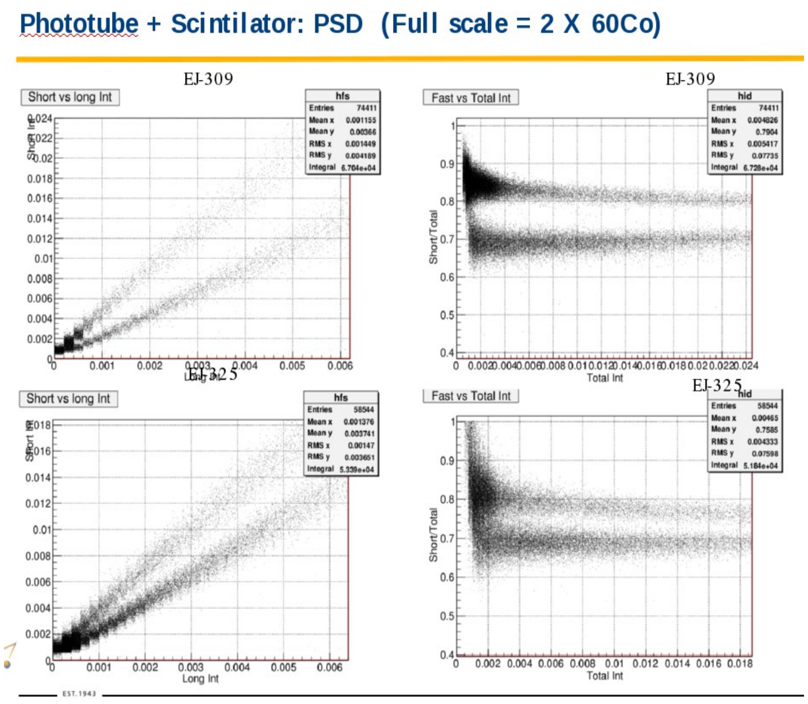




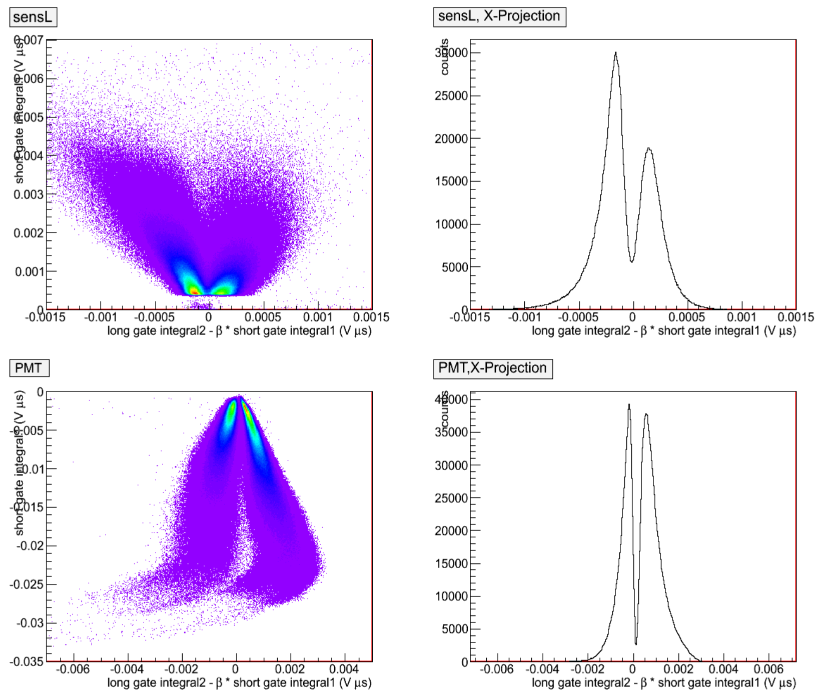
NEUANCE - NEUtron Array at daNCE

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

Liquid Scintillator + PMT



Stilbene + SiPM(6x6mm)



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