Current and future fission research at DANCE

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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 Jπ 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 BaF₂ 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
\[ \Sigma E_\gamma = Q \ (6.35 \text{ MeV}) \]
\[ M_\gamma = \text{narrow distribution} \]

Fission
\[ \Sigma E_\gamma = \text{wide distribution} \]
\[ M_\gamma = \text{wide distribution} \]
Capture and fission on actinides

- Fission can be identified using additional fragments detectors

Parallel Plate Avalanche Counter

\[
\text{Fission}\quad \Sigma E_\gamma = \text{wide distribution}
\]

\[
M_\gamma = \text{wide distribution}
\]
**Capture and fission on actinides**

- Fission can be identified using additional fragments detectors

**DANCE measurements**

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
Capture area

- Fission can be identified using additional fragment detectors.

Capture and fission on actinides

**Fission**

\[ \Sigma E_{\gamma} = \text{wide distribution} \]

\[ M_{\gamma} = \text{wide distribution} \]

**Parallel Plate Avalanche Counter**

Correlated prompt-fission gamma ray spectra are measured in coincidence 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 – $4\pi$ neutron detection
  - Funded by LDRD/DR (LANL), DOE
A) High fidelity neutron capture measurements at DANCE

**Capture XS: high precision U235 and Pu239**

- PFG spectra obtained using PPAC tagging
- Very good understanding of PFG($M\gamma$)
- 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 $^{235}\text{U}(n,\gamma)$
- Precision $<3\%$ was achieved using simultaneous rate determination;
  - Rates of $^{235}\text{U}(n,\gamma)$ and $^{235}\text{U}(n,f)$
  - The same target $\rightarrow$ same neutron flux for both reactions
  - Parallel Plate Avalanche Counter for (n,f)


- Successfully implemented for $^{239}\text{Pu}$
  S. Mosby et al., PRC 89, 034610

$$\sigma\left(^{235}\text{U}_{n,g}\right) \propto \frac{R\left(^{235}\text{U}_{ng}\right)}{R\left(^{235}\text{U}_{nf}\right)} \sigma\left(^{235}\text{U}_{n,f}\right)$$
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B) Correlations of prompt-fission gamma-rays and fission fragments

**DANCE – efficient gamma-ray calorimeter**

- With high efficiency and $4\pi$ solid angle, DANCE is ideal for prompt-fission gamma-rays studies
- We measure correlated events of $M_\gamma$, $E_\gamma$ and $E_{\gamma\text{tot}}$
- 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
B) Correlations of prompt-fission gamma-rays and fission fragments

**DANCE – Geant4 detector response**

- Total $\gamma$-ray energy spectra gated on cluster and crystal multiplicity
  - Experiment (thick lines)
  - GEANT4 (thin lines)
  - $M=2$ (black)
  - $M=3$ (red)
  - $M=4$ (blue)

- $^{88}\text{Y, }^{22}\text{Na, }^{60}\text{Co}$
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

PFG models

Vary model parameters

Calculate cascades of gamma-rays

Compare experimental and simulated data - Chi$^2$

Transport PFG in DANCE (Geant4)
B) Correlations of prompt-fission gamma-rays and fission fragments

Deducing the real PFG emission properties including correlations

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

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

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

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

- $p(M_{1,2}) = (2M_{1,2} + 1) e^{-M_{1,2} (M_{1,2} + 1)/2c_{1,2}^2}$
- $p_1(E_\gamma) \propto E_\gamma^2 e^{-t_1 E_\gamma}$
- $p_2(E_\gamma) \propto E_\gamma^3 e^{-t_2 E_\gamma}$

$M_y = M_1 + M_2$
$t_{1,2} = a_{1,2} + b_{1,2} M_y$

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: $E = \Sigma \chi^2$
- $\Sigma \chi^2 : 125 \times 20 \times 2 \times 4 = \text{experimental values compared to simulated}$
- 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
B) Correlations of prompt-fission gamma-rays and fission fragments

Deduced PFG for U-235(n,f)

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

M. Jandel et al., to be published in Physics Procedia, conf. proceedings of GAMMA-2, Sremski Karlovci, Serbia, 2013
B) Correlations of prompt-fission gamma-rays and fission fragments

Deduced PFG for U-235(n,f)

- Excellent agreement obtained using PM
- Correlation between $E_g$, Mg

\[
\begin{array}{cccccc}
\text{Nuclide} & \text{Mg} & \text{sig} & E_g & \text{sig} & E_{g,\text{tot}} & \text{sig} \\
235\text{U} & 6.31 & 3.02 & 1.025 & 0.8100 & 6.480 & 3.0700 \\
233\text{U} & 6.76 & 3.15 & 1.077 & 0.8300 & 7.240 & 3.3200 \\
239\text{Pu} & 7.21 & 3.42 & 1.036 & 0.8800 & 7.430 & 3.4300 \\
242m\text{Am} & 7.14(5) & 3.45(4) & 0.999(5) & 0.88(1) & 7.13(6) & 3.32(3) \\
252\text{Cf} & 8.11(7) & 3.77(4) & 0.891(9) & 0.807(9) & 7.22(6) & 3.33(3) \\
\end{array}
\]

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

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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 $M_\gamma$, energy $E_\gamma$ and total energy $E_{\gamma\text{tot}}$ 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 $\alpha_I=1.3$. Data on $E_\gamma$ from [13] and [8, 14] are shown using red markers and magenta dashed-dotted line, respectively.

!! If spectral intensity does not change with Mg – total energy is not reproduced well !!
B) Correlations of prompt-fission gamma-rays and fission fragments

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
  - Averages and variances of PFG distributions
- Improving transport codes
- MCNP6 development – de-excitation modules (gamma/neutrons in correlation)
B) Correlations of prompt-fission gamma-rays and fission fragments

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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C) Short-lived Actinide Isomers - NEUANCE

Isomeric states after U235+n

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


- $E_{\text{tot}}$ variations with $\Delta T$ and number of gamma-rays detected in a $\Delta T$ window

![Diagram of gamma-ray energy spectra with different multipolarities (M) and transition energies (E*)](image)

- Neutron-capture state
  - U-236($E^* = 6.54$ MeV)
  - $M_{1\gamma} = 4$
  - $E_{1\text{tot}} = 5.4$ MeV

- Isomeric state
  - U-236($E^* = 1.05$ MeV)
  - $T_{1/2} = 100$ ns
  - $M_{2\gamma} = 2$
  - $E_{2\text{tot}} = 1$ MeV

- Ground state U-236
  - $\Delta T = 5$ns
  - $\Delta T = 200$ ns
  - time (ns)
Isomeric states after U235+n

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

What is the population of these states after $^{235}\text{U}+n$?
What are the n-reaction cross sections on these states?
C) Short-lived Actinide Isomers - NEUANCE

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
C) Short-lived Actinide Isomers - NEUANCE

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
C) Short-lived Actinide Isomers - NEUANCE

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

fission efficiency ($\nu = 3.77$)

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

single-neutron efficiency

threshold (keV): 00 20 30 40 100

energy (MeV): 0.1 0.2 0.5 1 2 5 10 20
C) Short-lived Actinide Isomers - NEUANCE

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
C) Short-lived Actinide Isomers - NEUANCE

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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