Applications of Nuclear Science

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Joint DNP Town Meetings on Nuclear Structure and Nuclear Astrophysics

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Outline – examples of applications of Nuclear Science

- **Single event effects: neutron-induced failures in Semiconductor devices**

- **Production of medical isotopes for cancer therapy**

- **Fission reactions: cross sections, fission neutron output spectra and fission fragment production**

- **Neutron radiography of reactor fuel rods**

Neutron-induced failures in semiconductors- Single-Event Effects

Recent avionics incident highlight Single Event Effects (SEE) problem

- On October 7, 2008 , Quantas 72 was enroute from Singapore to Perth, Australia

- "While ..at 37,000 ft, **one of the aircraft's three Air Data Inertial Reference Units (ADIRU) started outputting intermittent, incorrect values**…Two minutes later …the aircraft flight control primary computers **commanded the aircraft to pitch down**. … **At least 110 of the 303 passengers and nine of the 12 crew members were injured**: 12 of the occupants were seriously injured and another 39 received hospital medical treatment." (Pg. vii)

- "The other potential **triggering event was a single event effect (SEE)** resulting from a high-energy atmospheric particle striking one of the integrated circuits within the CPU module. There was insufficient evidence available to determine if an SEE was involved, but **the investigation identified SEE as an ongoing risk for airborne equipment**." (pg. xvii)

- "Testing was conducted with neutrons at 14 MeV …the test was not sufficient to examine the …. susceptibility to the full range of neutrons at the higher energy levels that exist in the atmosphere". (pg. 147)

ATSB Transport Safety Report Aviation Occurrence Investigation AO-2008-70

- "The ATSB received expert advice that the best way of determining if SEE could have produced the data-spike failure mode was to test the affected units at a test facility that could produce a broad spectrum of neutron energies. However, the ADIRU manufacturer and aircraft manufacturer did not consider that such testing would be worthwhile for several reasons, including that:

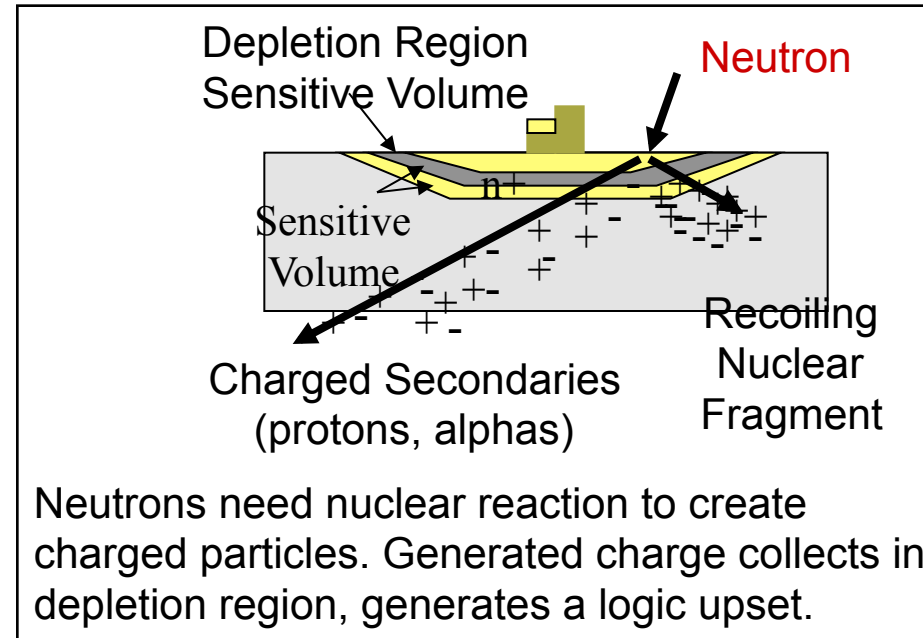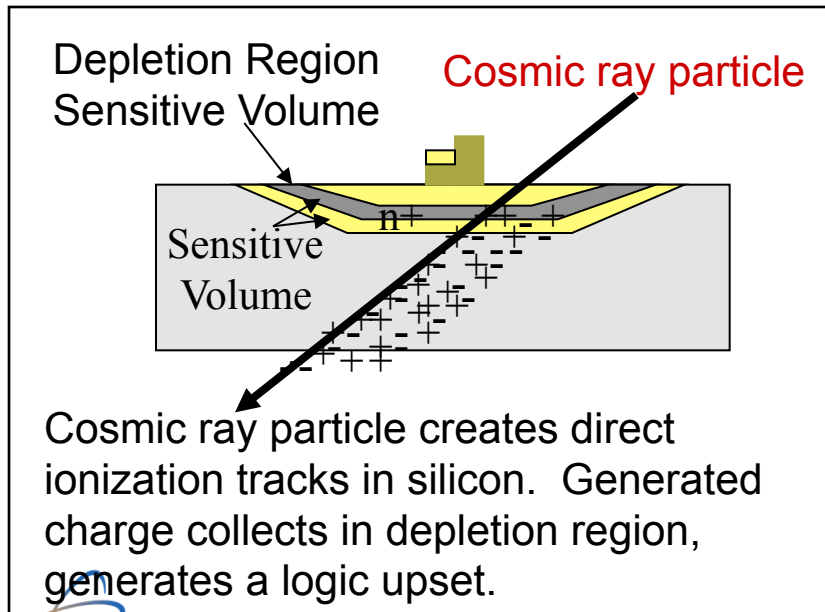- There were significant logistical difficulties in obtaining access to appropriate test facilities"

Neutron Single Event Effects (SEE) are faults in electronic devices caused by neutrons from cosmic rays
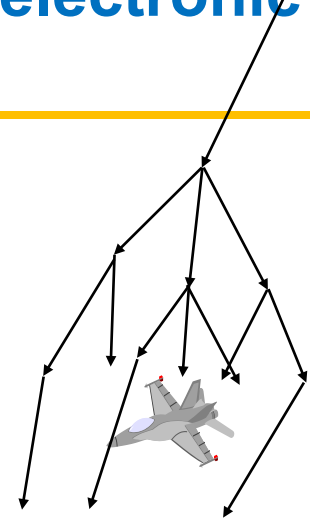
- **Neutrons are produced by cosmic rays in the upper atmosphere**

- **Neutrons have long mean-free paths so they penetrate to low altitudes**

- **Neutrons interact with Si and other elements in the device to produce charged particles**

- **Charged particles deposit charge in sensitive volume which cause state of node to change**

Depletion Region
Sensitive Volume

Cosmic ray particle

Sensitive Volume

n+

Cosmic ray particle creates direct ionization tracks in silicon. Generated charge collects in depletion region, generates a logic upset.

Depletion Region
Sensitive Volume

Neutron

Sensitive Volume

n+

Recoiling Nuclear Fragment

Charged Secondaries (protons, alphas)

Neutrons need nuclear reaction to create charged particles. Generated charge collects in depletion region, generates a logic upset.

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Many types of single-event effects can cause failures

- **Soft errors**
  - Single event upset
  - Multiple event upset (a few % of SEU rate)
  - Silent data corruption

- **Hard errors**
  - Single event latchup
  - Single event burnup, gate rupture, etc.

- **High power analog devices**

- **First experiments were performed by the Boeing Co. for 777 certification**

- **Industry trends to lower voltages and smaller feature size are thought to increase the failure rate due to SEE**

- **Similar devices have very different failure rates**

- **The failure rate due to SEU is equal to all the other failure modes combined**

- **" Since chip SER is viewed by many as a legal liability (something that you know may fail) the public literature in this field is sparse and always makes management nervous". *SER History, Trends and Challenges* James Ziegler and Helmut Puchner**

Cosmic-ray induced failure rates

- **The failure rate due to cosmic-ray events is given by:**

$$F/t = \sum_p \int f_p(E_p) * \Phi_p(E_p) \, dE_p$$

Failure function depends on
Device characteristics
Particle type
Particle energy

Particle flux depends
Particle type
Altitude
Latitude
Solar activity
Local geometry
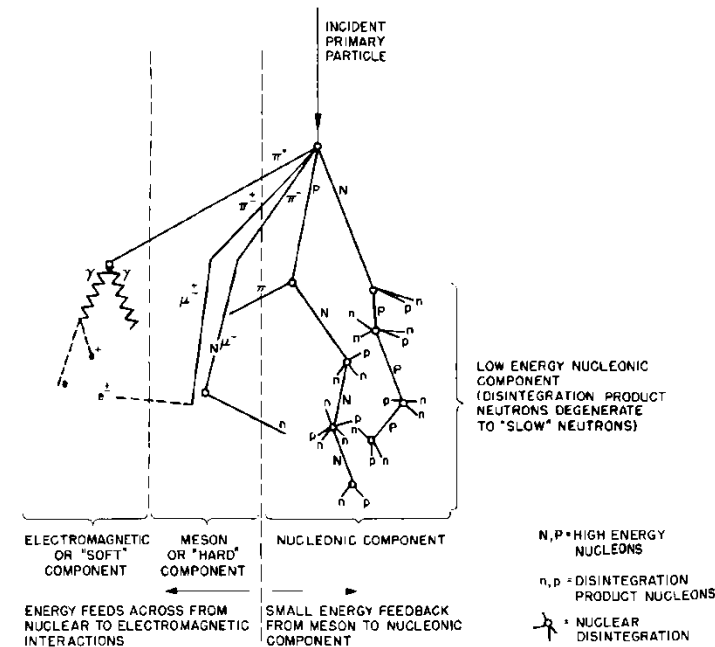
Schematic Diagram of Cosmic Ray Shower

F/t is the number of fails / time

p is the particle type (neutron, protons, pions,…)

$f_p(E_p)$ is the number of fails /particle with energy E_p

$\Phi_p(E_p)$ is the number of particles/sec with energy E_p

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Slide 7

Measured cosmic ray flux agrees with formulas at 7000 ft at Los Alamos

- **The neutron flux was measured by Goldhagen et al. (1997) using Bonner spheres**

- **Cosmic-ray neutron flux depends on altitude, lattitide, geometry, etc.**

Los Alamos Cosmic-Ray Neutron Spectrum
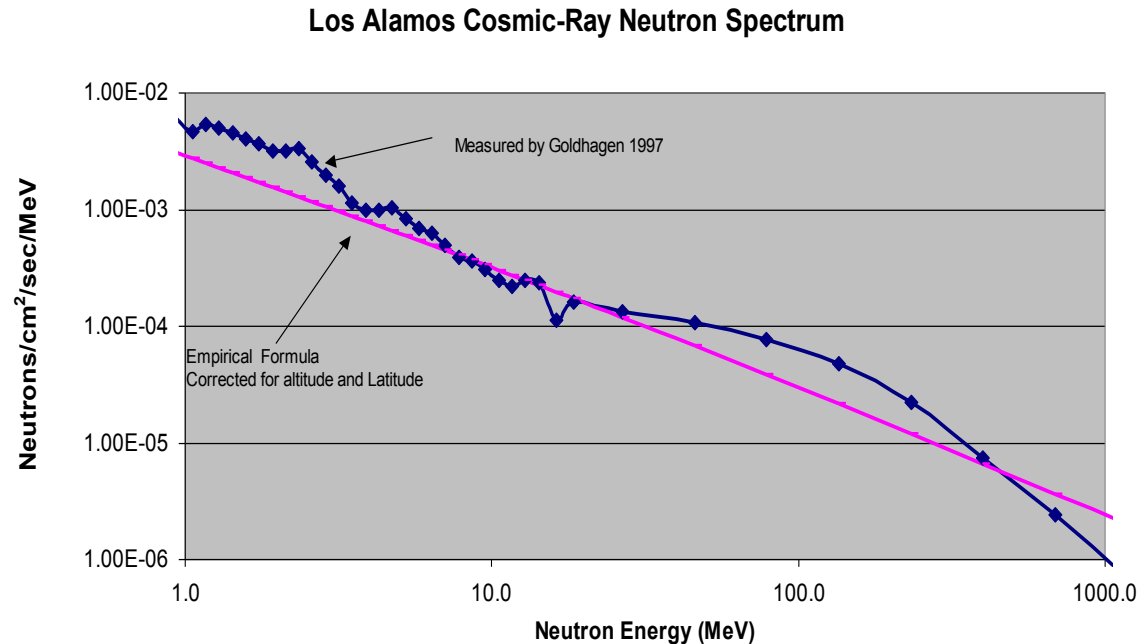
Integrated cosmic-ray neutron flux above 10 MeV (neutrons/cm^2/sec)

	n/cm2/s	Relative
Sea level (New York City)	**0.00565**	**1**
7000 ft (Los Alamos)	**0.019**	**3.4**
40,000 feet	**1.53**	**270**

When neutrons interact with Si charged particles are produced

- **Neutrons strike silicon and produce recoil Silicon nuclei and alpha particles, etc.**

Incident neutron energy (MeV)	Max recoil energy (MeV)	Range of particle in Si (μm)	Energy loss (keV/μm)
30	6 (Si)	3.6	2750
100	14 (Si)	6.2	3300
50	40 (α)	710	32

- Simple models exist to estimate upset rates based on recoil spectra
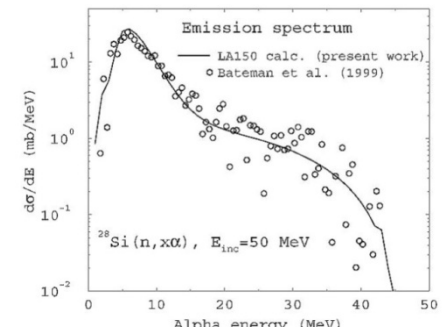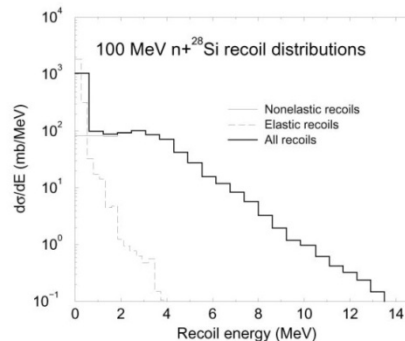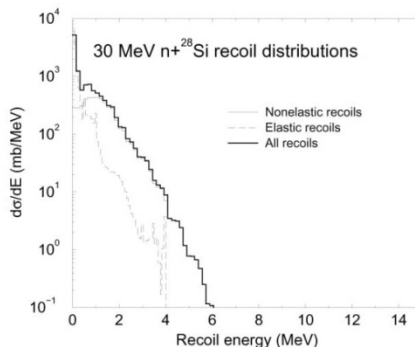
Accelerated testing is essential

- **Design criteria for servers (100 GB memory) is 1 fail / year from SEU**
    - If need to know the failure rate to 10%, need 100 fails
    - Need to run server for 100 years! RAMs change every 18 months

- **Need to perform accelerated testing with acceleration rate~ 5000 (3.6×10^4) to get answer in 1 week (1 day) if testing entire server**

Neutron Flux at Los Alamos and LANSCE/WNR

Neutron spectrum at LANSCE/WNR divided by 5×10^9

Flux mesurement by Goldhagen 1997 at Los Alamos

y-axis: $N/cm^2/MeV/sec$
x-axis: Neutron Energy (MeV)

- **Need to test individual chips before they go into system**
    - A 100GB server may have ~300 memory chips
    - The failure rate of a single chip is 1 fail / 300 years
- **This requires an acceleration factor of ~ 10^7 for 1 day of testing to get 100 fails**
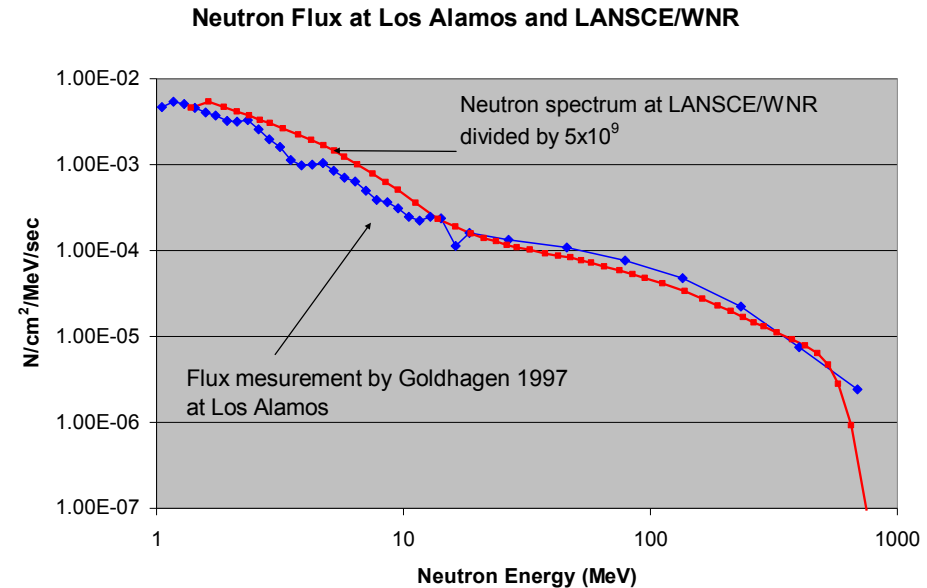
Neutrons can cause failures in high-power semiconductor devices

- **IGBT are semiconductor devices that are used in many high-power applications such as BART, hybrid cars, accelerator RF systems, etc.**

- **The lifetime of these devices in neutron fields depends on the electric field or the applied voltages**

- **Tests show a dramatic decrease in lifetime at a critical voltage which is significantly below the rated operating voltage**

IGBT DATA SUMMARY
3300 V Devices

Beam Lifetime (minutes) vs C/E Voltage (Volts)

One neutron can stop a train

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NNSA
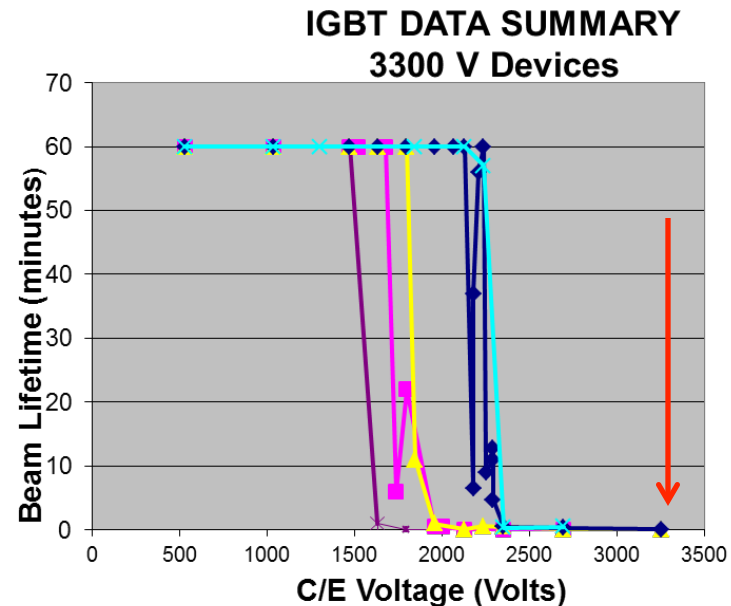
Results of LANSCE/WNR measurements determine problem with ASCI Q-Machine

- The ASCI Q-Machine has 2048 nodes with a total of 8192 processors.

- During commissioning, it was observed that the Q-machine had a larger than expected failure rate. Approximately 20 fails / week (~3 fails / day).

- The question was whether this could be the result of neutron single-event upset.

ASCI Q-Machine at Los Alamos National Laboratory

Fails/day ~ [# of fails/neutron] * [# neutrons/day]

Measured at LANSCE

Cosmic-ray neutron flux

The neutron environment and the system response was measured

- The neutron intensity was measured in the Q-Machine room. The values obtained agreed with the Goldhagen values

- The system response was measured by putting one module of the Q-Machine in the LANSCE/WNR beam.

- Results of measurement accounted for approximately 80% of the failures (IEEE Trans. Dev. Mat. Reliab. 5 2005)

- The failures were traced to a cache memory that was not error corrected.

- This result may have significant impact on future large computer systems
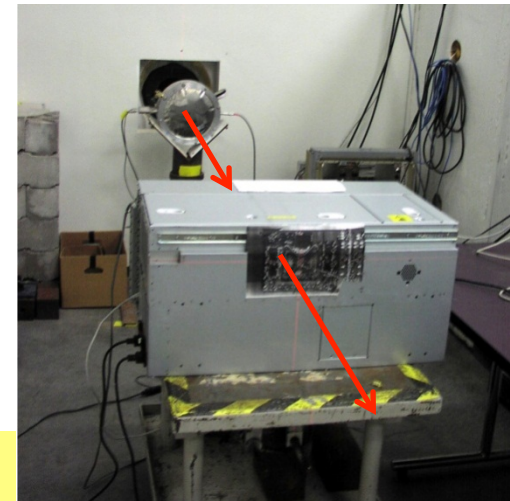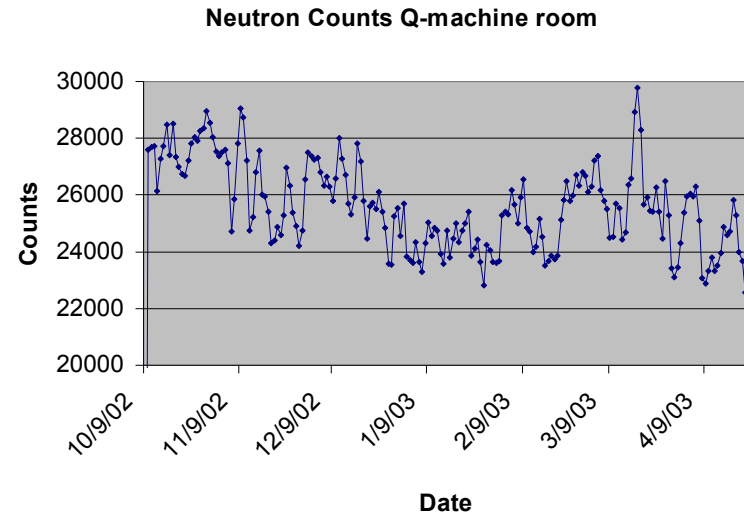
One neutron can stop a calculation

Neutron Counts Q-machine room

Applications Advances Ac-225 for Cancer Therapy

Background: Ac-225 for Cancer Therapy
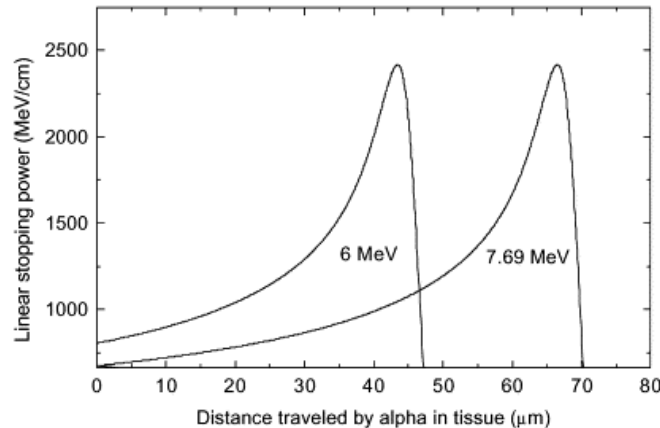
☐ **Alpha emitters have great advantages in cancer therapy**

- ○ **high linear energy transfer (LET)**

- ○ **limited alpha range in tissue (few cell diameters)**

☐ **4 alpha particles are emitted by an Ac-255 nucleus and its daughters**

☐ **Ac-225 also used as a Bi-213 generator**

☐ **Presently Bi-213 (1 alpha) is being evaluated as a cancer therapy agent in pre-clinical research**
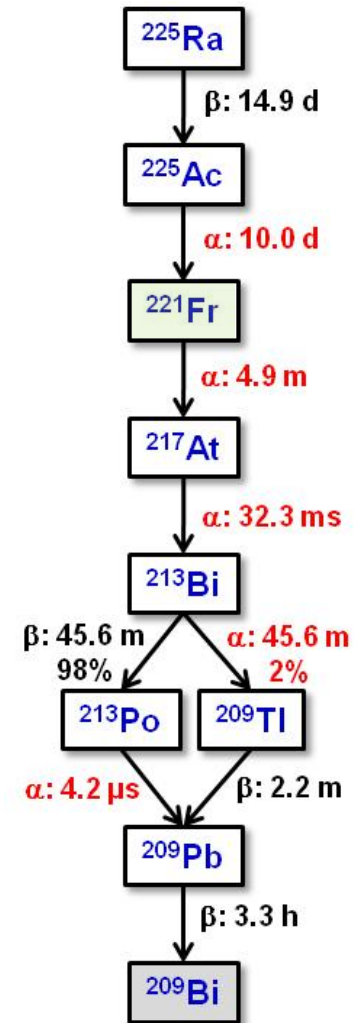
Present Ac-225 supply is limited

❑ **Most of the present global supply comes from decay of a Th-229 cow located at ORNL (~1 Ci annually)**

❑ **50 Ci and more is required to support clinical trials**

Year	Amount (mCi)	Program
2008	750	Clinical trials/R&D support
2009	1,600	Clinical trials (1 multi- center) /R&D support
2010	3,100	Clinical trials (2 multi- center) /R&D support
2011	4,600	Clinical trials (2 multi- center) /R&D support
2012	7,400	Clinical trials (3 multi-center)/R&D support
2013	15,000	One approval; Clinical trials(2 multi-center)/R&D
2014	50,000+	Two approvals; Clinical trials/R&D support

Accelerator Production Routes

Lower energies (ORNL)

^{232}Th(p,4n)^{229}Pa $\rightarrow$ ^{229}Th

^{232}Th(p,p3n)^{229}Th

High energies (LANL)

^{232}Th(p,x) ^{225}Ac

^{232}Th(p,x)^{225}Th $\rightarrow$ ^{225}Ac

^{232}Th(p,4n)^{229}Pa $\rightarrow$ ^{225}Ac

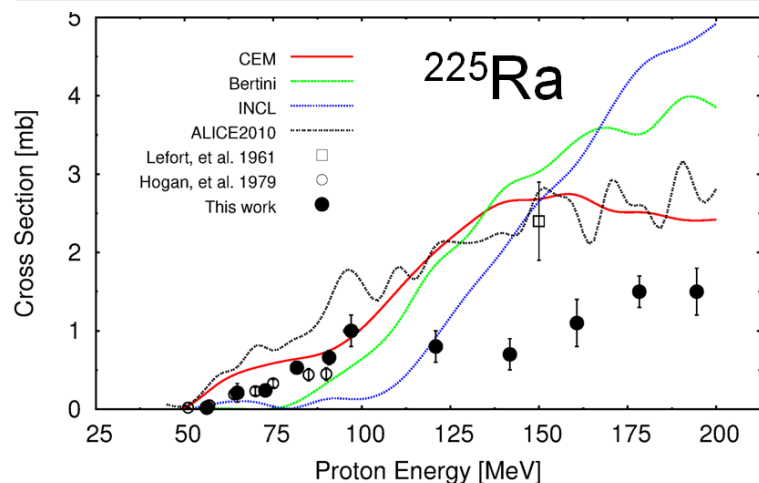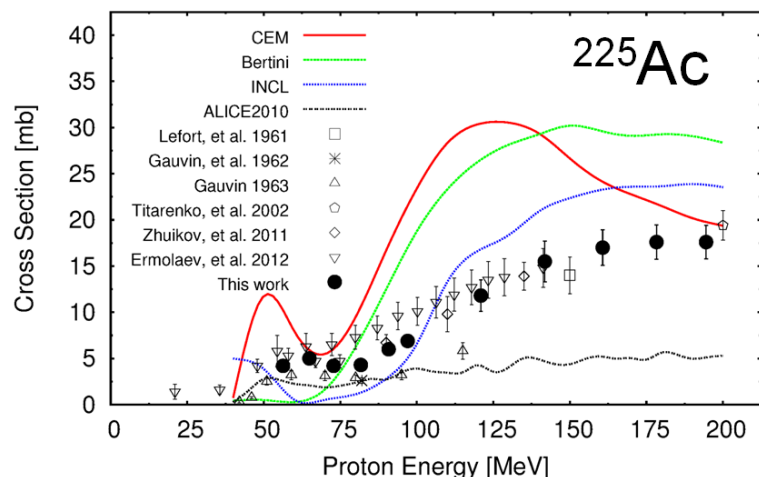^{232}Th(p,x)^{225}Ra $\rightarrow$ ^{225}Ac

Cross sections were measured as a function of energy using the well known stacked foil technique

■ **Data were obtained at 13 energies**

- 1 at 800 MeV
- 12 in the energy range 40-200 MeV

Al proton fluence monitor

Thorium sample

800 MeV Beam

200 MeV Beam

100 MeV Beam

Proton energy degrader
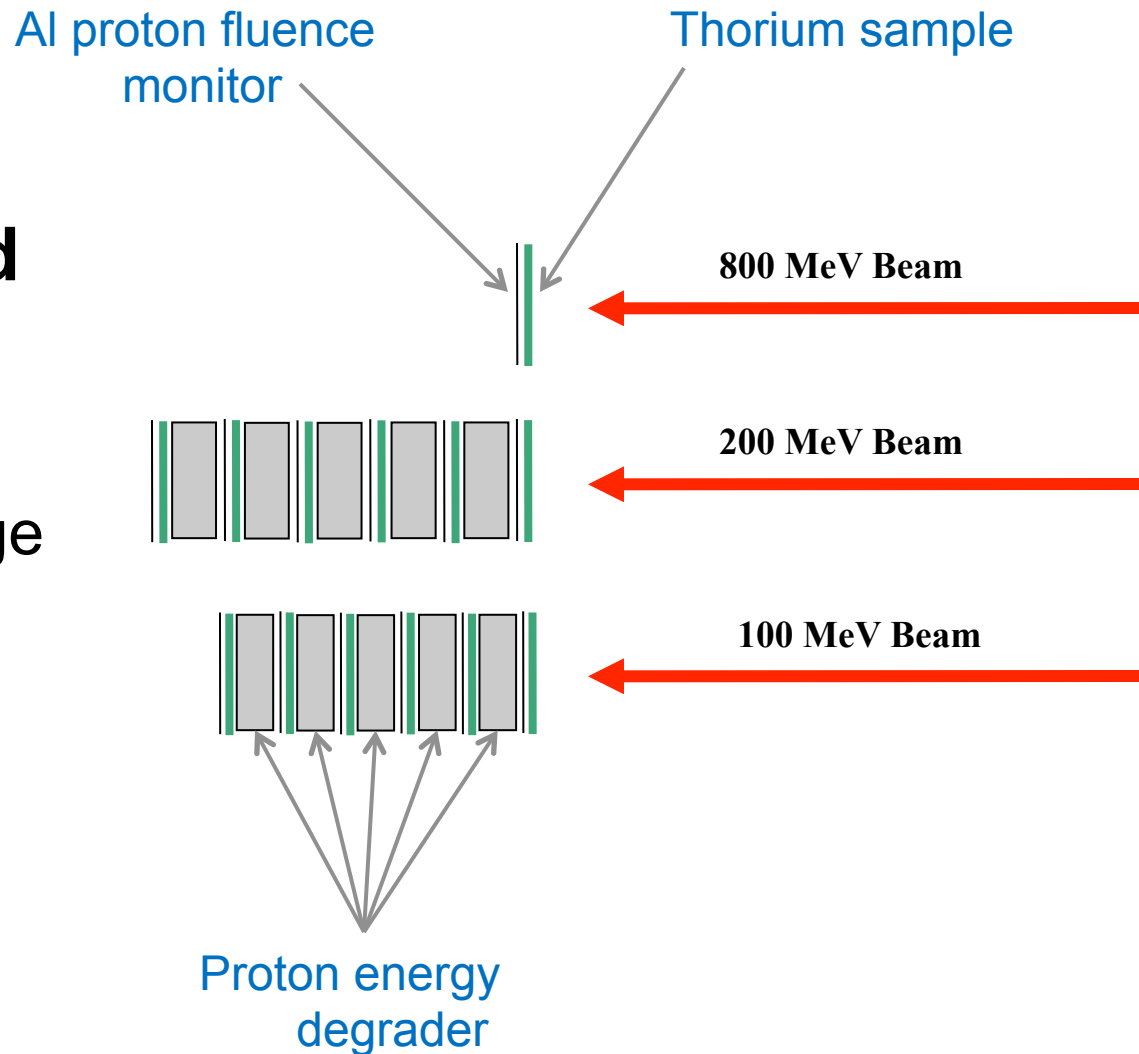
Production of ^{225}Ac

| Anticipated Thick Target Yields	5 g/cm^2 target yield for a 10 day irradiation	
	Ac-225 (Ci)	**Ra-225** (Ci)
IPF (250 µA)	1.4	0.1
BNL (100 µA)	2.0	0.1

- **Data show that large scale production is feasible at IPF and BLIP**

- **This part of the work produced 2 publications**
  J.W. Weidner et al. Appl. Radiat. Isot. 70 (2012) 2590
  J.W. Weidner et al. Appl. Radiat. Isot. 70 (2012) 2602

- **A third manuscript is in preparation**

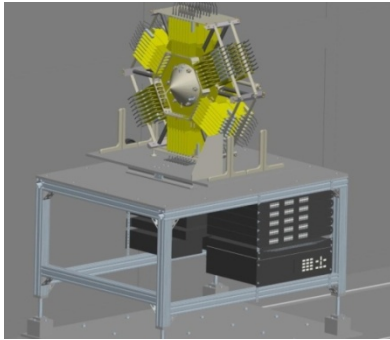# Extracted impurity cross sections are compared with literature data and model predictions
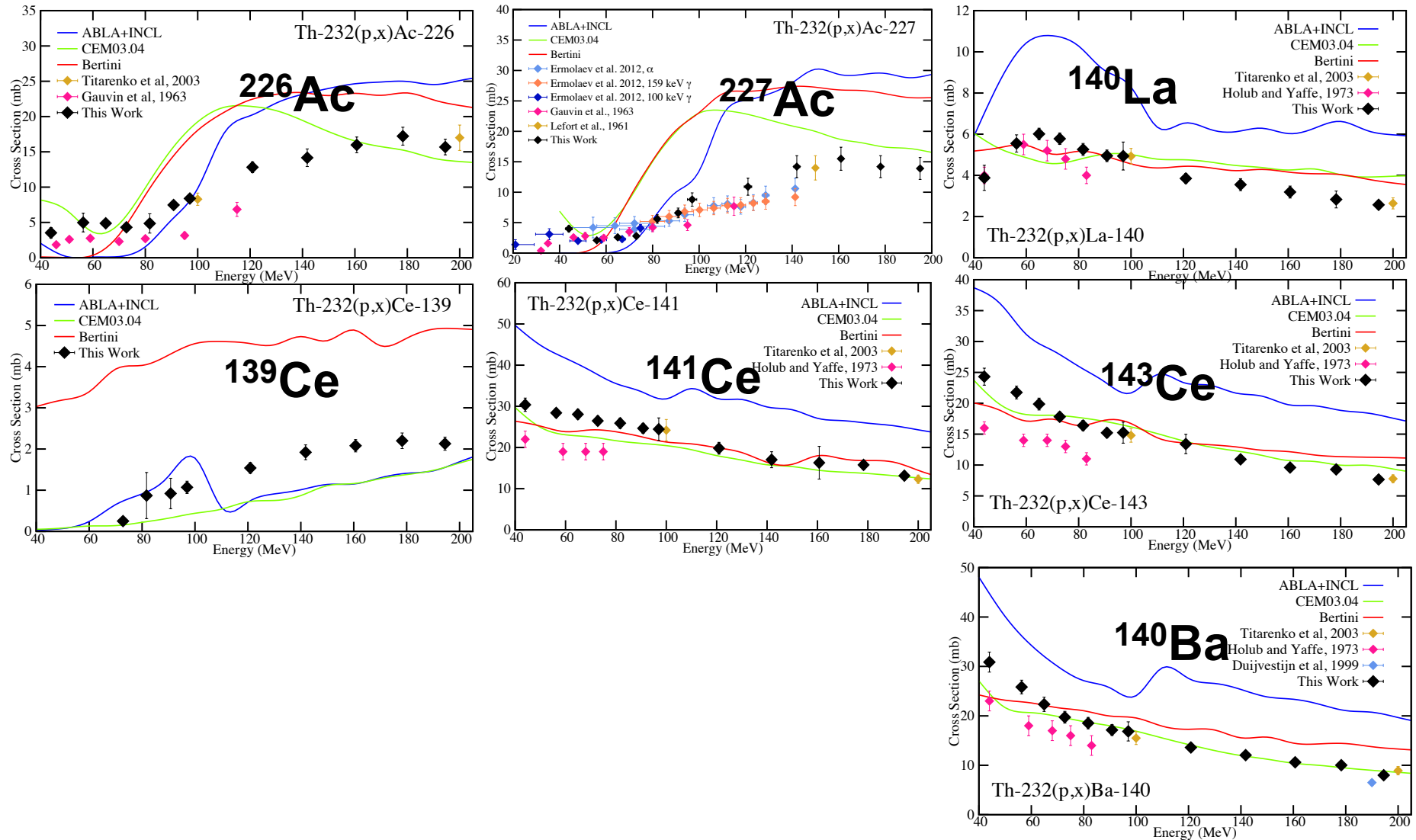
Fission reaction studies

Fission cross sections are important for Nuclear Energy technology and Defense Program applications

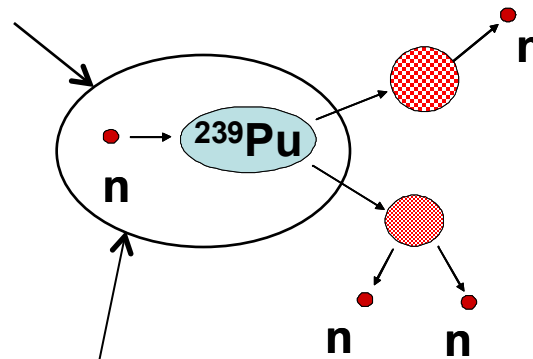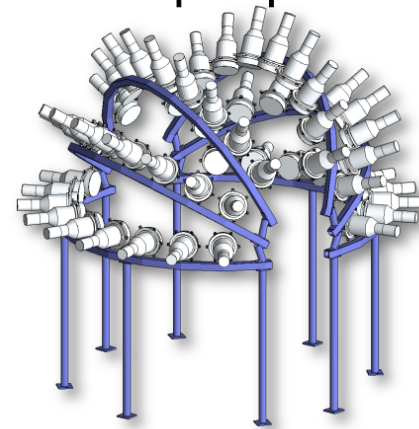## Time Projection Chamber (TPC)
High precision fission cross sections

Chi Nu (n,xn+γ)
Neutron output spectra

n

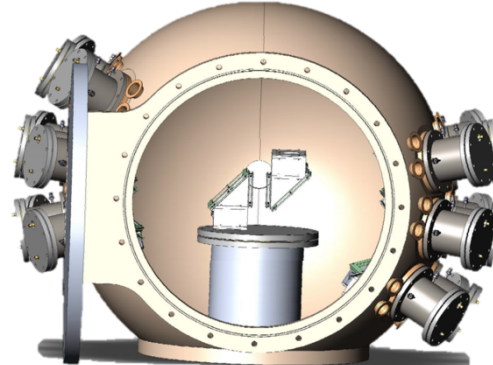^{239}**Pu**

n

n   **n**

LSDS
Very small samples

SPIDER
Fission fragments

Time Projection Chamber will improve on past measurements

- **TPC collection foil with pixilated collection plane**

- **TPC allows 3-D event track reconstruction**

- **TPC allows particle identification. Alphas are clearly differentiated from fission fragments**

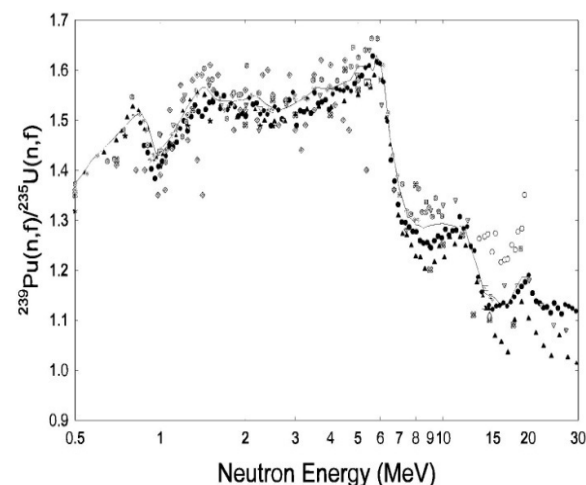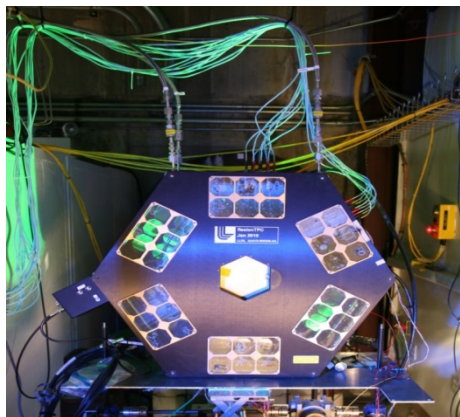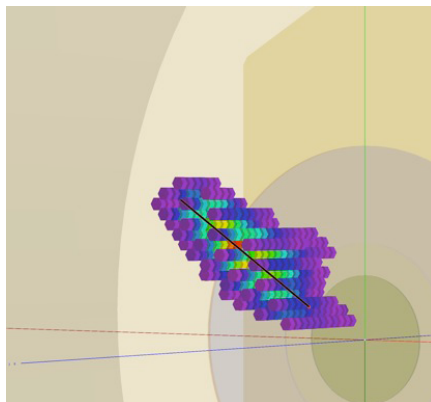- **Measurements will be made relative to ^{235}U and n-p standard cross sections**

Fig. 3. Ratio of neutron-induced fission cross sections for ^{239}Pu/^{235}U to 30 MeV compared to other measurements (Refs. 1, 7, 8, 17, 19, 20, 23, 24, 25, 26, and 28) and ENDF/B-VI (solid line).

Time Projection Chamber (TPC)

Fission fragment track
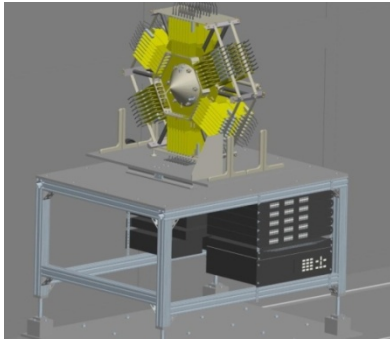

2 α-particle tracks

Fission cross sections are important for Nuclear Energy technology and Defense Program applications

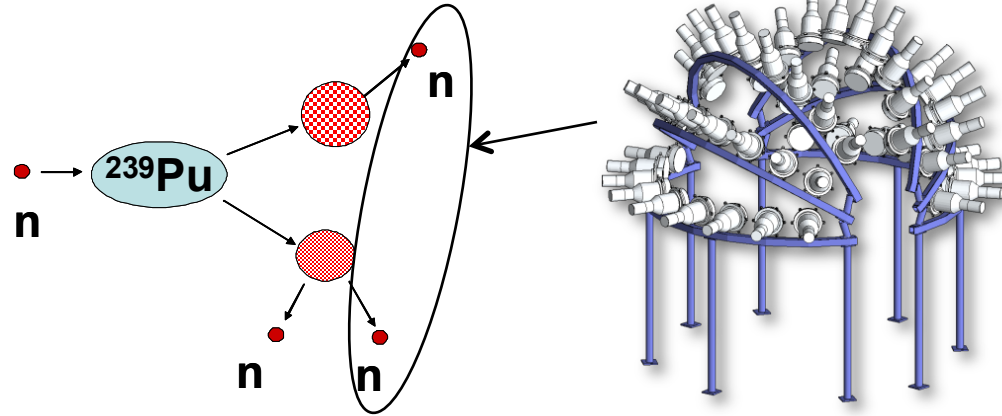**Time Projection Chamber (TPC)**
High precision fission cross sections

Chi Nu (n,xn+γ)
Neutron output spectra

^{239}Pu

n

n

n

n

LSDS
Very small samples

SPIDER
Fission fragments

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Fission neutron output measurements are important data for Nuclear Energy and Defense Programs

- An accurate determination of the neutron output spectra following fission is important for nuclear energy and defense program applications

- We measure these spectra as a function of incident neutron energy by a "double time-of-flight" experiment

- Experiment is challenging because low-energy part of spectrum has large backgrounds room scattered neutrons and high energy part has low production rate (large number of liquid scintillators)

Plot: Ratio to Maxwellian (T=1.42) vs E_n^{out} (MeV)

- Knitter, 1975 (0.215 MeV)
- Staples, 1995 (0.5 MeV)
- Lajtai, 1985 (thermal)
- Boytsov, 1983 (thermal)
- ENDF/B-VII.0
- Talou Monte Carlo, 2011

Detectors ~ 1 m from fission chamber →

LANSCE/ WNR source

Fission chamber

TOF(1)

Fission cross sections are important for Nuclear Energy technology and Defense Program applications

Time Projection Chamber (TPC)
High precision fission cross sections
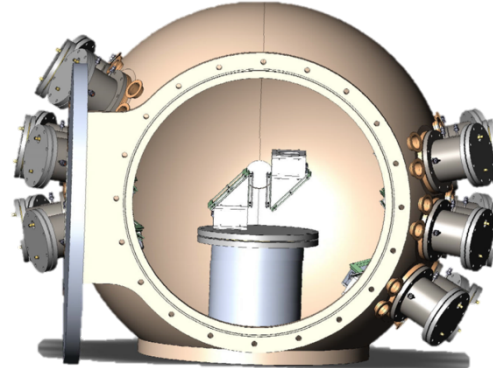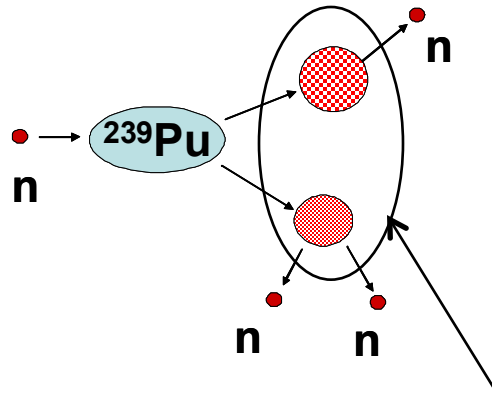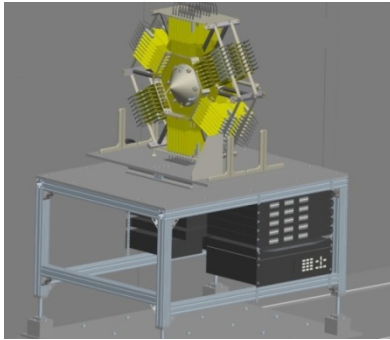
Chi Nu (n,xn+γ)
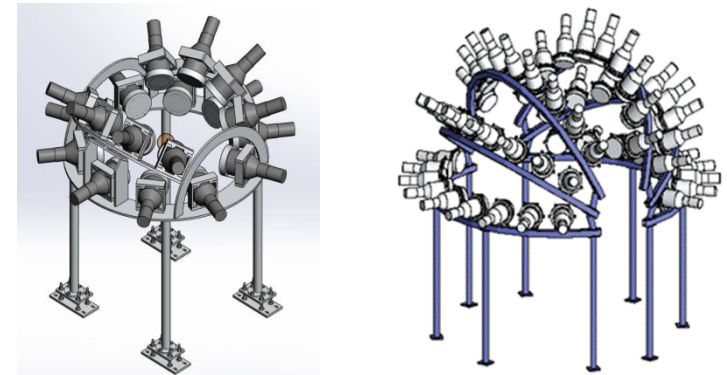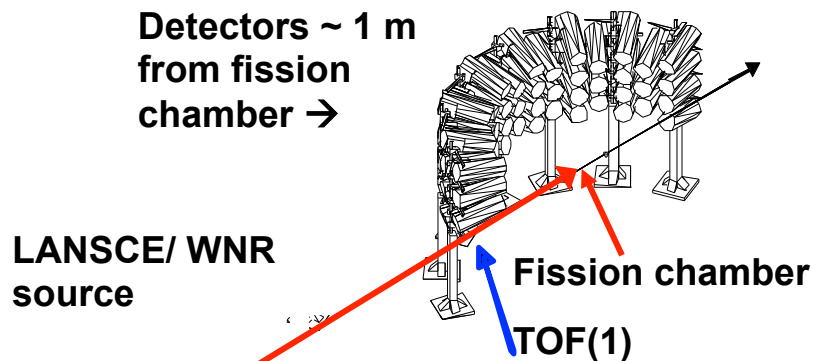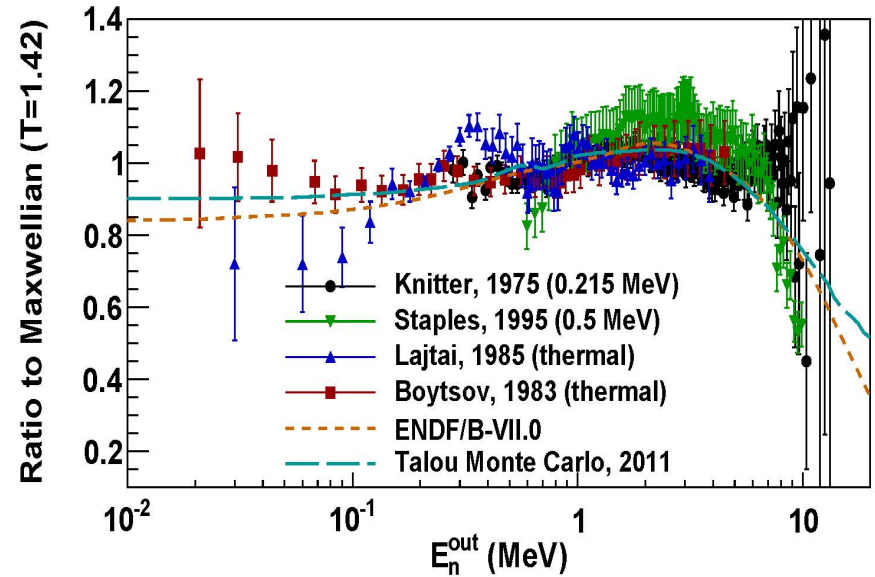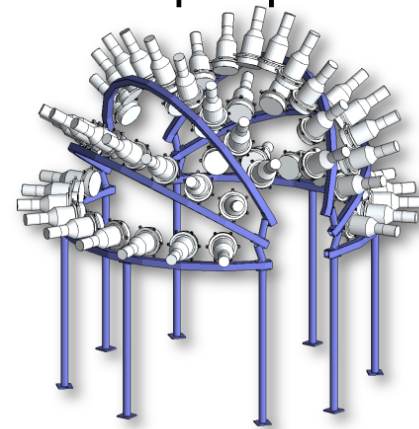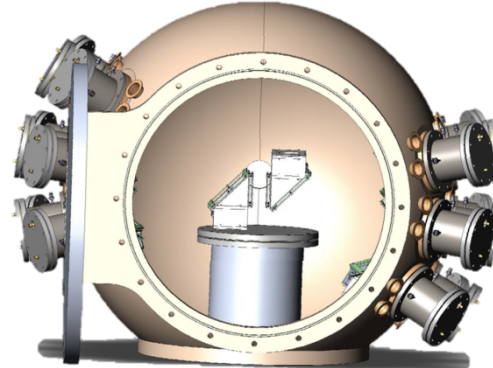Neutron output spectra
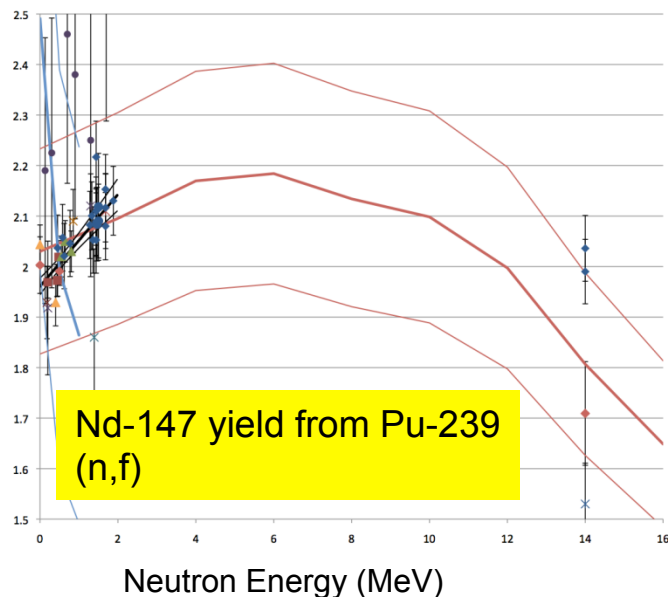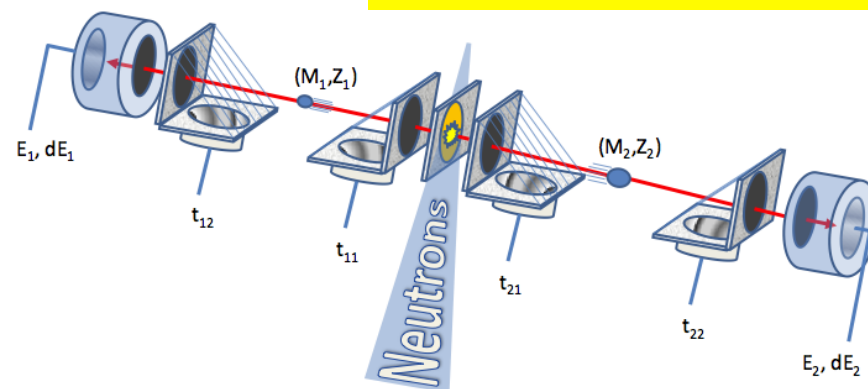

LSDS
Very small samples

SPIDER
Fission fragments

SPIDER is a new instrument for fission fragment research

Nd-147 yield from Pu-239 (n,f)

Neutron Energy (MeV)

The SPIDER instrument will identify fission fragments from actinide samples

E_1, dE_1 t_{12} (M_1, Z_1) t_{11} Neutrons t_{21} (M_2, Z_2) t_{22} E_2, dE_2

- **Fission product yields are important diagnostics for nuclear energy and defense program applications**

- **The accuracy of these yields need to be improved, and the energy dependence better understood.**

- **The SPIDER detector will be used at LANSCE to identify fission fragments based on time-of-flight, kinetic energy, and Bragg spectroscopy**

Neutron Radiography is a valuable tool for looking inside thick objects

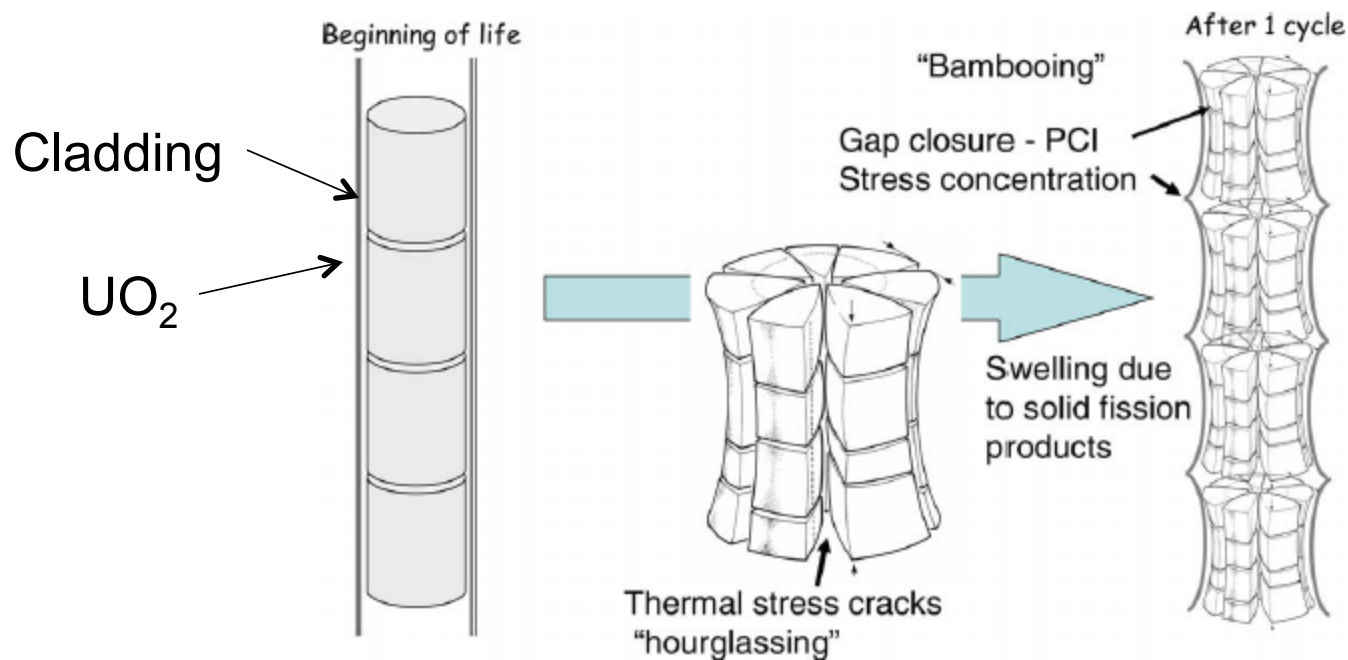# Neutron radiography is a useful tool to characterize features inside thick objects

- **Neutron Radiography has been developed and used for many years at reactors and continuous neutron sources**

- **Recently, neutron radiography techniques have been used at pulsed neutron sources**

- **Pulsed sources such as LANSCE and SNS provide the possibility of identifying elements**

- **Multiple views allow tomographic reconstruction**

Object

2-D Neutron Detector with time resolution

Neutron source

Object can be rotated for tomography
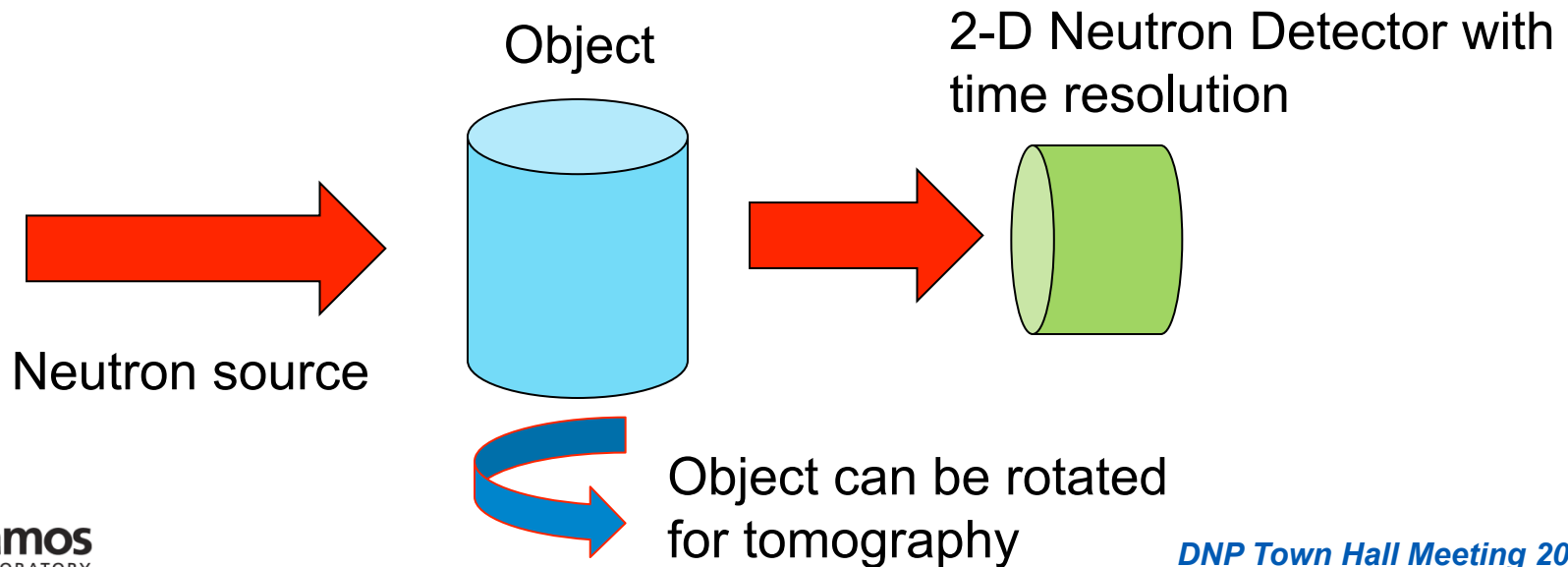
Nuclear fuel undergoes changes while in service

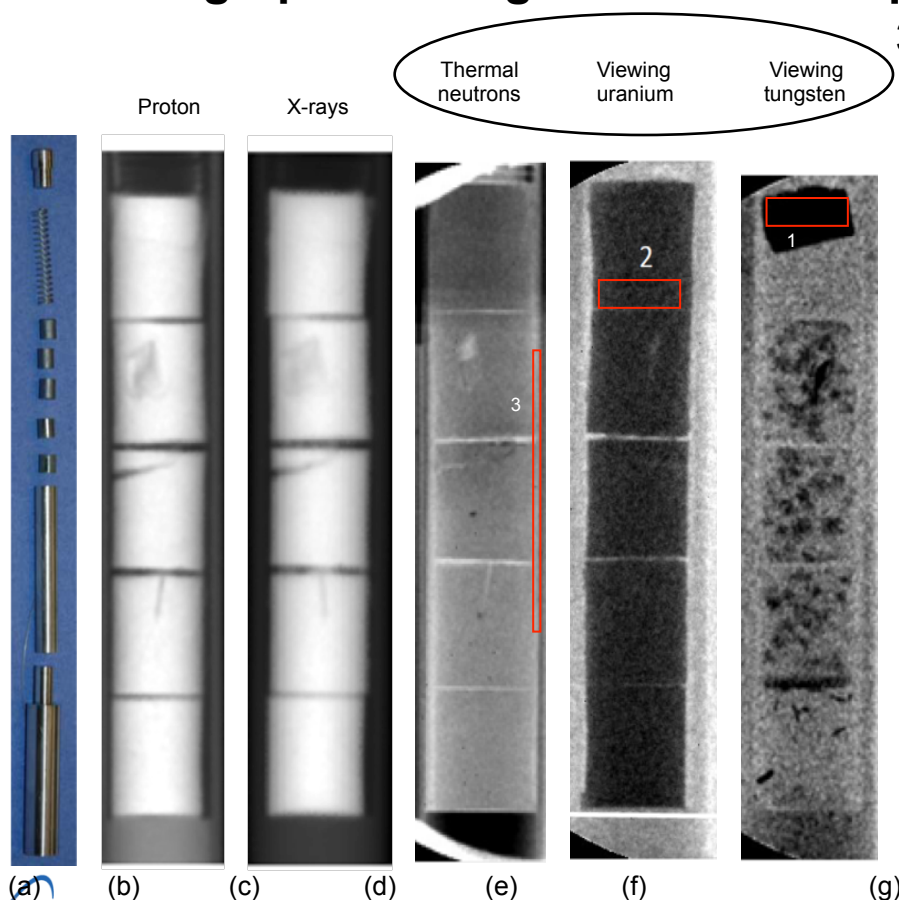- **Large thermal gradients across fuel pellets 800°C - 2000°C**

- **Radiation displacement damage**
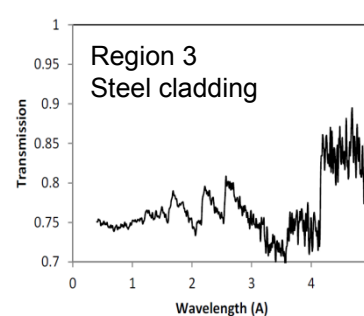

D. Olander/Journal of Nuclear Materials 389 (2009) 1–22

Cladding

UO_2

Beginning of life

"Bambooing"

Gap closure - PCI
Stress concentration

After 1 cycle

Swelling due
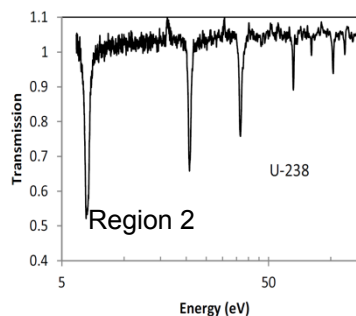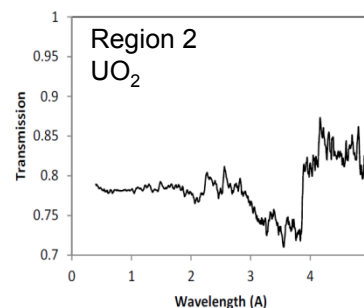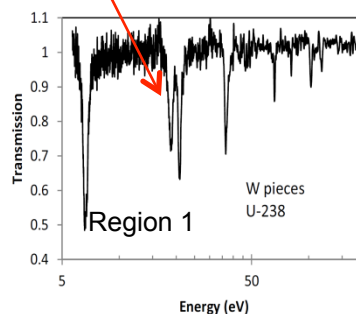to solid fission
products

Thermal stress cracks
"hourglassing"

Comparison of X-ray/Proton/Neutron Radiography

- **Test pellets consisting of UO$_2$ with tungsten inclusions were radiographed using various techniques**

3 Views obtained simultaneously

Thermal neutrons | Viewing uranium | Viewing tungsten

Tungsten resonance

Region 1 — W pieces U-238

Region 2 — UO$_2$

Region 2 — U-238

Region 3 — Steel cladding

(a) (b) (c) (d) (e) (f) (g) (h)

Steel fuel rodlet
with urania pellets

Summary

- **Nuclear science contributes to the solution of a wide range of "real-world" problems**

- **The nuclear technology to solve these problems come from having a strong national Nuclear Physics research program.**

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