Idaho Accelerator Center: Overview of Nuclear Physics Research

D.P. Wells, Director
Idaho Accelerator Center
Idaho State University

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Idaho Accelerator Center

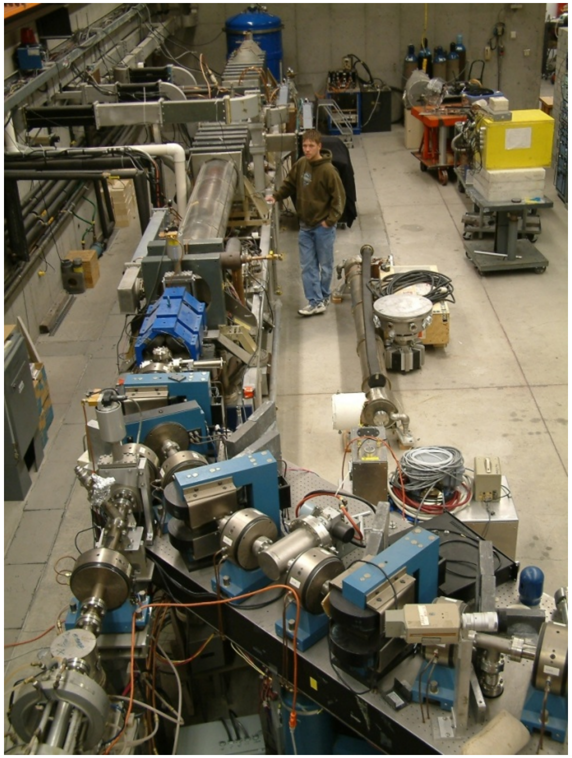
The
Idaho Accelerator Center:
(IAC)

Founded in 1996, it is now one of the largest university accelerator centers in North America.

What is the Idaho Accelerator Center?

- **Electrons/Gammas**
  - 4 MeV LINACs
  - 10 MeV Induction Accel. (~10 kA)
  - (4) 25 MeV e- LINACS
  - High Rep-Rate 15 MeV e- Linac
  - **44 MeV, 6 kW Short Pulse LINAC**
  - **In Storage: BOEING FEL (100 MeV, 100 mA, 1MW)**
- **Numerous X-Ray tubes and Neutron Sources**
- **Light Ions**
  - 2 MeV Van de Graaff
- **Accelerators in Storage**
  - 20 Electron Linacs: P, L, S and X-band
  - 18 MeV Cyclotron
  - 20 MeV Betatron
  - Tandetron

L-Band Traveling Wave Linac



- **Infrastructure**
  - ~3,500 M^2 Lab Space
  - Machine Shop
  - Electronics Shop

Idaho Accelerator Center

Capabilities Today: 3 Labs

- Main Lab:
  - 44 MeV, 6 kW fast-pulse e-linac
  - 25 MeV, 2 kW e-linac
  - 70 GW (peak-power) pulsed-power electron accelerator,
  - Research focuses on high energy-density physics, device testing, nuclear physics, isotope production, non-proliferation/homeland-security and novel x-ray/gamma beams.

- Airport Lab:
  - X-ray machines (INL) and 25 MeV, mobile e-linac (INL).
  - Research, mostly led by INL, focuses on national/homeland security applications and testing ground.

- Physics Lab
  - High repetition-rate e-linac (3kHz rep rate, 20 MeV) and 2 MV positive-ion Van de Graaff
  - Research focused on materials, non-proliferation/homeland security applications, positron beam physics, and polarized gamma-beams.

Capabilities Tomorrow: Main Lab

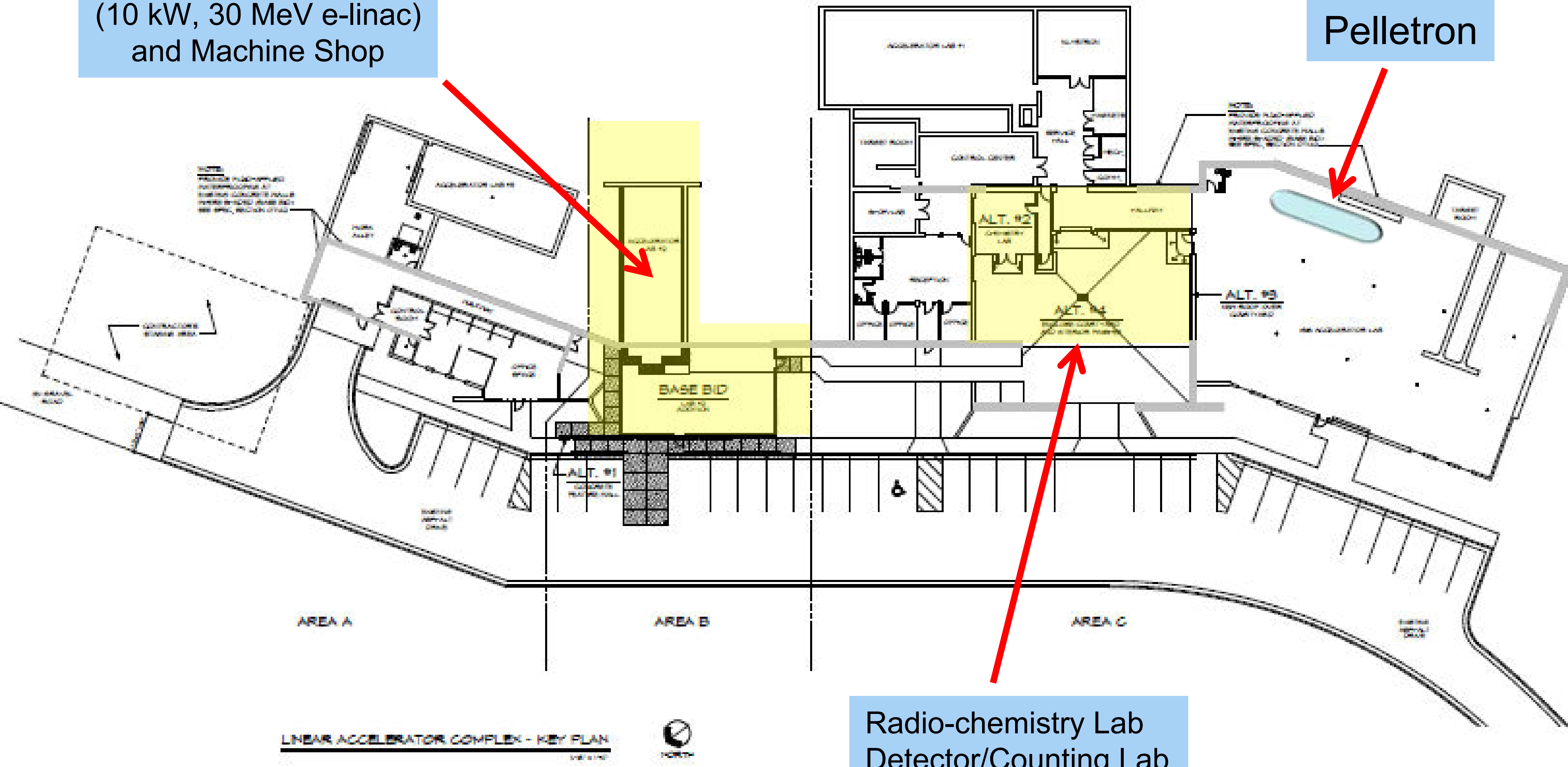
- 6 MV tandem Pelletron (INL):
  - Intense Neutron Source
  - NTOF and low-energy neutron cross sections
  - Materials irradiation, radiation effects on devices, ion beam analysis, positron annihilation spectroscopy, nuclear physics, radio-biology, ….

- 10 kW, 30 MeV e-linac:
  - Isotope production, photon activation analysis,

- Add-on to 44 MeV e-linac?:
  - Storage Ring and Tagger?

- New Lab Space:
  - New radio-chemistry lab, electronics shop, counting/detector lab
  - New machine shop, conference room, offices, library.

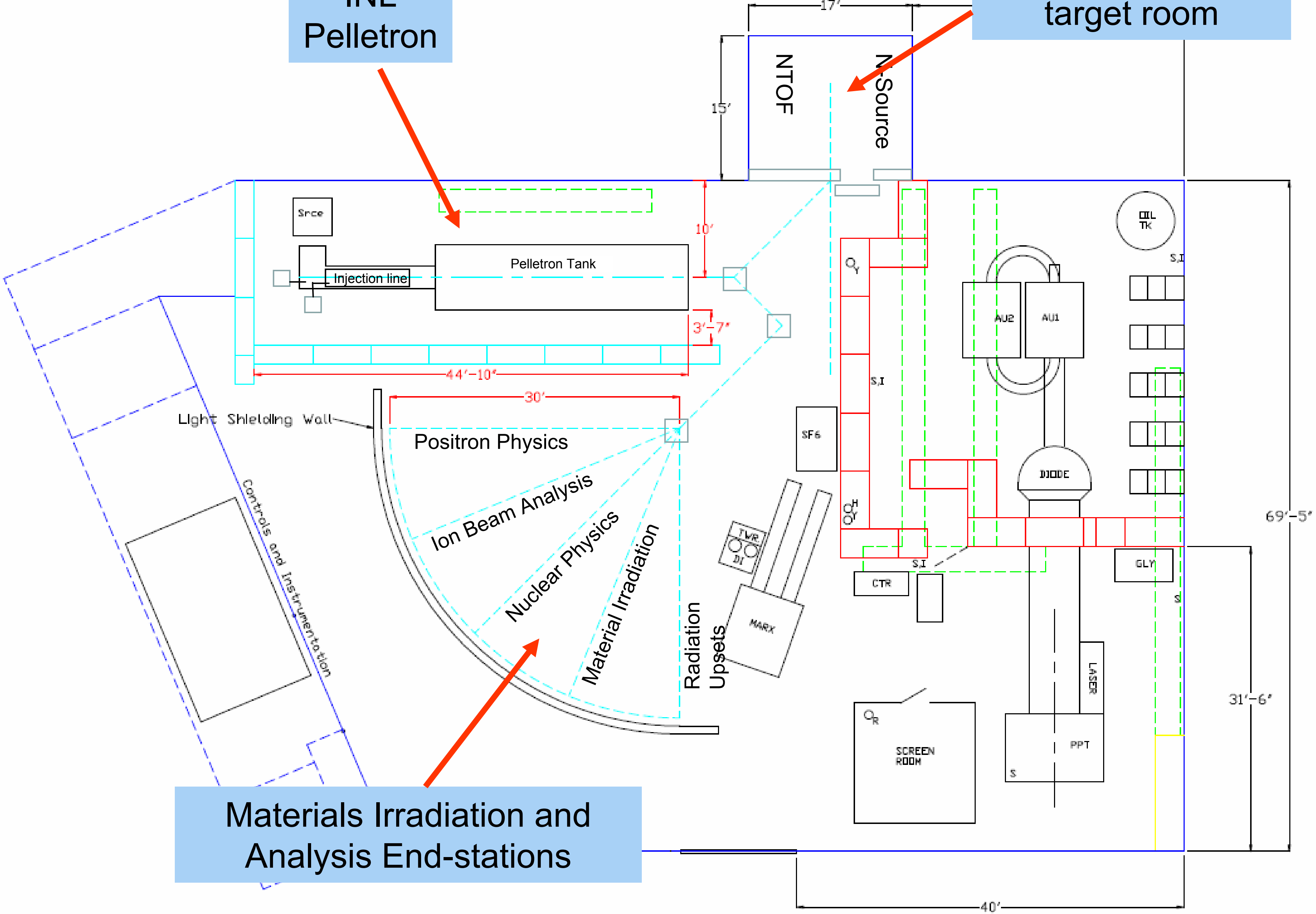
IAC New Additions…



High-power Cell
(10 kW, 30 MeV e-linac)
and Machine Shop

INL
Pelletron

Radio-chemistry Lab
Detector/Counting Lab
Conference Room
Offices
Electronics Lab

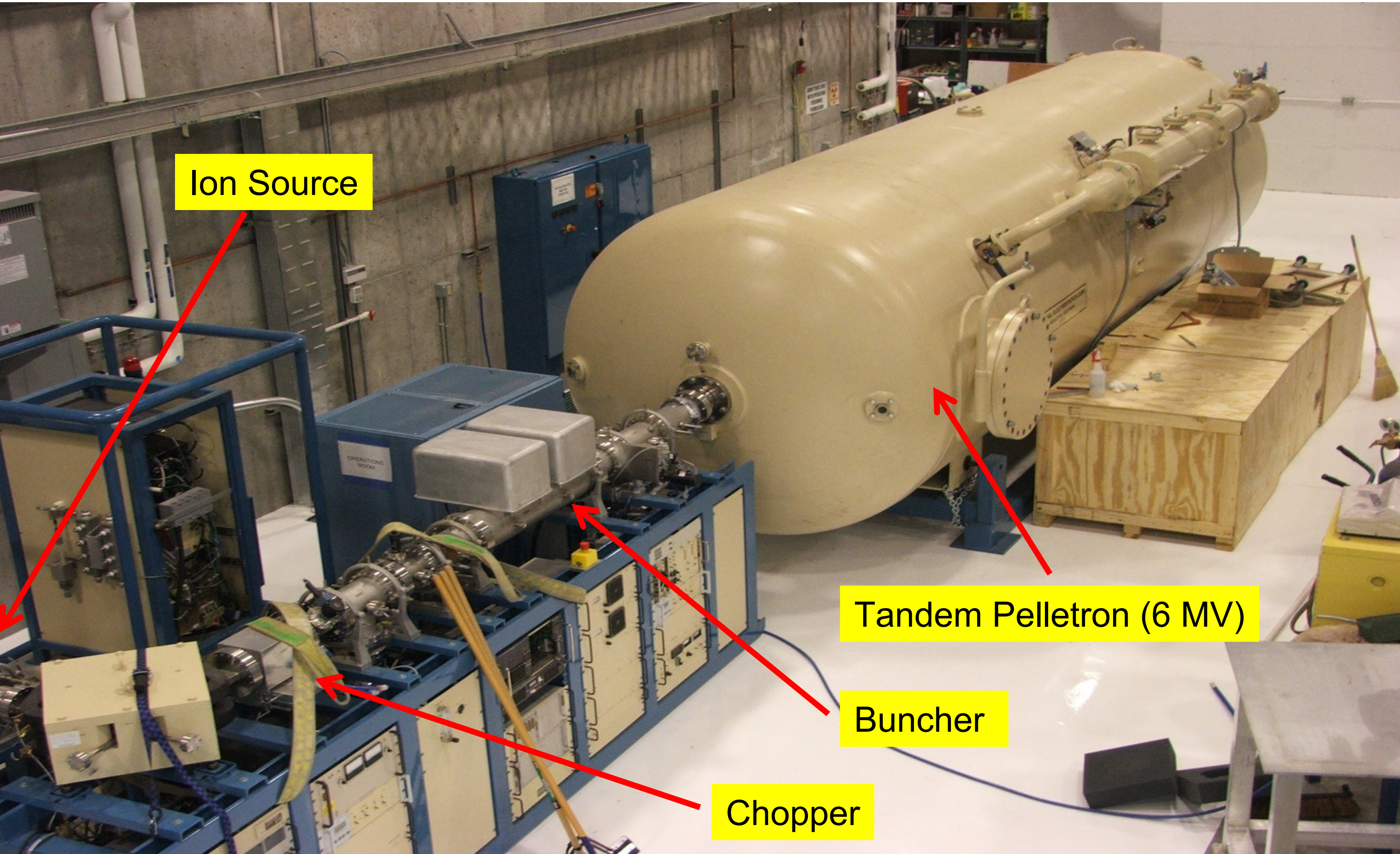


INL Pelletron

neutron-production target room

Materials Irradiation and Analysis End-stations

INL Pelletron in position…



Ion Source

Tandem Pelletron (6 MV)

Buncher

Chopper

Current
Research and Education Emphases:

- Nuclear non-proliferation and homeland nuclear security research
  - Partners with DHS, DOE (INL and other labs) DoD and private sector (L3 Communications, Battelle).

- Non-destructive Materials Analysis
  - Partnerships with the private sector, DOE and DoD to pursue novel, penetrating non-destructive measurements on structural and fuels materials

- Fundamental Nuclear Physics at J-Lab

- Isotope Production and other medical physics
  - Partnering with DOE (PNNL and other labs), Lockheed-Martin, and private sector partners.

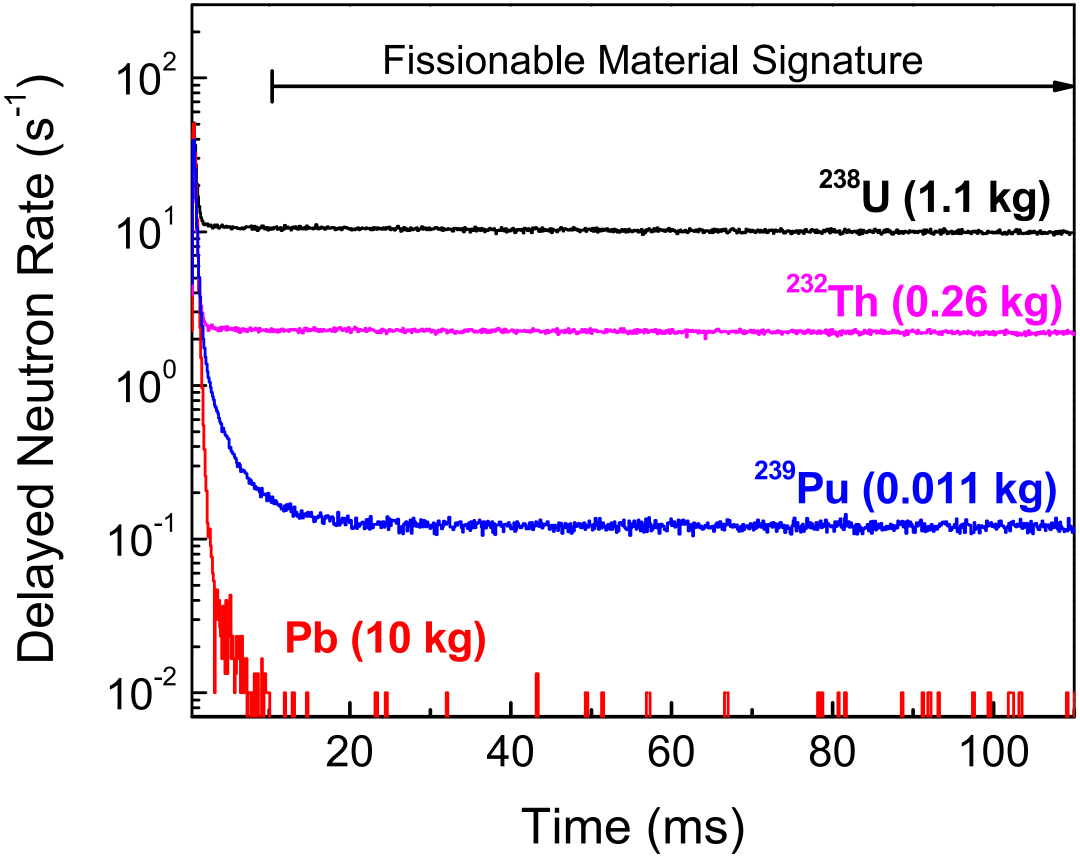
- Note: ALL of these areas require nuclear data measurements:
  - Elastic and Inelastic Neutron Cross Sections for Nuclear Fuels Materials
  - Photo-fission, neutron-fission, NRF
  - Photo-production (photo-activation)
  - Elastic and inelastic electron/phton scattering data at J-Lab

Photo-fission yields Multiple Signals for fissionable-material signatures and a lot of the phase-space remains unexplored:

$$d\sigma^{X}/dE_{n1}{}^{*}dE_{n2}{}^{*}\ldots.$$

- Photo-fission induces a large number of potential signals (and correlations thereof) for analysis:
  - Prompt and delayed gammas
    - temporal, spatial and energy asymmetries
    - temporal, spatial and energy correlations
    - temporal, spatial and energy mutiplicities
    - Polarization observables
  - Prompt and delayed neutrons
    - temporal, spatial and energy asymmetries
    - temporal, spatial and energy correlations
    - temporal, spatial and energy mutiplicities

IAC Basic Research into Signatures of Fissionable Materials



- "Delayed" Neutrons are Almost Exclusively from Fissionable Materials:
  - Millions More Neutrons Detected for uranium than for lead.
- Sensitivity for ^{238}U, ^{232}Th and ^{239}Pu ~5 mg (approximately 1/6 of an ounce):
  - Easy to Improve with Application Specific Detectors.

Potential Applications of Active Inspection

- **Waste Assaying**
  - **Nuclear energy**
  - **Sensitivity, specificity, accuracy**
- **Safeguards (MPACT)**
  - **Nuclear energy**
  - **Specificity, accuracy, speed**
- **Treaty Verification**
  - **Nonproliferation, Diplomacy**
  - **Sensitivity, specificity**
- Nuclear Forensics
  - Military, law enforcement
  - Specificity, speed, accuracy
- Cargo Screening
  - Security, customs
  - Sensitivity, speed, environment
- Long Standoff
  - Military
  - Sensitivity, speed, environment

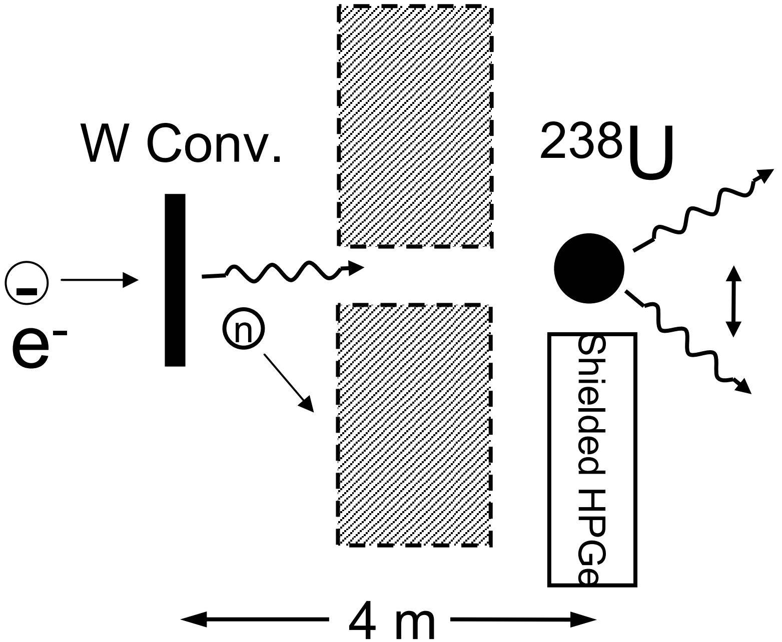
L3 Communications
CX-6000R

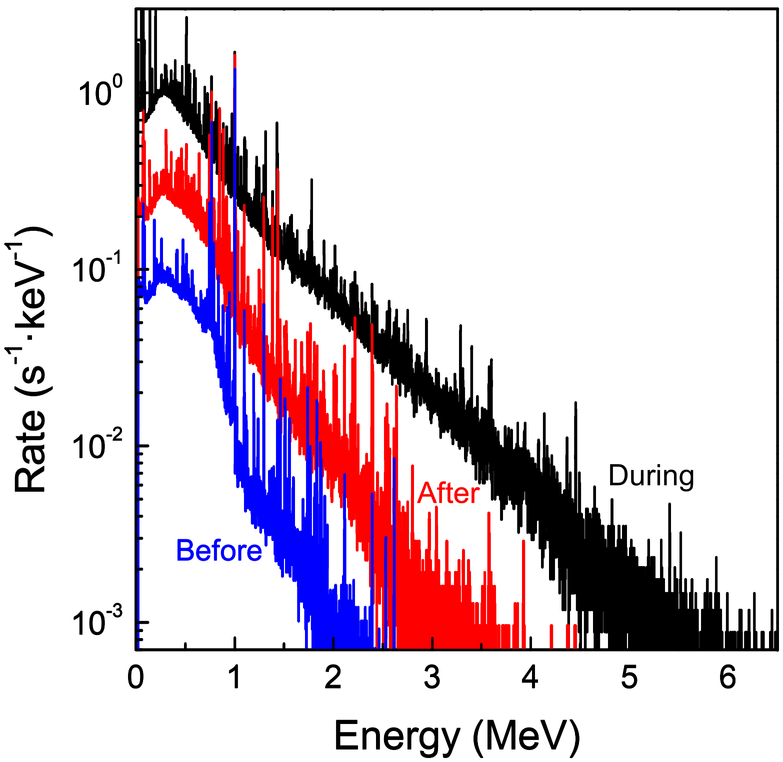
Nondestructive Key!

- **S**ensitivity – Minimal detectable mass
- **A**ccuracy – Mass determination
- **S**peed – How fast is inspection
- **S**pecificity – Isotope identification
- **E**nvironment – How much dose

Example 1: Plethora of Delayed γ-Rays with Stimulation

Experimental Setup

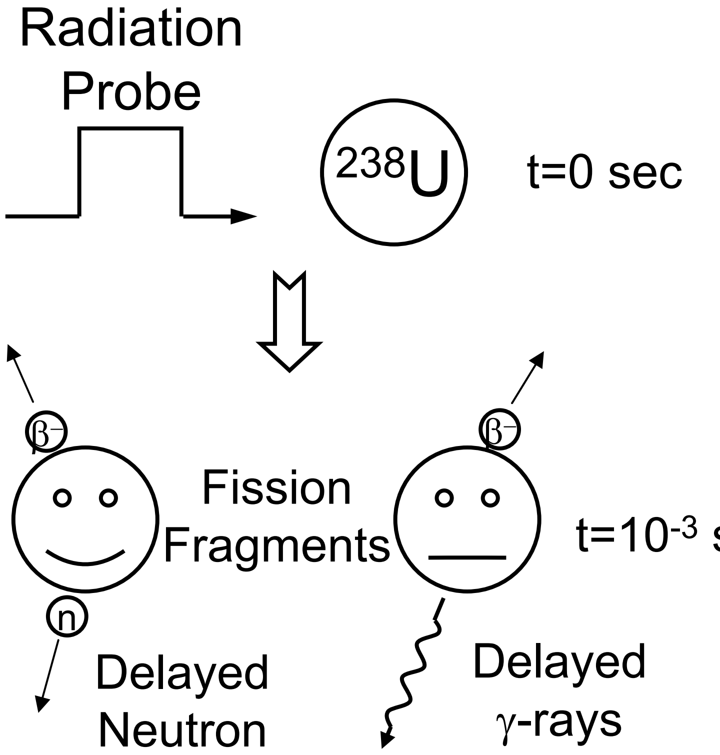




- Bremsstrahlung pulse
  - 17 MeV, 4 μs, ~67 μGy
- Irradiation
  - 15 Hz, 2 hours
- Target: 52.3 g ^{238}U in 1 L H_2O

- “During” irradiation
  - Acquire between pulses 32 to 66 ms
  - Avoids detecting (n,γ) reactions
  - Plethora of high-energy γ-rays
  - Fingerprint of fissioning system

Fission Fragments Dictate Spectrum


Radiation Probe

^{238}U

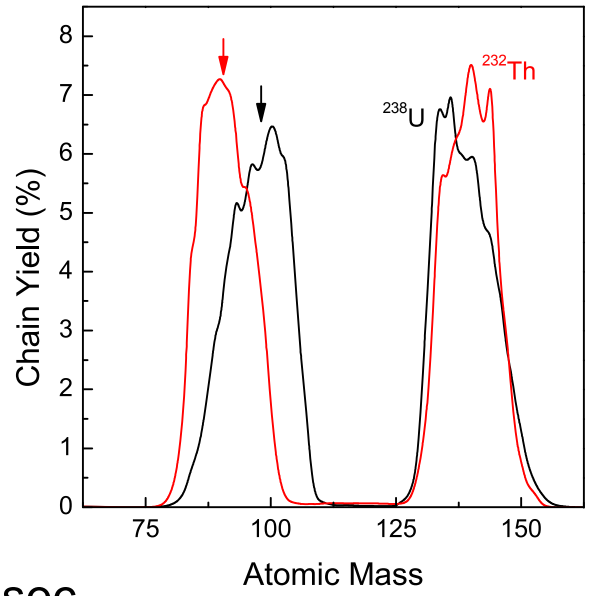
t=0 sec

Fission Fragments

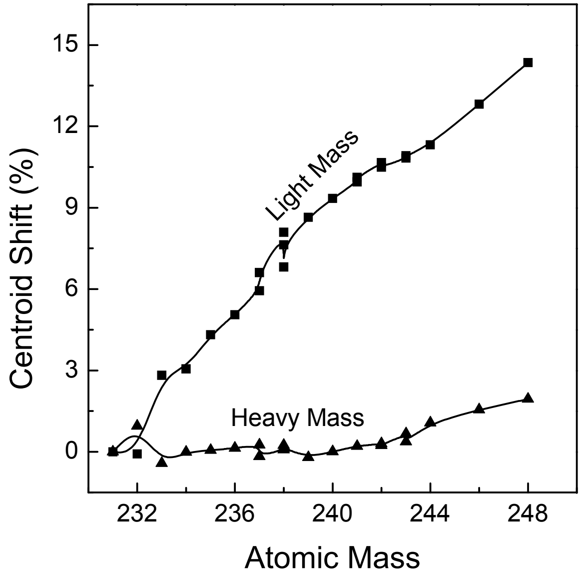
t=10^{-3} sec

Delayed Neutron

Delayed γ-rays

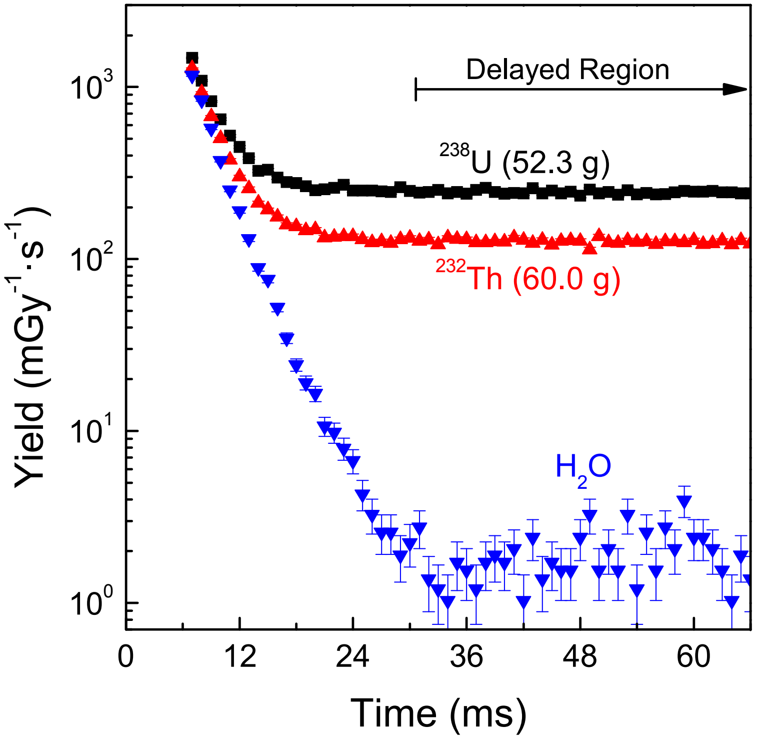


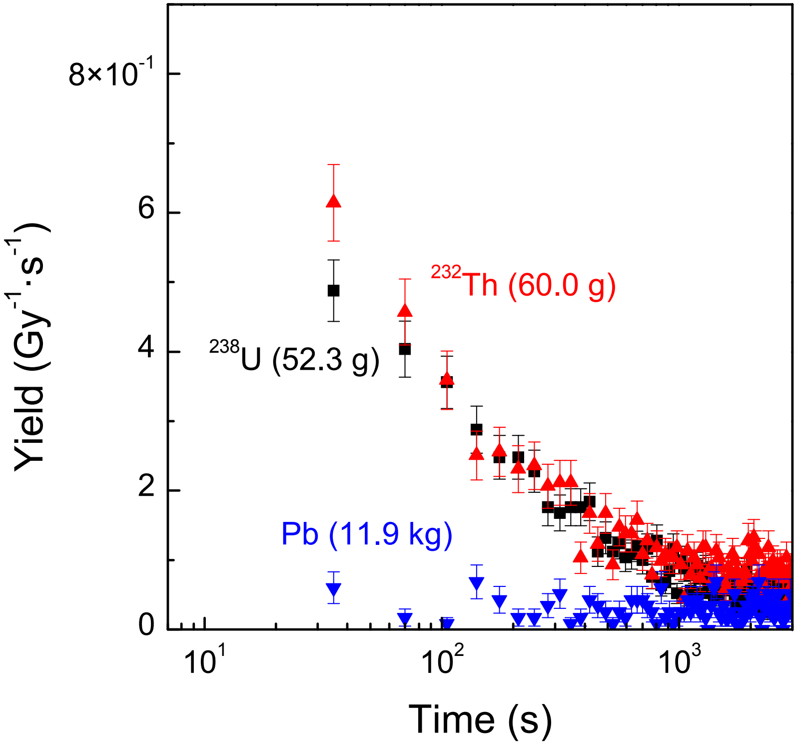
* Neutron induced fission
Fission spectrum



- Light mass shifts linearly
- Heavy mass almost constant
  - Magic numbers pin centroid
- Fingerprint changes with isotope
  - Energy and temporal
- Lack of photofission data

Detection Signature is Straight Forward

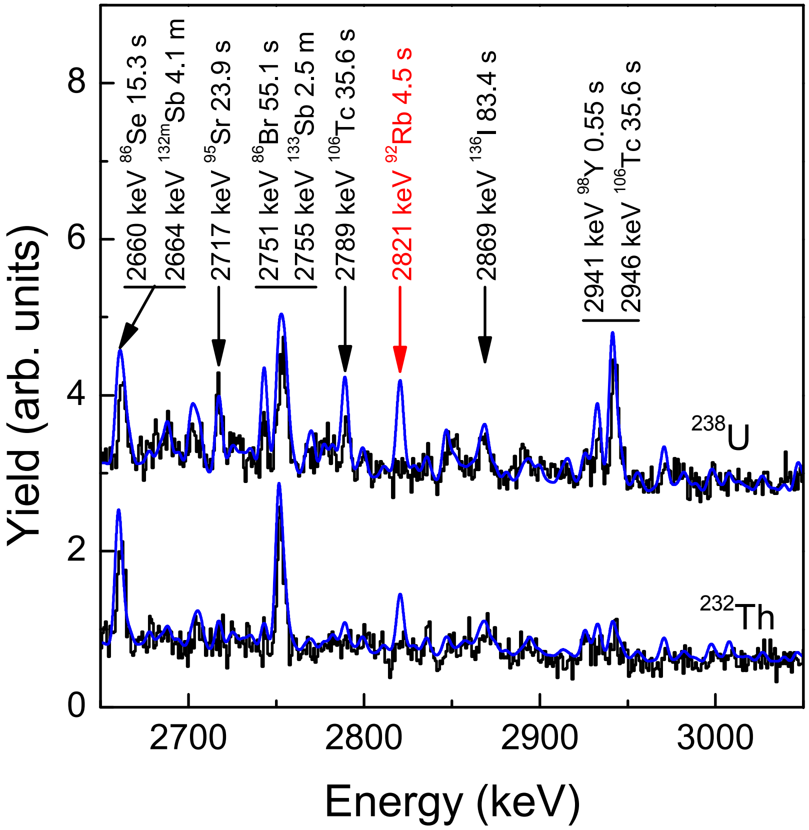


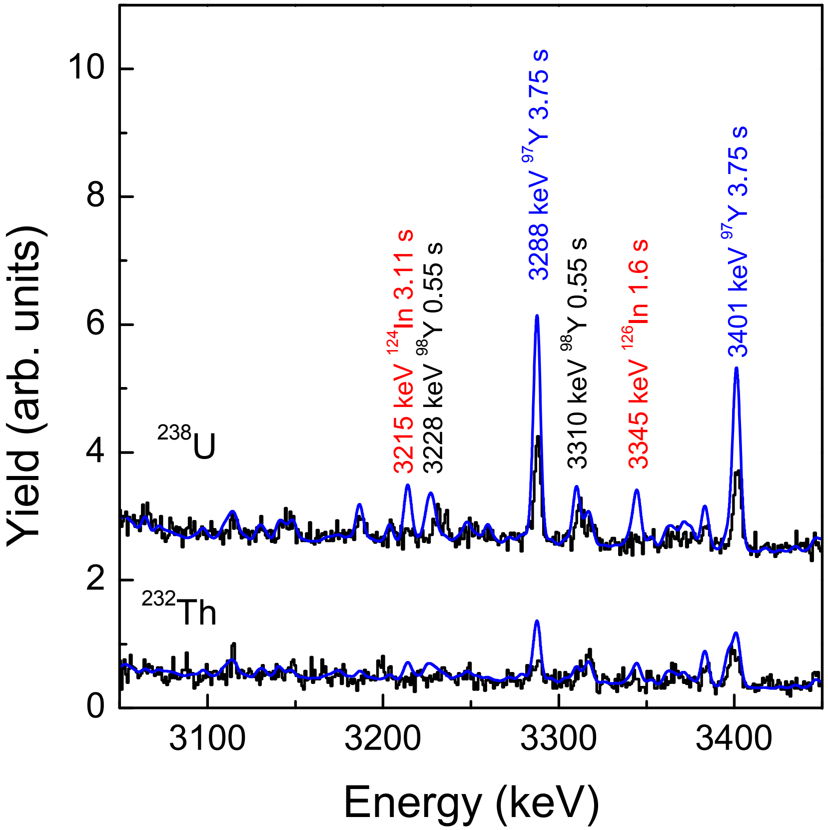


- Initial decay from (n,γ) reactions
- Delayed γ-ray signature
  - Above 3 MeV, times beyond ~32 ms
- Nearly constant between pulses
- Minimal Det. Mass: ~90 mg (6.8 ppm)
- Decay more obvious on longer timescale

- Fission fragments determine
  - High-energy yield
  - Temporal characteristics

Discrepancies Identified with Fragment Distribution

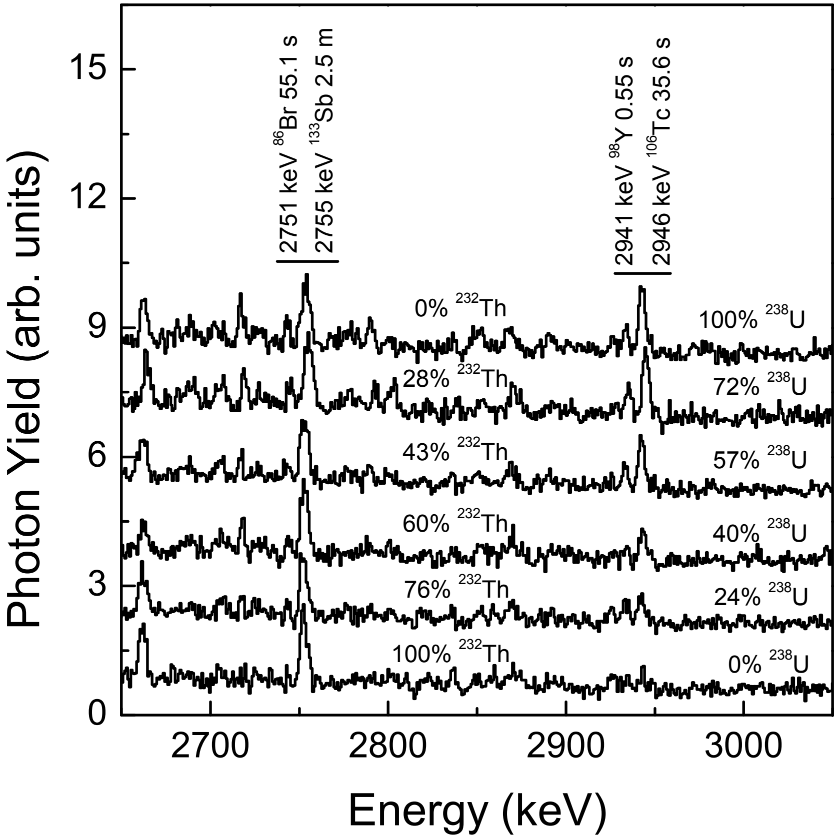


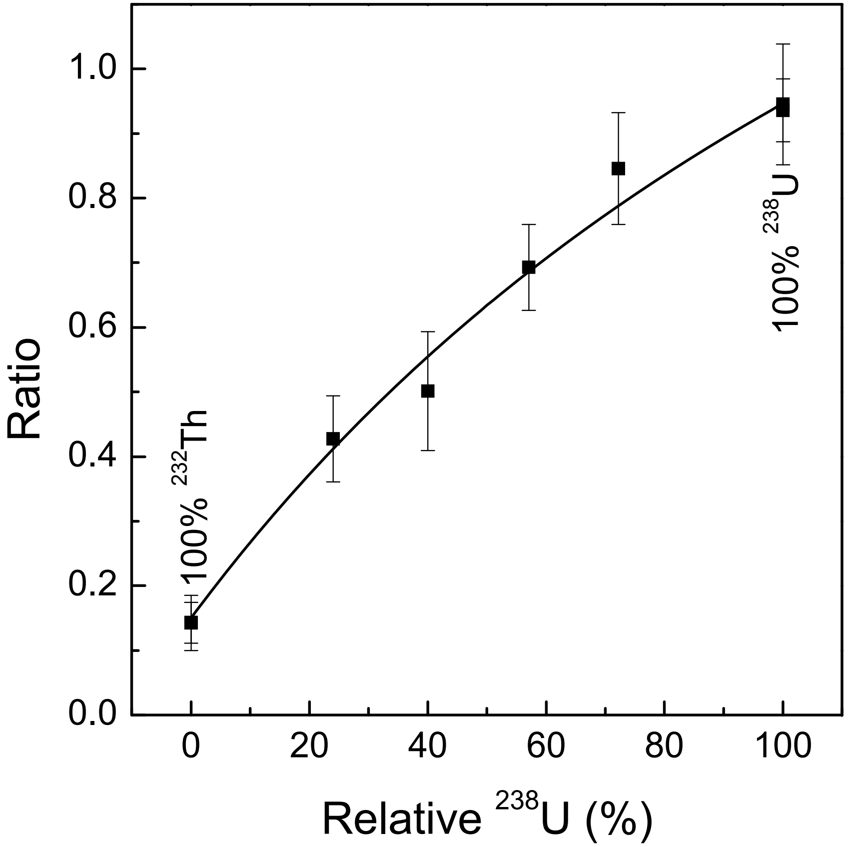


- Normalize to fiducial ^{86}Br, ^{133}Sb
- Short-lived isotopes dominate
- Distribution spectra is not bad
  - There are problems

- Discrepancies
  - Isotopes missing in data
  - Lines missing from distribution
  - (n,f) dist. compared to (γ,f) data

Discrete γ-Ray Lines Allow Isotope Identification





- ^{86}Br, ^{133}Sb strong in ^{232}Th and ^{238}U
  - Use as fiducial
- ^{98}Y, ^{106}Tc weak in ^{232}Th but strong in ^{238}U
  - Use as signature
- Ratio of signature to fiducial
  - Uniquely determines isotopic ratio
  - Large errors: subset of data, hard fit
  - Can we do better?

Use basis spectra to determine isotopic ratios

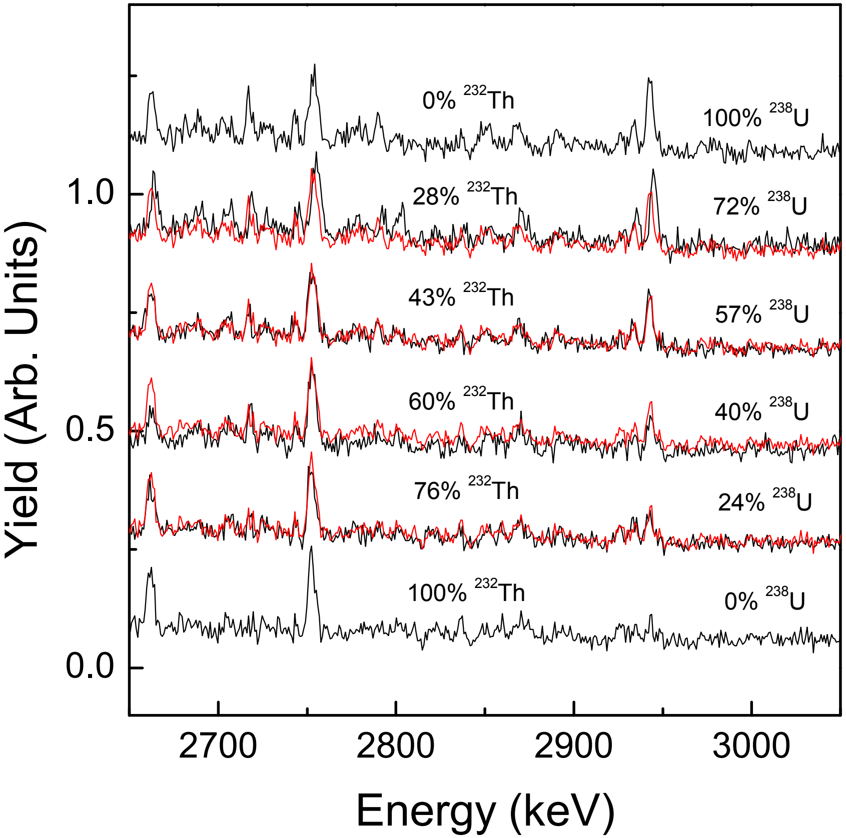
$$\Phi(E_\gamma) = \beta_{238} \cdot \phi_{238}(E_\gamma) + \beta_{232} \cdot \phi_{232}(E_\gamma)$$

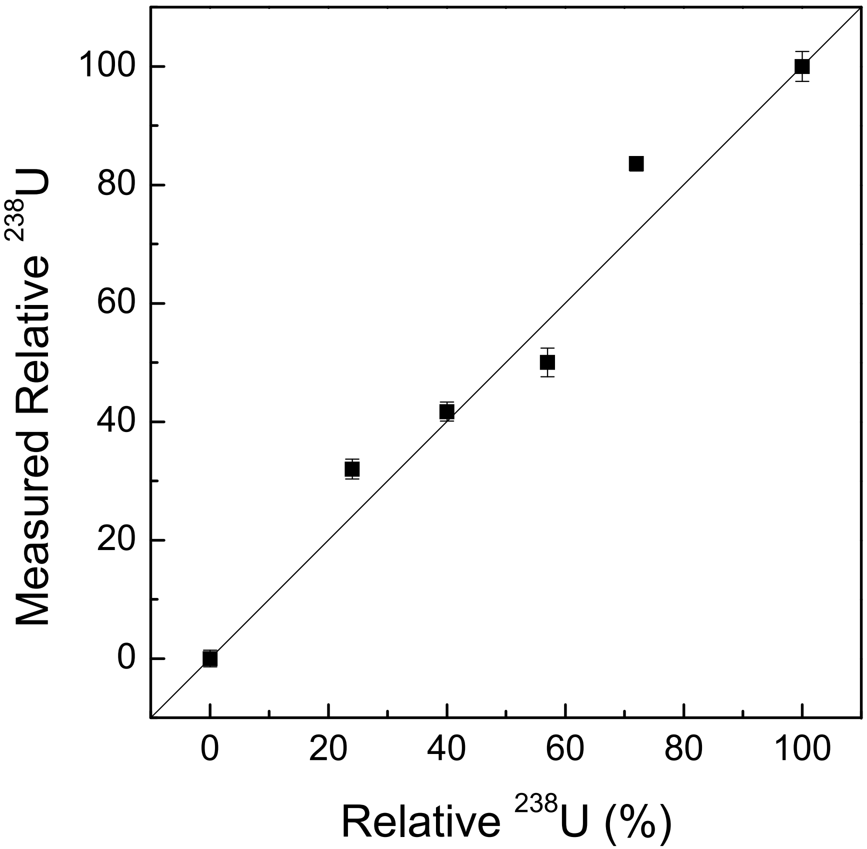
Measured Spectra Basis Spectra

- More accurate isotopic ratios
  - Use more of the available data
  - “Eliminate” difficulty in fitting individual peaks

- Need basis spectra
  - Use experimental spectra
    - Accuracy due to statistical errors
  - Use spectra based on fission fragment distribution (are they correct)
    - Are distributions correct
- Determine β ‘s
  - Linear regression (uniqueness?)
  - Non-orthogonal basis set (uniqueness?)
  - Construct orthogonal basis set (how to develop?)

Experimental Basis Set → Smaller Errors





- Smaller statistical error bars
- Systematic error?
  - Slight differences in background
- Model independent but experiment specific

- Model based basis?

Fast and Complete Delayed γ-Ray Modeling

Program Flow:

MCNPX → CINDER → CODE → MCNPX

MCNPX

(fluxes)

- 63-group n flux,
- p flux,
- h flux

CINDER

(isotope production, decay chains, TS inventory, TS-integrated decays)

- 60 (n,f) yield sets,
- 3400 isotopes with comprehensive decay paths

CODE

(DG spectra:
- discrete
- binned,
normalization, etc.)

ENDF-VI
NSDEF file 8
979 nuclides
- discrete γ-lines,
- X-rays,
- everything else

MCNPX

(optional, detector response)

- resolution,
- GEB,
- efficiencies

- Fast deterministic calculation; Extensive library, reconstructs all known chains
- Photofission is a challenge in CINDER
- Algorithm to be incorporated into MCNP6

* V. Mozin and S. J. Tobin

Conclusions I

- Plethora of delayed γ-rays
  - Detection: High-energy γ-rays (> 3 MeV) at long times
    - True for (γ,f)
    - (n,f) may have issues from $^{A}Z(n,\gamma)^{A+1}Z$ reactions (e.g. ^{56}Mn)
  - Identification: Discrete delayed γ-rays provide fingerprint
    - Line ratios: Straight forward, large statistical error bars
    - Basis spectra: More complicated, smaller error bars, systmatic error bars

- Delayed γ-ray modeling
  - Fast deterministic algorithm (MCNPX → CINDER → VM Code → MCNPX)
  - Great agreement: ^{239}Pu experiments and simulation/model
  - Need to extend: other targets, determine ^{235}U contribution, etc…
  - Incorporate photofission
  - Algorithm to be incorporated into MCNP6

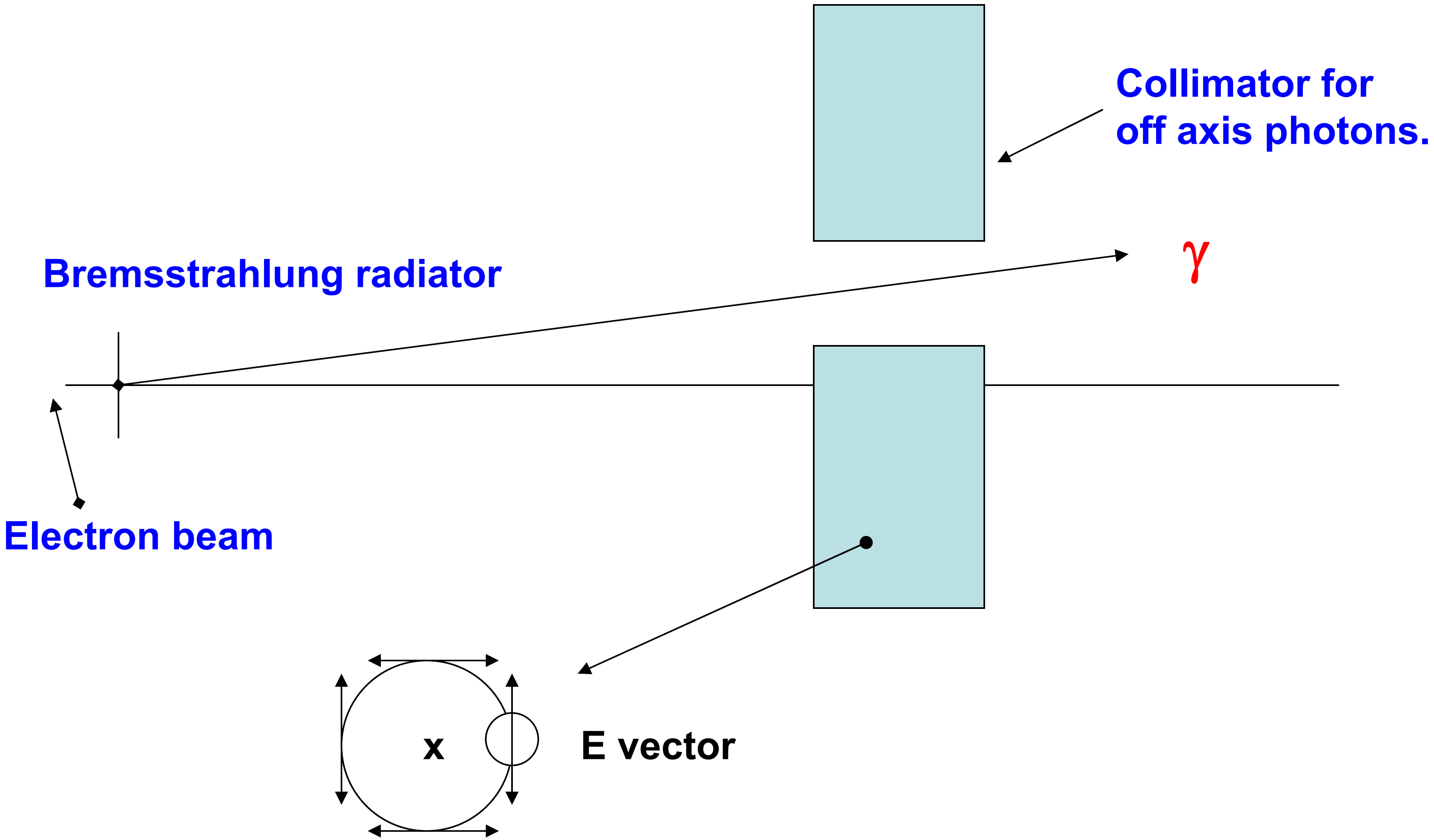
Conclusion II

- What about ^{235}U and ^{239}Pu
  - Currently have 11 g of ^{239}Pu
  - NRC permit allows ~290 g of ^{235}U (HEU)
    - Currently installing security
    - Will acquire sample from DOE
  - Extract ^{235}U spectra from moderated neutron data

- Tons of ^{239}Pu data
  - Photofission, “fission” neutrons, moderated neutrons, Cd wrapped
  - Binary data is very large; especially with thermal neutrons
    - Problem with Microsoft STL file handling: 64-bit pointer converted to 32-bit
    - Workaround should be finished this week

- Coincident delayed γ-ray
  - Almost all data taken has included 2 HPGe detectors in coincidence
  - Preliminary photofission data analyzed

Example 2: Novel Beams - the ISU Polarized Photon Facility



Collimator for off axis photons.

Bremsstrahlung radiator

Electron beam

E vector

Goals

- Explore a possible new signature from polarization observables for fissile materials.
- Investigate potential for quantification of fissile isotopes.
- Determine potential for isotopic specificity.
- Increase database on nuclear photofission.
- Do a little interesting fundamental nuclear physics.

The question:

- In photofission, neutrons “boil off” of fission fragments isotropically in their c.o.m. frame. $\beta_n \sim 0.04c$.
- Fission fragments have non-isotropic angular distribution w.r.t. incoming photon beam. $\beta_{FF} \sim 0.05c$.

Will this be reflected in the neutron angular distribution?

Photofission fragment angular distributions

- **First measurement: Winhold and Halpern Phys. Rev., 103, number 4, p. 990, 1956.**

  $a + b \sin^2 \theta$

  a/b depends on
  - **energy of photons**
  - **target**
  - **fission fragments observed**

- **Is this reflected in neutron angular distribution?**

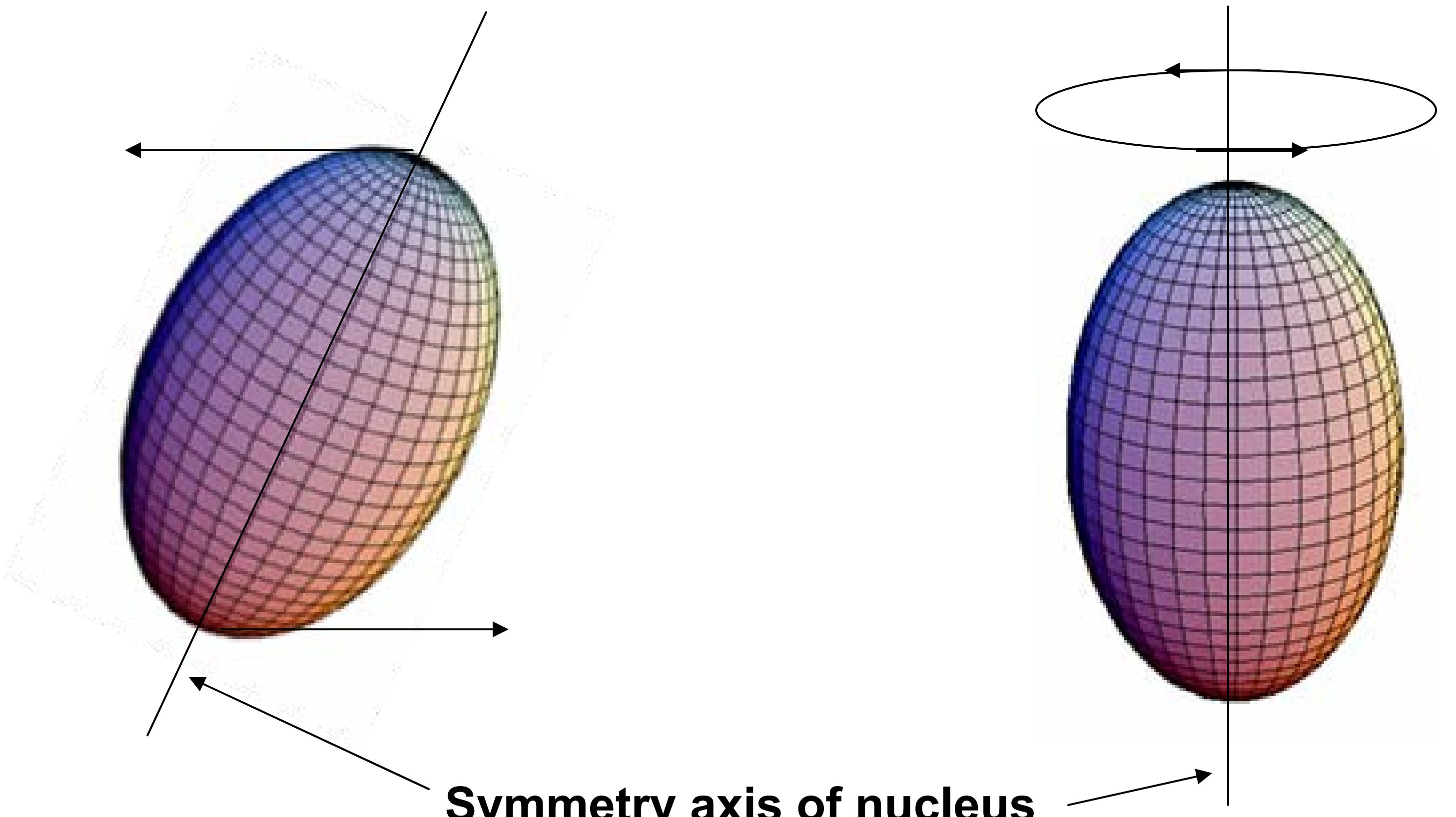
Difficult to see.

If the photons are polarized quantum mechanics says:

$W(\theta,\phi) = A_o + A_2(P_2(\cos\theta) + P\gamma\ f_2(1,1)\cos 2\phi\ P^2{}_2(\cos\theta))$

- A_0 and A_2 depend on the transition state (J,K).
- $P\gamma$ is the photon polarization.
- $f_2(1,1) = 3 \sin^2\theta$.
- θ is the polar angle with respect to the beam.
- ϕ is the azimuthal angle.

Angular distribution of fission fragments depends on angular momentum of transition state:

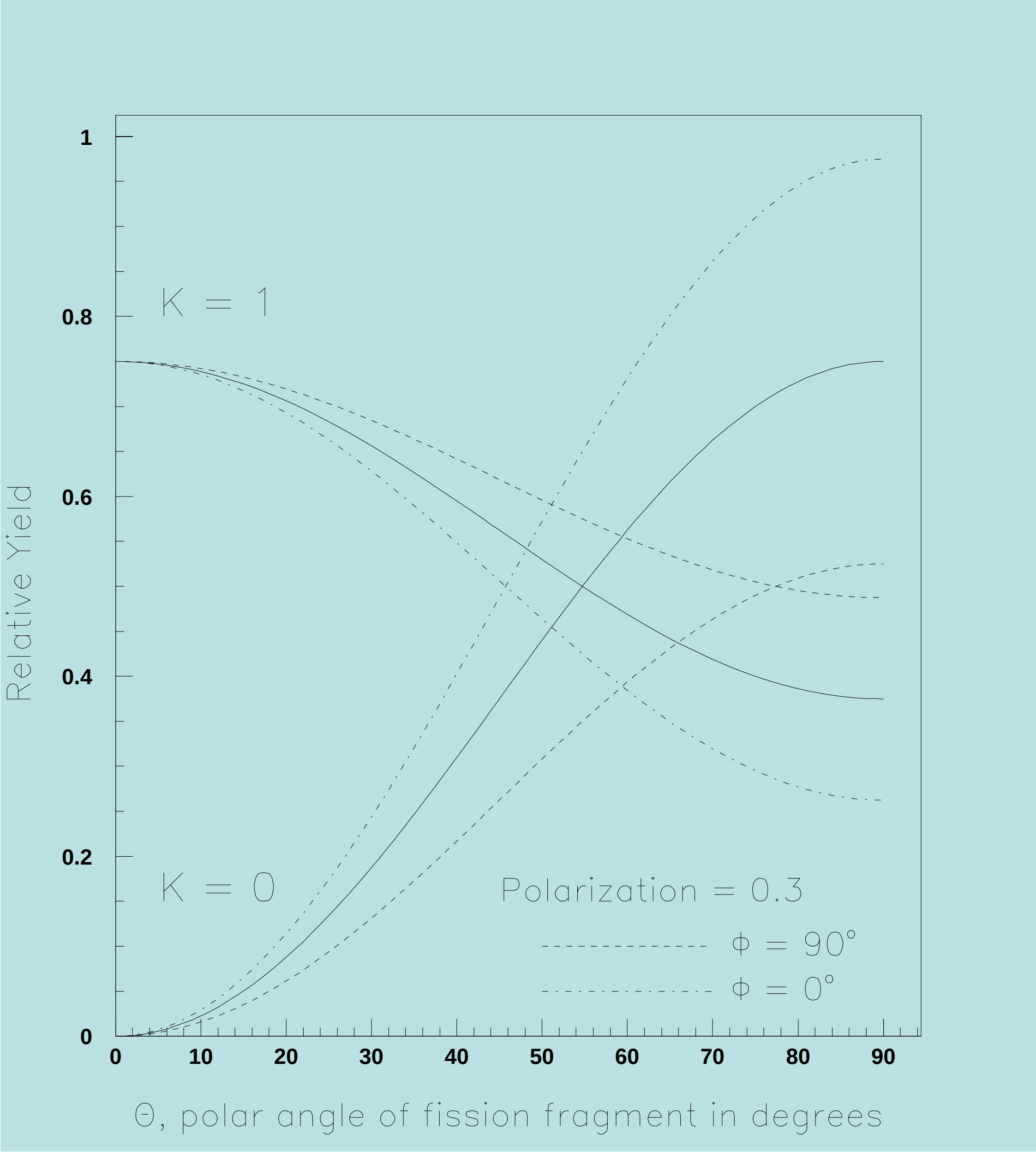


Symmetry axis of nucleus

K = 0

K = 1

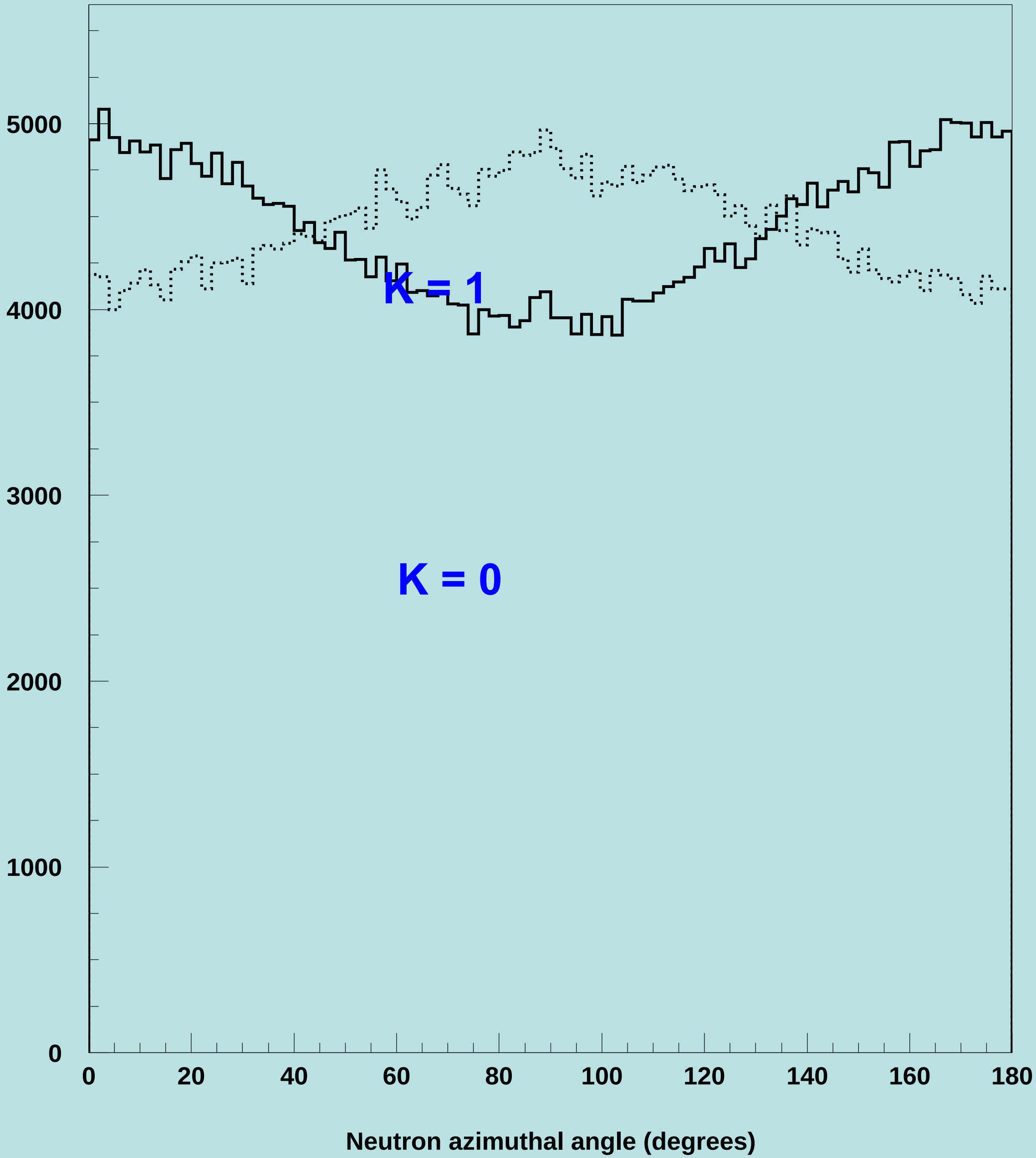
K: Projection of angular momentum on symmetry axis of nucleus



θ distribution of fission fragments with photon beam polarization of 30% for K = 0,1 and φ = 0, 90°.

Adopted from: Ratzek, et al. Z. Phys A – Atoms and Nuclei 308 63-71 (1982)

Simulated azimuthal distribution of neutrons: 30% photon polarization



Key point:

Fission fragment angular distribution reflected in neutron azimuthal angle distribution.

Study this with the following approximations

- The fission fragment mass distribution was sampled uniformly from $85 < A < 105$ and $130 < A < 150$.
- A fixed amount of total kinetic energy, 175 MeV , is given to the fission fragments.
- Neutrons are emitted isotropically in the center of mass of the fully accelerated fission fragments with an energy distribution given by:

$$N(E) = E_n^{1/2}\, \boldsymbol{exp}(-E_n/0.75)$$

- The fission fragment angular distribution is sampled in both θ and ϕ for either $K = 0$ or $K = 1$, and the neutrons were given the appropriate kinematic boost.

Simulated asymmetries

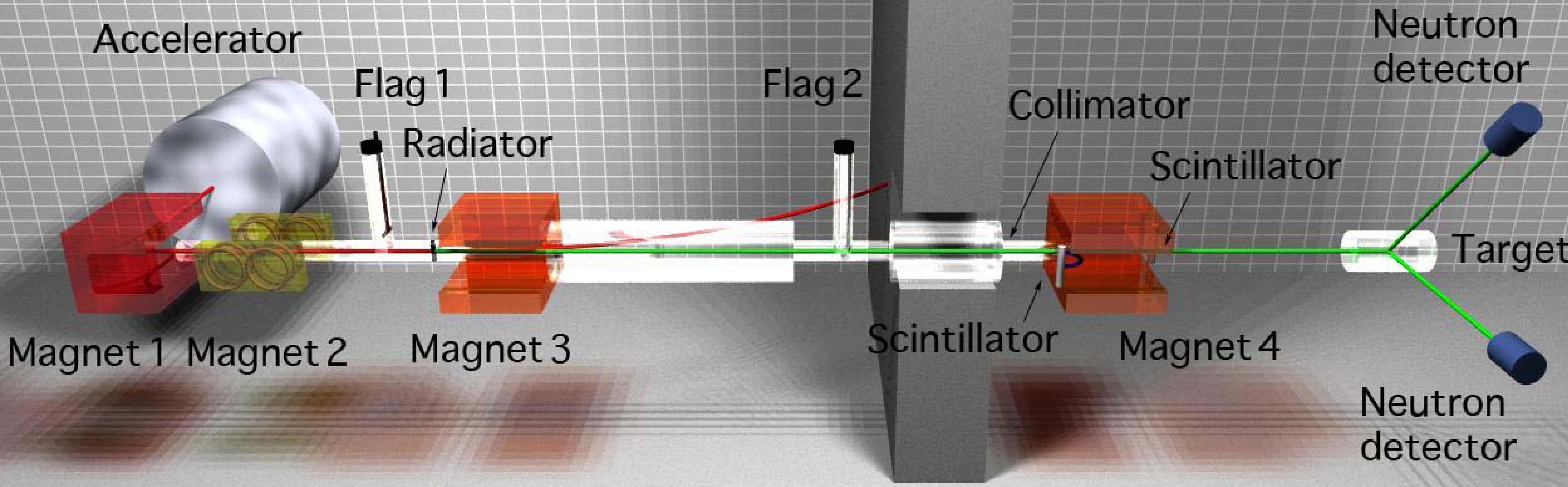
Pure K = 0:

- $N(\theta = 0, \phi = 0)/N(\theta = 0, f = \pi/2) = 1.25$
  with no cut on neutron energy.

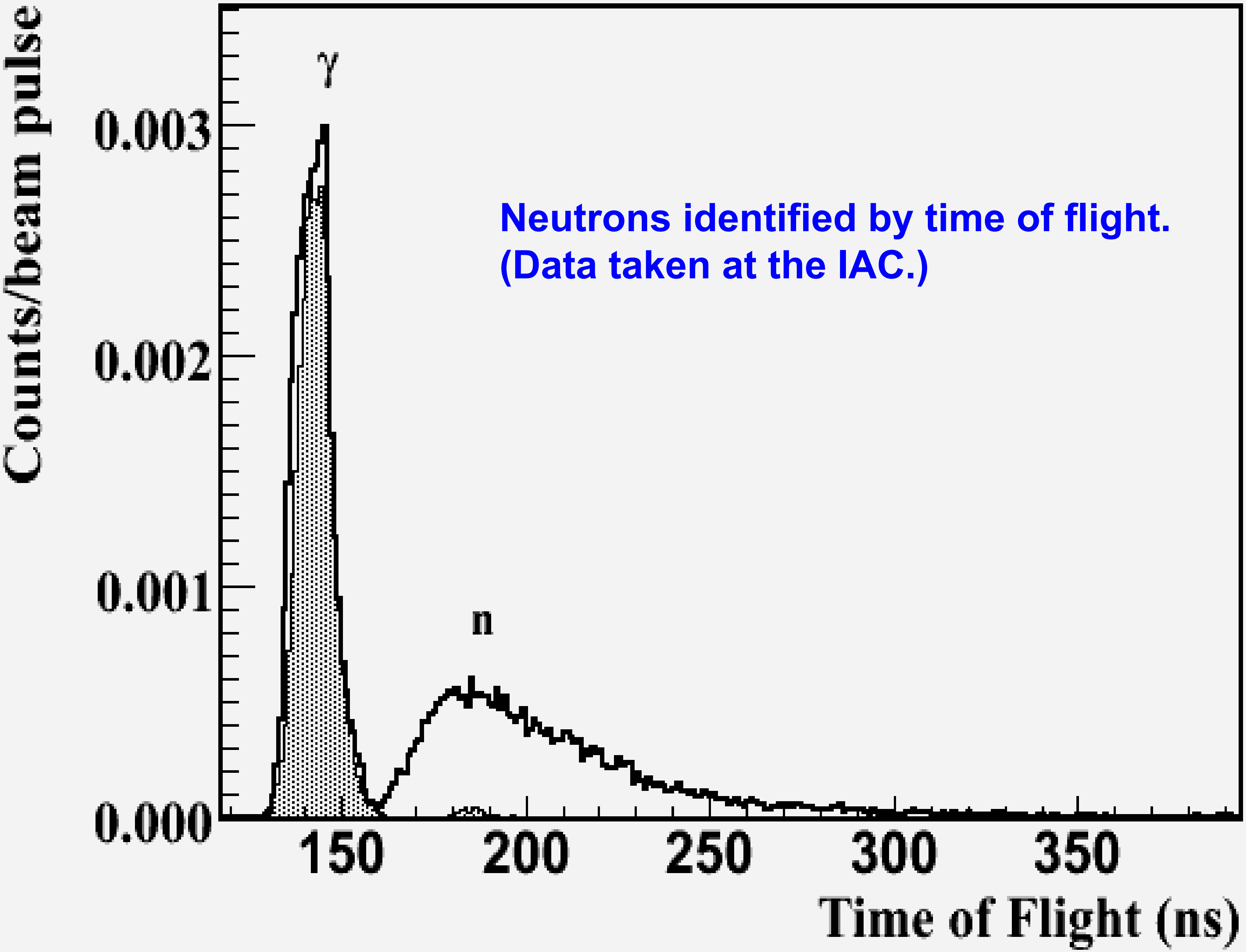
- $N(\theta = 0, \phi = 0)/N(\theta = 0, \phi = \pi/2) = 1.37$
  if $E_n > 2$ MeV

Pure K = 1:

- $N(\theta = 0, \phi = 0)/N(\theta = 0, \phi = \pi/2) = 0.84$
  with no cut on neutron energy.



Experimental setup



Neutrons identified by time of flight.
(Data taken at the IAC.)

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