Evaluation of a Photon Interrogation System of Detection of Shielded Highly Enriched Uranium

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Objective

- **Simulation of measurements based on photofission for active interrogation of nuclear material**
- **Past work on prompt emissions from photofission presented at INMM annual meeting in Phoenix, AZ on July 11-15, 2005**
- **Present study is concerned with DELAYED neutrons emission from photofission**
- **Beam off measurements:**
  - **Minimize the background**

Delayed Neutrons from Photofission

- **Decay of special fission fragments "precursors"**
- **Lower average kinetic energy than most other fission neutrons**
- **Born at a time in between 10^{-1} and 10^{-2} second after fission**
- **Classified into eight groups according to precursors half-life**

Typical yield as a percentage of v_p

P_u^{239}	**0.1**
U^{235}	**0.4**

Monte Carlo Implementation Steps

- **Establishing the yield of delayed neutrons**
- **Establishing the eight delayed neutron groups**
- **Assigning each neutron to a group**
- **Assigning a birth-time to each neutron**
- **Assigning an energy to each neutron**

Similarity of Neutron-Induced and Photon-Induced Fission Yield

- **Fragments have no memory about the fission type**
- **Fragments mass distribution curve shape depends upon the compound nucleus initial excitation energy**
- **Possible to find equivalent energies**

$$E_\gamma \square B_{(A+1)} + E_n \frac{A}{A+1} \approx B_{(A+1)} + E_n$$

- **Ganich & sikora formula:**

Where

$$\omega = 0.19004 * [2.626 * Z - A_f + \nu(E_\gamma)]^2 + 0.1125 * (Z - 90)$$

$$\nu_d * 100 = \exp[2.4 - 0.7\omega]$$

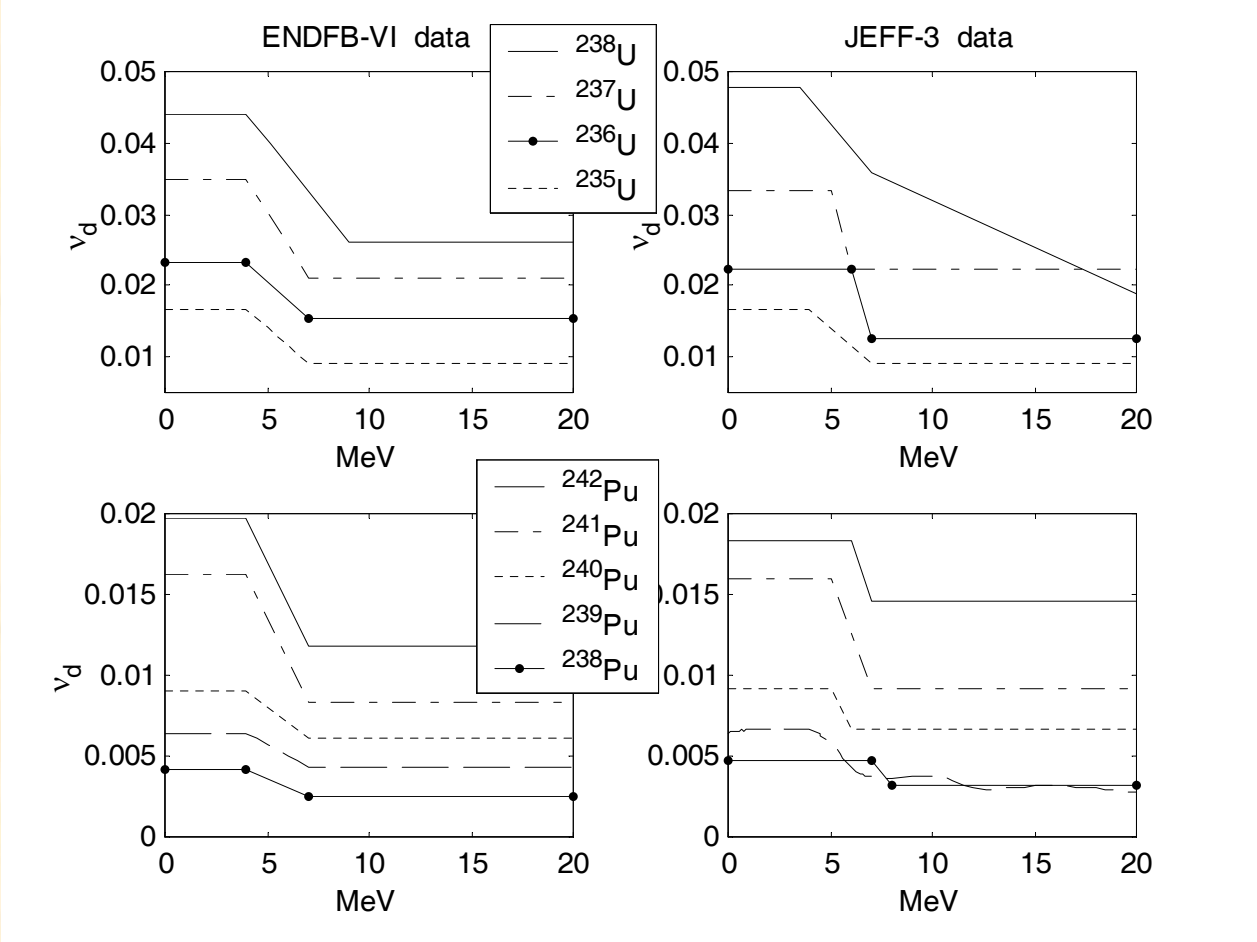
Establishing the Multiplicity of Delayed Neutrons

- **Similarity of neutron-induced and photon-induced fission yield:**

← Experimental photon-induced →									Neutron Exp. Data	Calcul. Photon Induced
^{A+1}Z	B_{A+1} (1)	E_e (2)	E_γ (2)	ν_p (2)	ν_d (2)	^{A}Z	E_n (3)	ν_p (2,3)	ν_d (4)	ν_d (5)
^{232}Th	**6.438**	**8**	**6.80**	***1.96***	.0310	**^{231}Th**	**0.36**	***2.13***	(.035)	.0381
"	"	**10**	**7.99**	***1.89***	.0306	"	**1.56**	***2.13***	(.035)	.0381
"	"	**10.2**	**8.14**	***1.89***	.0267	"	**1.71**	***2.13***	(.035)	.0381
"	"	**12**	**9.44**	***2.08***	.0259	"	**3.02**	***2.13***	(.035)	.0381
^{235}U	**5.298**	**8**	**6.80**	***2.46***	.0090	**^{234}U**	**1.51**	***2.56***	.0129	.0112
"	"	**10**	**7.99**	***2.70***	.0088	"	**2.70**	***2.72***	.0129	.0104
"	"	**10.2**	**8.14**	***2.61***	.0113	"	**2.85**	***2.74***	.0129	.0103
"	"	**12**	**9.44**	***2.96***	.0112	"	**4.16**	***2.91***	.0126	.0095
^{238}U	**6.154**	**8**	**6.80**	***2.46***	.0306	**^{237}U**	**0.65**	***2.48***	.0350	.0369
"	"	**10**	**7.99**	***2.63***	.0276	"	**1.84**	***2.65***	.0350	.0350
"	"	**10.2**	**8.14**	***2.59***	.0306	"	**1.99**	***2.67***	.0350	.0348
"	"	**12**	**9.44**	***2.80***	.0275	"	**3.30**	***2.85***	.0350	.0329
^{239}Pu	**5.647**	**8**	**6.80**	**--**	--	**^{238}Pu**	**1.16**	***3.08***	.0042	.0039
"	"	**10**	**7.99**	***3.32***	--	"	**2.35**	***3.25***	.0042	.0035
"	"	**10.2**	**8.14**	***3.17***	.0037	"	**2.50**	***3.27***	.0042	.0035
"	"	**12**	**9.44**	***3.43***	.0037	"	**3.81**	***3.46***	.0042	.0031

Relations Governing Delayed Neutron Yield in Neutron-Induced Fissions

Delayed Neutrons yield per fission



Energy of Incident Neutron

Equivalence of Neutron-Induced Fissions and Photon-Induced Fissions

- **V_d constant for energy > 7 mev for neutron-induced fission $\Rightarrow$ v_d constant for energy >~ 12 mev for photon-induced fission**
- **The ratio of the two plateaus is ~ 0.6**
- ***V_d emitted by Z^A* is ~ 0.6* v_d emitted by Z^{A+1}**
- **Ronen regards as equivalent for v_d nuclei having the same 2Z—*N value***

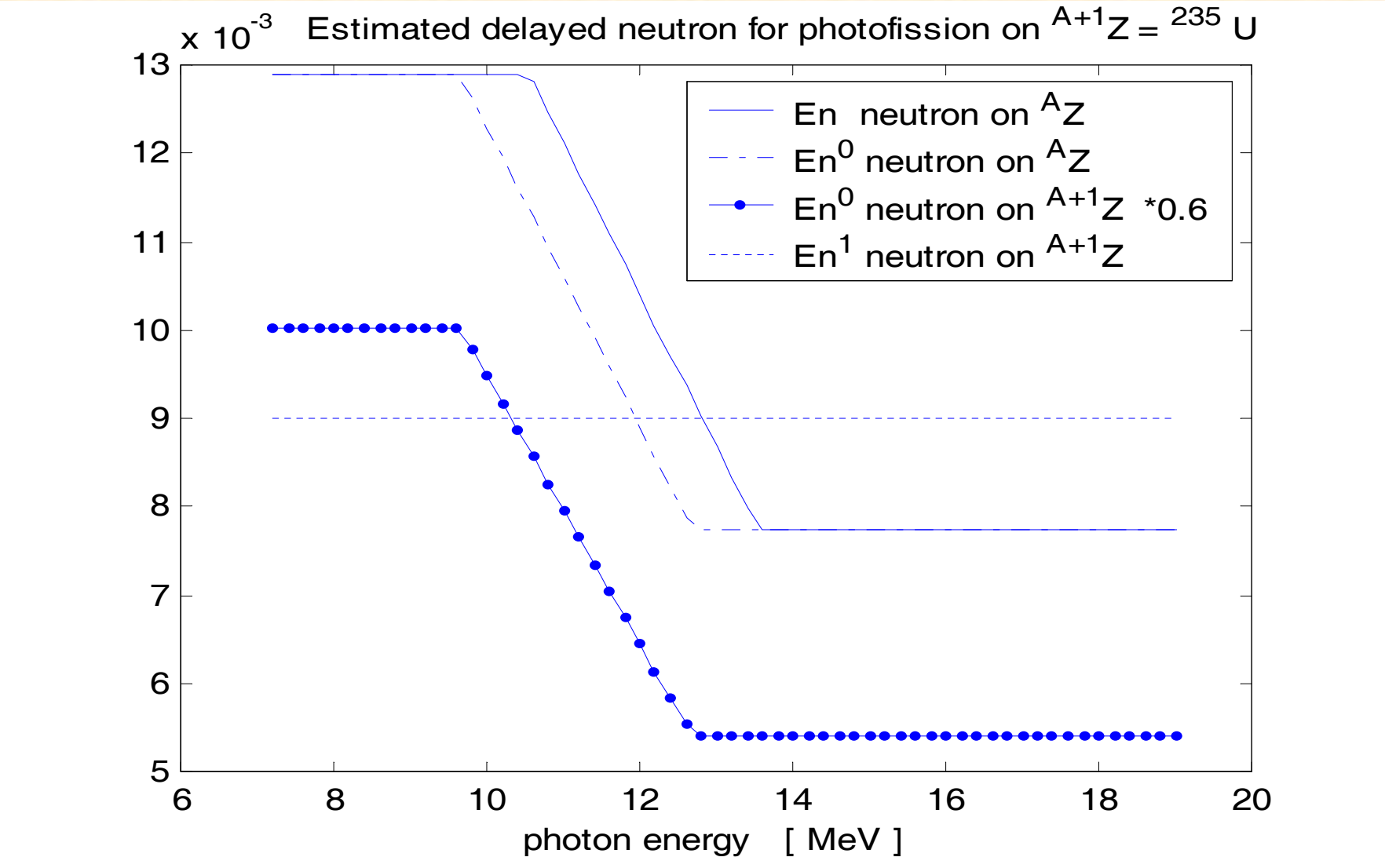
Similarity of Neutron-Induced and Photon-Induced Fission Yield

- **Two contrasting theories:**
- **Neutron-induced fission with energy e_γ on $Z^{(A+1)}$ equivalent to photon-induced fission with energy e_n Z^A**
- **The available experimental data (caldwell, et a) for delayed neutron yield from photofission indicate that v_d is independent of the source photon energy in the giant dipole resonance energy range**

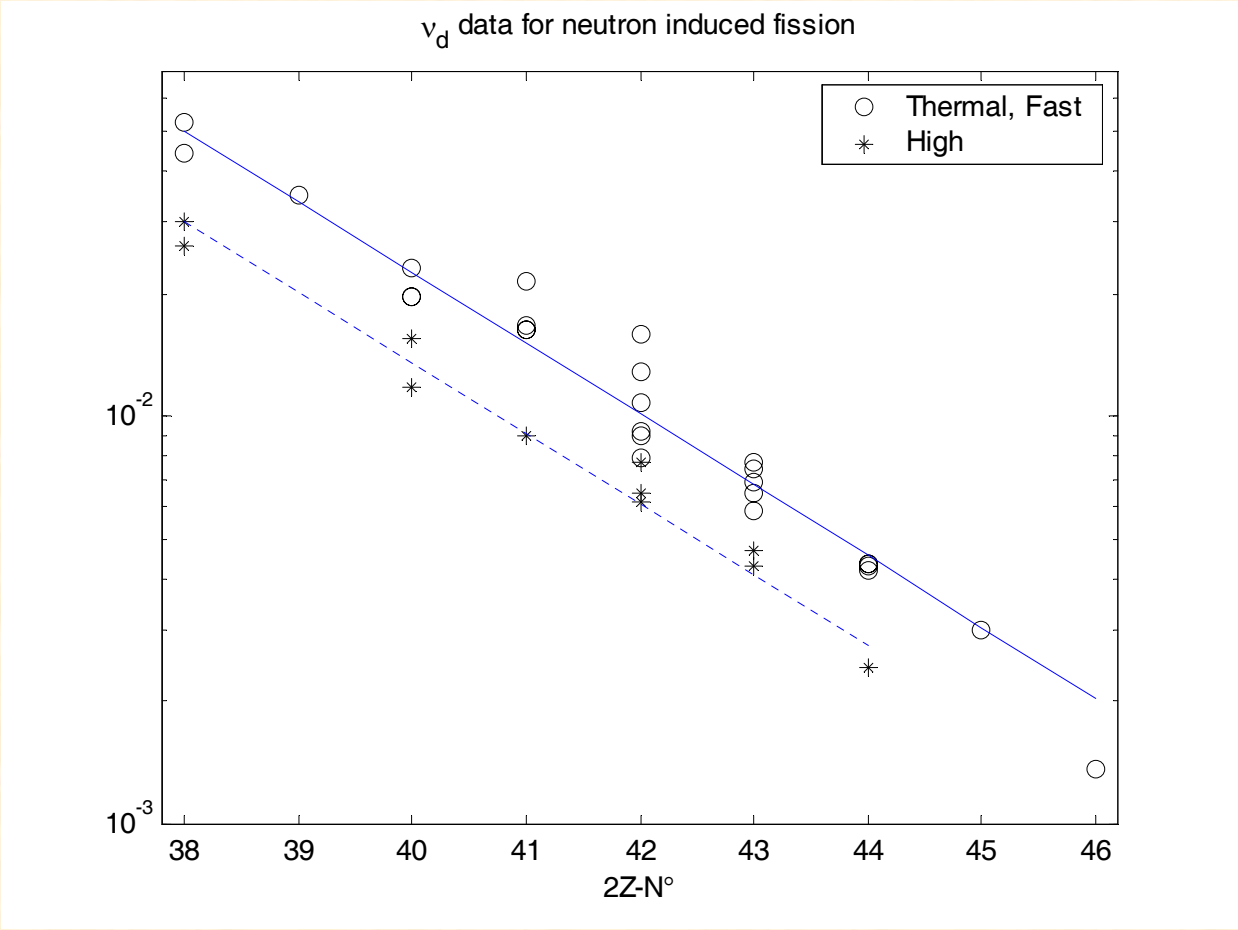
Adopted /Equation for Photofission

Many ways to approximate the number of delayed neutrons ν_d in photofission reactions:

- **Similarity of the compound nucleus**
- **Similarity with the fission fragments**

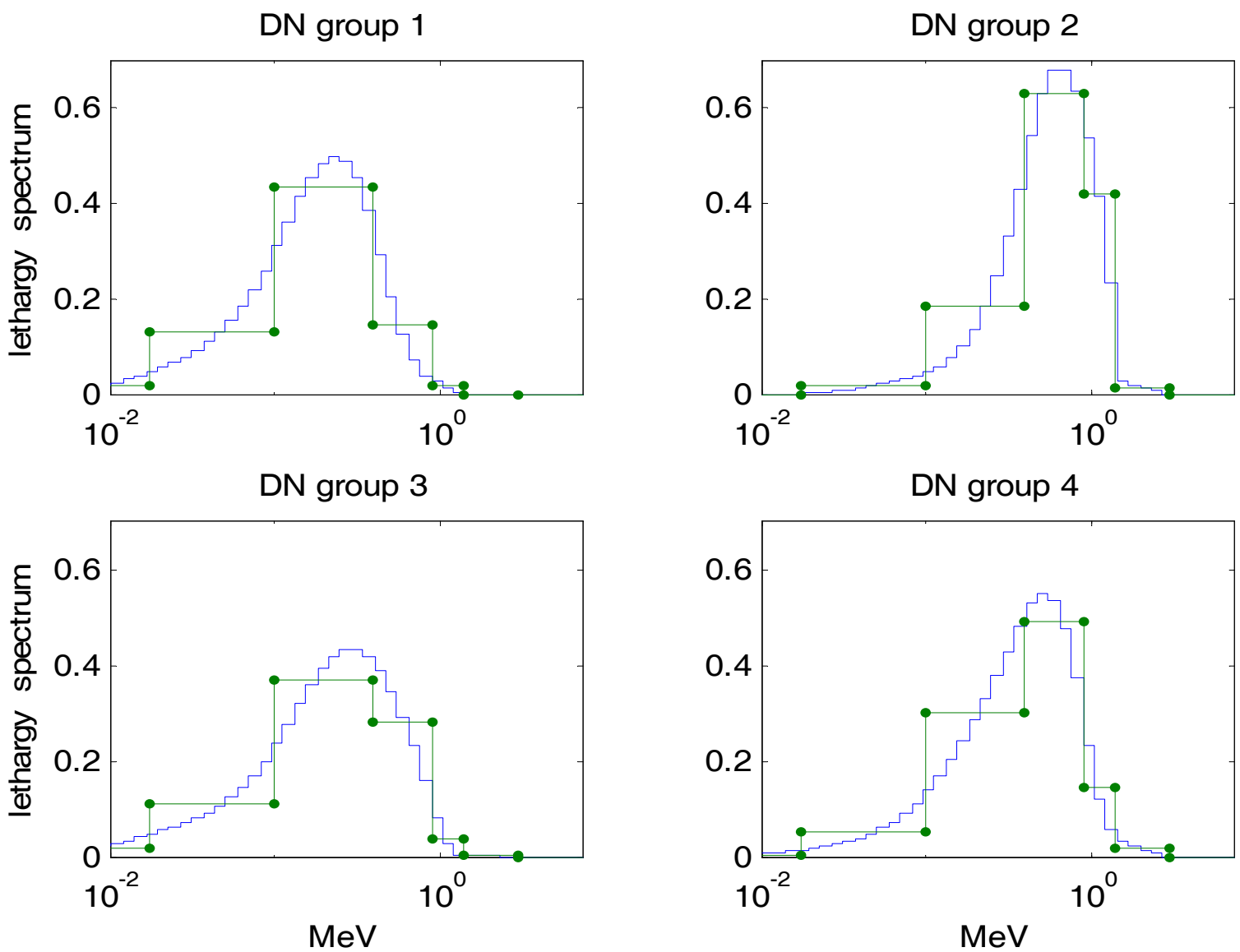

x 10^-3
Estimated delayed neutron for photofission on A+1Z = 235 U
13
12
11
10
9
8
7
6
5
6
8
10
12
14
16
18
20
photon energy [MeV]
En neutron on AZ
En0 neutron on AZ
En0 neutron on A+1Z *0.6
En1 neutron on A+1Z

Relationship Between Actinides and V_d for Neutron-Induced Fission



Calculated and Measured Values

nuclide	2Z–N	calculated $\nu_d^{(1)}$	Photofission experimental data (Caldwell et.al.) $\nu_d^{(2)}$	Photofission experimental data (Moscati et.al.) $\nu_d^{(3)}$
^{232}Th	38	.030	.026÷.031	.027÷.030
^{235}U	41	.009	.009÷.011	--
^{238}U	38	.030	.027÷.031	~.036
^{239}Pu	43	.0041	~.0037	--

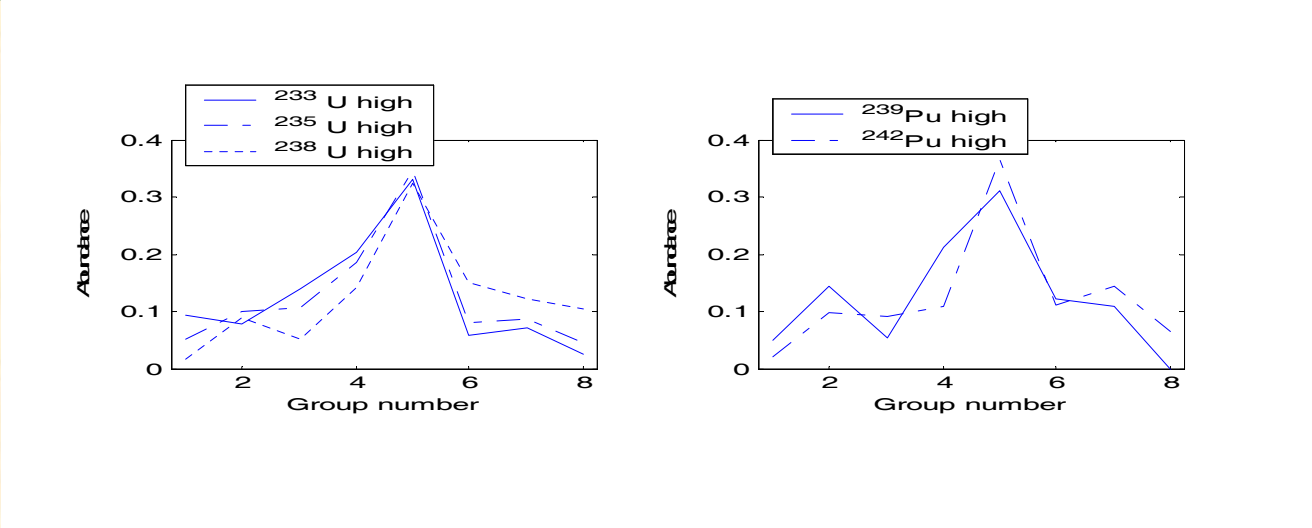

DN group 1
DN group 2
DN group 3
DN group 4
lethargy spectrum
0.6
0.4
0.2
0
10^{-2}
10^{0}
MeV

Assigning Each Neutron to a Group

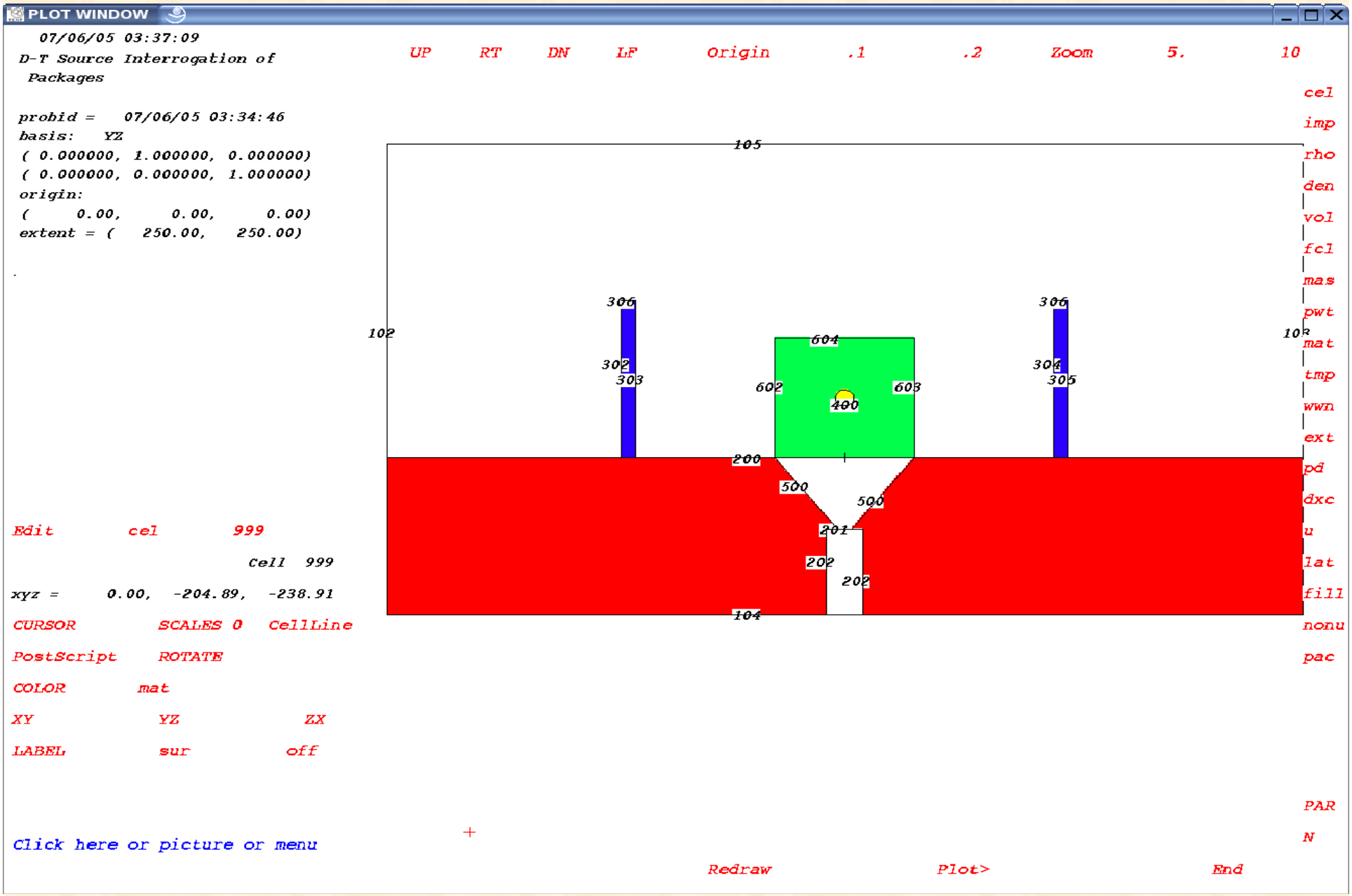
No groups data available for photofission →use groups data for neutron-induced fission

- **Complete groups data for "high-energy" neutron-induced fission**
  - **Use data from fast or thermal neutrons induced fission on a nucleus Z^A**
  - **Interpolate data from "high-energy" neutrons induced fission on other isotopes of the same atomic species**
  - **Use data for closest isotope fissioned by "high-energy" neutrons**
  - **Use the data for another nuclide having the same (2Z-N) value**
- **Latter method justified by the few data available for U and pu isotopes**

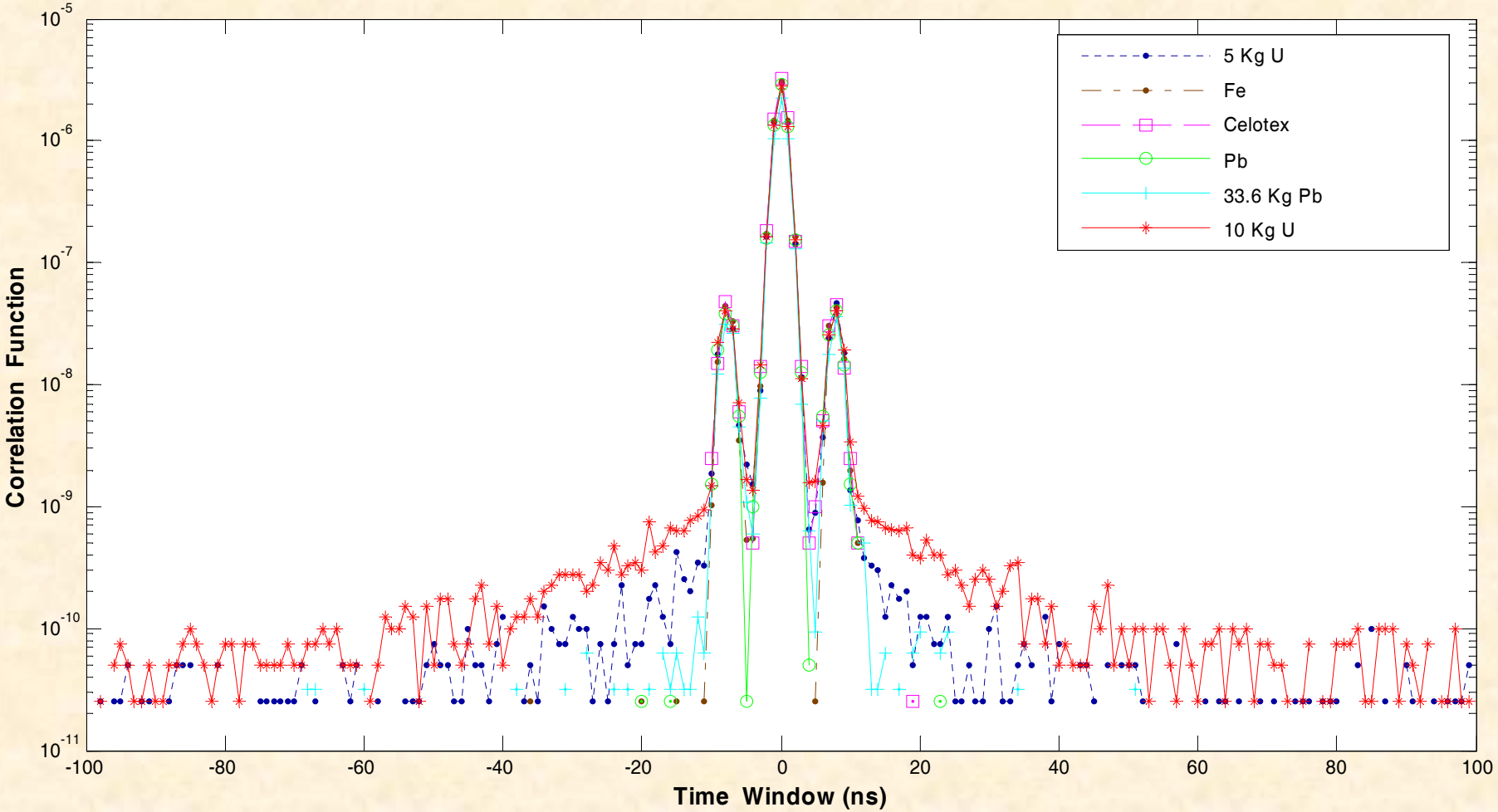
Assigning Delayed Neutrons to Groups



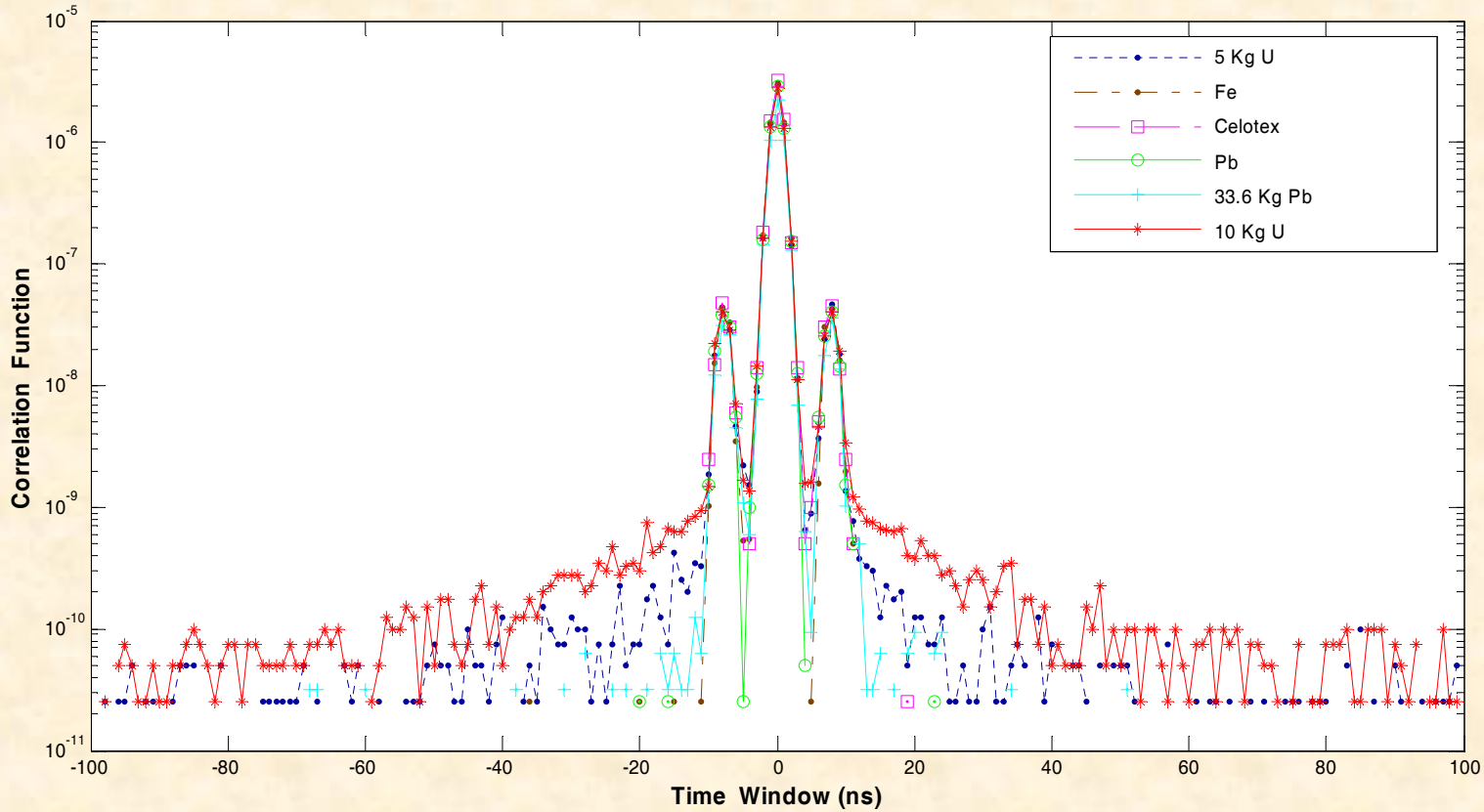
- **Group 5 dependance upon the isotope is negligible**
- **Groups from 1 to 4 are negatively correlated to the isotope mass**
- **Groups 6,7, and 8 the relative abundances are positively correlated to the isotope mass**


PLOT WINDOW
07/06/05 03:37:09
D-T Source Interrogation of
Packages
probid = 07/06/05 03:34:46
basis: YZ
(0.000000, 1.000000, 0.000000)
(0.000000, 0.000000, 1.000000)
origin:
(0.00, 0.00, 0.00)
extent = (250.00, 250.00)
UP RT DN LF Origin .1 .2 Zoom 5. 10
cel
imp
rho
den
vol
fcl
mas
pwt
mat
tmp
wwn
ext
pd
dxc
u
lat
fill
nonu
pac
PAR
N
105
102
103
306
302
303
304
305
604
602
603
400
200
500
201
202
104
Edit cel 999
Cell 999
xyz = 0.00, -204.89, -238.91
CURSOR SCALES 0 CellLine
PostScript ROTATE
COLOR mat
XY YZ ZX
LABEL sur off
Click here or picture or menu
Redraw Plot> End

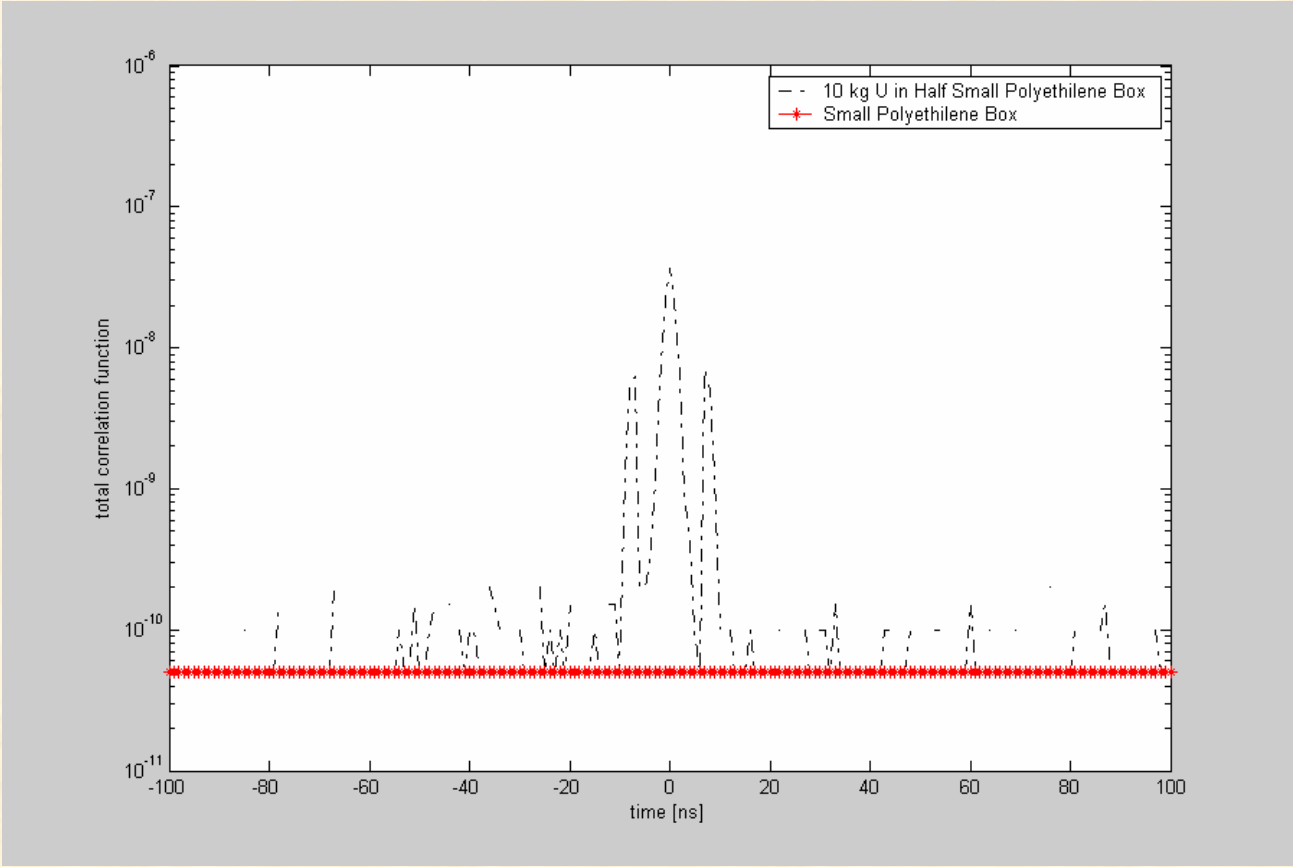
Belt Conveyor: Small Celotex Package Beam On



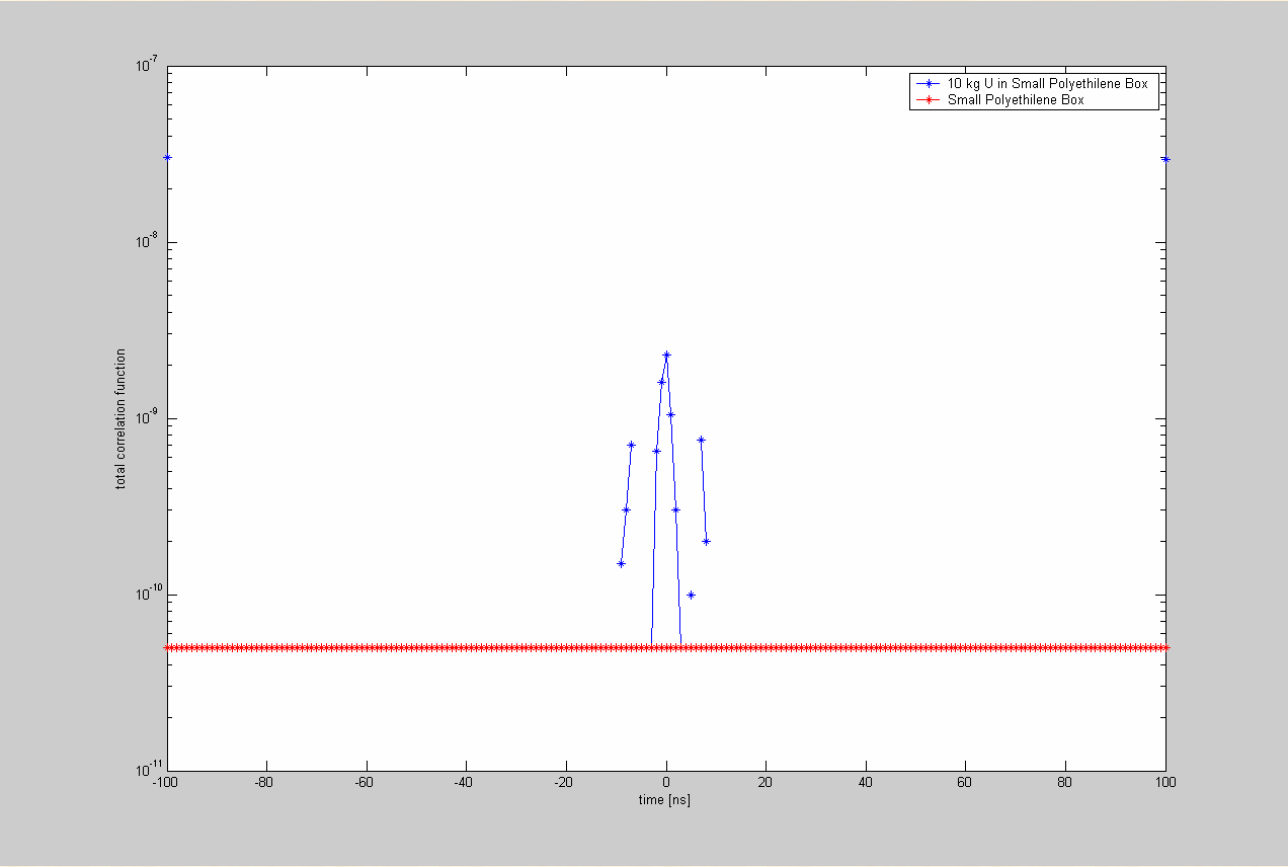
Correlation Function Between Detectors for 10 kg U Sphere in Empty Box, Beam Off



Correlation Function Between Detectors for 10 kg U Sphere in Celotex Half Small Box, Beam Off



Correlation Function Between Detectors for 10 kg U Sphere in Celotex Small Box, Beam Off



Delayed Neutrons Distributions

- **Precursors number at beam shutdown depends on**
  - **Beam pulse duration**
  - **Neutrons average life-time in surrounding medium (some msec)**

⇓⇓

- **Short pulse respect precursors average life-time (<0.1s)**

$$N_i = f v_d p_i$$

  - **Sample from dnd**
  - **Compute CDF directly from the discrete distributions**
- **Long pulse respect precursors average life-time (> min.)**
  - **Sample from the dntd**
  - **Weight single distribution through respective time delay**
  - **Compute CDF from the time-weighted discrete distributions**

Acquisition Schemes

- **Eight groups characterized by their own life-time:**

$$\lambda_1 < \lambda_2 < \lambda_3 < \lambda_4 < \lambda_5 < \lambda_6 < \lambda_7 < \lambda_8$$

- **Short pulse ~ 0.1 s ≈**
  - **Counting delayed neutrons from fastest precursors**
- **Long measurement time**
  - **Counting delayed neutrons from slowest presursors**

Sensible Measurements

Average neutron survival time in high H and C medium ~ 100 μsec half-life of delayed neutron precursors spans: 0.19s – 55.6 s

$\Downarrow$

Maximize delayed neutron coincidence counts

- **Measurements lasting from ½ to 1 minute to capture neutrons from longest-lived precursors**

Maximize system throughout

- **Measure both prompt and delayed radiation**
- **Analyze prompt and delayed signals separately**