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Experimental Progress Report--Modernizing the Fission Basis

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Experimental Progress Report
Modernizing the Fission Basis
TUNL
July 24-31, 2011
R. Macri (LLNL) for the collaboration

Preamble

This document formalizes the earlier experimental report demonstrating the experimental capability to make accurate (< 2 %) precision gamma-ray spectroscopic measurements of the excitation function of high fission product yields of the 239Pu(n,f) reaction (induced by quasimonoenergetic neutrons). A second experiment (9/2011) introduced an compact double-sided fission chamber into the experimental arrangement, and so the relative number of incident neutrons striking the sample foil at each bombarding energy is limited only by statistics. (The number of incident neutrons often limits the experimental accuracy.) Fission chamber operation was so exceptional that 2 more chambers have been fabricated; thus fission foils of different isotopes may be left in place with sample changes. The scope of the measurements is both greatly expanded and the results become vetted. Experiment 2 is not reported here. A continuing experiment has been proposed for February 2012.

Introduction

In 2010 a proposal (Modernizing the Fission Basis [1]) was prepared to "resolve long standing differences between LANL and LLNL associated with the correct fission basis for analysis of nuclear test data". Collaboration between LANL/LLNL/TUNL [2] has been formed to implement this program by performing high precision measurements of neutron induced fission product yields as a function of incident neutron energy. This new program benefits from successful previous efforts utilizing mono-energetic neutrons undertaken by this collaboration [3-5]. The first preliminary experiment in this new program was performed between July 24-31, 2011 at TUNL and had 2 main objectives:

1) demonstrating the capability to measure characteristic γ-rays from specific fission products.
2) studying background effects from room scattered neutrons.

In addition, a new dual fission ionization chamber has been designed and manufactured. The production design of the chamber is shown in the picture below. The first feasibility experiment to test this chamber is scheduled at the TUNL Tandem Laboratory from September 19 – 25, 2011. The dual fission chamber design will allow simultaneous exposure of absolute fission fragment emission rate detectors and the thick fission activation foils, positioned between the two chambers.

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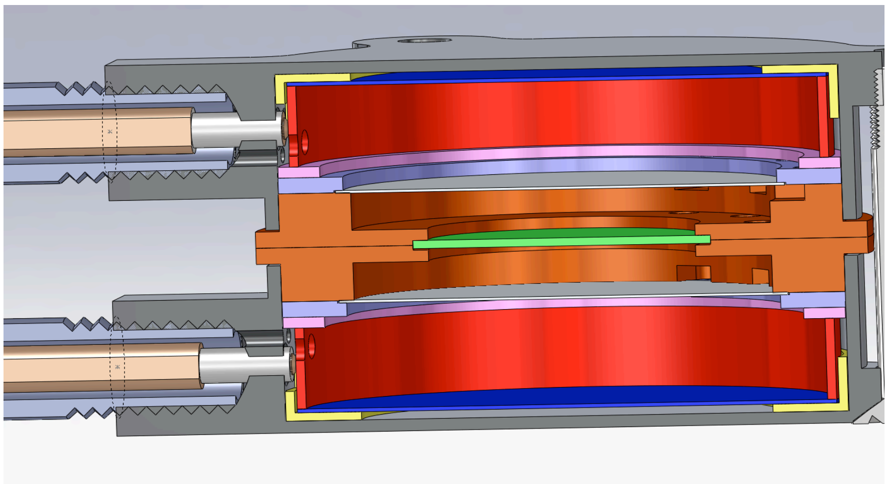


Fig. 1. Schematic of the design of the dual fission chamber.

Experimental details

For the first preliminary experiment the ^{235}U and ^{238}U targets were shipped from LANL to TUNL. In addition various monitor foils (Al, In, Au, ^{235}U) were available at TUNL for characterizing experimental parameters. Given that there was only one set of U targets available for this run we decided to have a single production run using 9 MeV neutrons generated from the d(d,n)^{3}He reaction. This was a convenient energy to operate the TUNL FN-Tandem at and the 9 MeV neutrons were in the "plateau" region of the (n,f) cross section for both U targets.

The deuterium production gas target consisted of a cylindrical gas cell pressurized to 102 PSI with 99.99% pure deuterium gas. Deuteron ions entered the cell through a 6.35 **μ**m Havar foil, which separated the deuterium gas from the vacuum of the beam line. The downstream end of the gas cell was capped by a 0.1 cm thick tungsten beam stop. The gas cell was a 3 cm long copper cylinder with a diameter of 1 cm. The cell was cooled by an air jet**.** The target irradiation position was 2.7 cm downstream from the end of the gas target. The deuterium beam energy was chosen to be 6.4 MeV. The energy loss in the Havar foil was ~ 330 keV resulting in an incident deuterium beam energy of 6.07 MeV at the entrance into the gas cell. The exit energy of the deuterium emerging from the gas cell was 5.44 MeV. This gave a mean neutron energy of 8.97 MeV and a full width spread of 0.61 MeV (i.e. the neutron energies impinging on the target varied between 8.67 and 9.23 MeV.

Unfortunately, the run got off to a slow start due to ion source difficulties. The first 3 days of beam time were essentially lost while the TUNL technical staff attempted various remedies. By the 4th day the beam was stabilized and ran very smoothly for the remainder of the week long experiment.

Two γ-ray spectrometers were available (the 3rd one that is generally available at TUNL had been sent back to the factory for refurbishment). This limited the counting capacity and judicious choices had to be made to count the large number of samples expected. We had arranged to ship some irradiated foils back to LLNL (and possibly LANL) for further counting following the experiment.

Flux Determination

The first experiment consisted of a stack of monitor foils (Al, In, Au) wrapped in 0.5 mm Cd in the target position and a set of two off-axis monitor foils (In, ^{235}U) located 22.77 cm below the primary target. Each were 3.5 cm from the vertical center line and one of the sets was wrapped with 0.5 mm Cd while the other one was bare. The main production targets were designed to monitor the primary neutron flux while the off-axis foils were to monitor the effects of target and room scattered neutrons. All of the monitor foils were 0.5 inch in diameter except for the ^{235}U foils which were square foils 1 inch on a side.

Run 1 – Monitor Foils			
Neutron Energy	9 MeV		
Start (7/28/11)	14:38		
End (7/28/11)	22:24		
Production Target	Al	In	Au
Weight (mg)	18.91	971.1	118.7
Off Axis Target (22.5 cm)	In	^{235}U	
Weight (each of two) (mg)	961	1500	

A second experiment on a new stack or monitor foils (each 0.5 inch in diameter) was also done. This time there were no “off –axis” targets used. The parameters of this irradiation were:

Run 2 – Monitor Foils			
Neutron Energy	9 MeV		
Start (7/28/11)	23:19		
End (7/29/11)	11:20		
Production Target	Al	In	Au
Weight (mg)	9.43	950.2	63.32

The results from the flux analysis for these two monitor foil runs are:

Monitor Foil Flux Analysis				

Target	Reaction	γ-Energy (keV)	x-sect (mb @ 8.7 MeV)	Calc flux (n/sec)
Al-run 1	$^{27}Al(n,\alpha)^{24}Na$	1368	60	4.24E7
In-run 1	$^{115}In(n,n')^{115m}In$	336	296	4.06E7
Au-run 1	$^{197}Au(n,2n)^{196}Au$	355.6	240	4.70E7
Al-run 2	$^{27}Al(n,\alpha)^{24}Na$	1368	60	4.95E7
In-run 2	$^{115}In(n,n')^{115m}In$	336	296	4.92E7
Au-run 2	$^{197}Au(n,2n)^{196}Au$	355.6	240	5.83E7

The extracted flux within each run should have been the same. As seen in the above table, within a run, the flux differed by 15-20%. The largest variations were for the Au monitor foils. At our experimental conditions, the ^{197}Au(n,2n) reaction is not an ideal flux monitor since it has a threshold energy of 8.1 MeV and is rapidly rising at the neutron bombarding energy of this experiment ($\langle E_n \rangle$ = 9 +/- 0.3 MeV). The statistical errors on the γ-ray counting were less than 3% for all measured. If we just use the Al and In monitor foils then the measured flux within a run differs by $\leq$ 4%.

For the final experiment of this series we irradiated, in the 0^0 beam position, a foil stack that consisted of Al and Au monitor foils with ^{235}U and ^{238}U fissile targets. All of the production targets were 0.5 inch in diameter. These "production" targets were wrapped with 0.5 mm Cd foils. In this experiment off-axis foil stacks were also used. As with Run 1 above, two sets of foils were located 22.77 cm below the target position. One each 3.5 cm left and right of the center line. These used Au (0.75 inch diameter) and In (0.5 inch diameter) with one set being wrapped in 0.5 mm Cd. Another set of off-axis foils were mounted below the first set at a distance of 54.21 cm below the production target center line. One each 3.5 cm left and right of the center line. These used similar Au and Al foils as the first off-axis set but, in addition, the 54.21 cm off-axis set that had 0.5 mm of Cd wrapping also had a 1 inch square ^{235}U foil.

Production Run				
Neutron Energy	9 MeV			
Start (7/29/11)	11:49:30			
End (7/30/11)	21:51			
Production Target	Al	Au	235U	238U
Weight (mg)	56.2	366	282	442
Off-Axis Target (22.77 cm)	In	Au		
Weight (each of two) (mg)	238	545		
Off-Axis Target (54.21 cm)	In	Au	235U	
Weight (each foil) (mg)	239	545	1500	

Again, the flux could be calculated using the in beam monitor foils

Production Foil Flux Analysis				
Target	Reaction	γ-Energy	x-sect	Calc flux

		(keV)	(mb @ 9MeV)	(n/sec)
Al	$^{27}Al(n,\alpha)^{24}Na$	1368	60	4.57E7
Au	$^{197}Au(n,2n)^{196}Au$	355.6	240	4.66E7

The flux was ~ 4.5E7 n/sec which is similar to what was observed in the two monitor foil runs shown above.

Fission Determination

In the production run two fissile targets (^{235}U and ^{238}U) were measured simultaneously. Though both are fissile they have different (n,f) cross sections at the 9 MeV neutron energy measured. Also the chain yields [6] to specific isotopes differs for the two cases. For our initial analysis we have concentrated on two high yields, relatively short lived isotopes: ^{133}I (20.8 hr) and ^{135}I (6.57 hr). Properties of these isotopes are:

Isotope	Half life (hr)	γ-Energy (keV)	BR (%)	^{235}U 9 MeV (CY-%)	^{238}U 9 MeV (CY-%)	^{235}U thermal (CY-%)
^{133}I	20.8	530	87	5.92	6.32	6.70
^{135}I	6.57	1260	28.7	5.08	6.10	6.28

Using the data in the above table and from the Production Run irradiation table parameters we can calculate the effective flux for the fission reactions as well:

Fission Flux Analysis				
Target	Reaction	γ-Energy (keV)	x-sect (mb @ 8.7MeV)	Calc flux (n/sec)
235U	(n,f) ^{133}I	530	1790	3.19E7
235U	(n,f) ^{135}I	1260	1790	4.96E7
238U	(n,f) ^{133}I	530	1008	3.97E7
238U	(n,f) ^{135}I	1260	1008	4.07E7

The fission extracted flux has a mean value about 10% smaller than that obtained from the monitor foil analysis and also has a larger variance than the values extracted from the various monitor foils. This is not too surprising. This preliminary analysis only uses 2 fission products (^{133}I and ^{135}I) and inherent uncertainties about their cumulative fission yields will directly impact the extracted cross section. Also, the ^{235}U target had intrinsically high γ-ray activity that may be effecting the extraction of specific γ-rays. A more thorough analysis of the data is ongoing.

A very encouraging conclusion from the comparison of the two U targets is that they are reasonably consistent (at the ~20% level) and give a calculated flux that is acceptably close to the monitor foil values. If there were large contributions of thermal or low energy neutrons present then the thermally fissile ^{235}U would be grossly different from the thresholding ^{238}U value –which it is not. More of these important background issues are discussed below.

Time of Flight Measurements

A pulsed deuteron beam was produced by a duoplasmatron ion source located in the low-energy end of the TUNL accelerator bay. A continuous beam of ions was extracted from the source head which was held at -50 kV with respect to the ground. After extraction, the ion beam was pulsed using a combination of two electrostatic choppers and a single double-drift buncher. The beam had a pulse width of 2 ns and a repetition rate of 1.25 MHz. After being pulsed, the deuteron beam was accelerated by the FN Tandem Van de Graaff accelerator before bombarding a cylindrical gas cell pressurized to 102 PSI with 99.99% pure deuterium gas.

A neutron-monitor (NE 213) was positioned in the neutron-beam at 354.3 cm from the end of the gas cell. In addition two ^{3}He gas scintillators were positioned at +/- 16.6 degree from the 0-degree line at 286.5 cm from the end of the gas cell. ^{3}He gas cells were filled with ^{3}He and nat-Xe. The gas composition was 28.7 atm of ^{3}He and 2.6 atm of natural Xe [7,8].

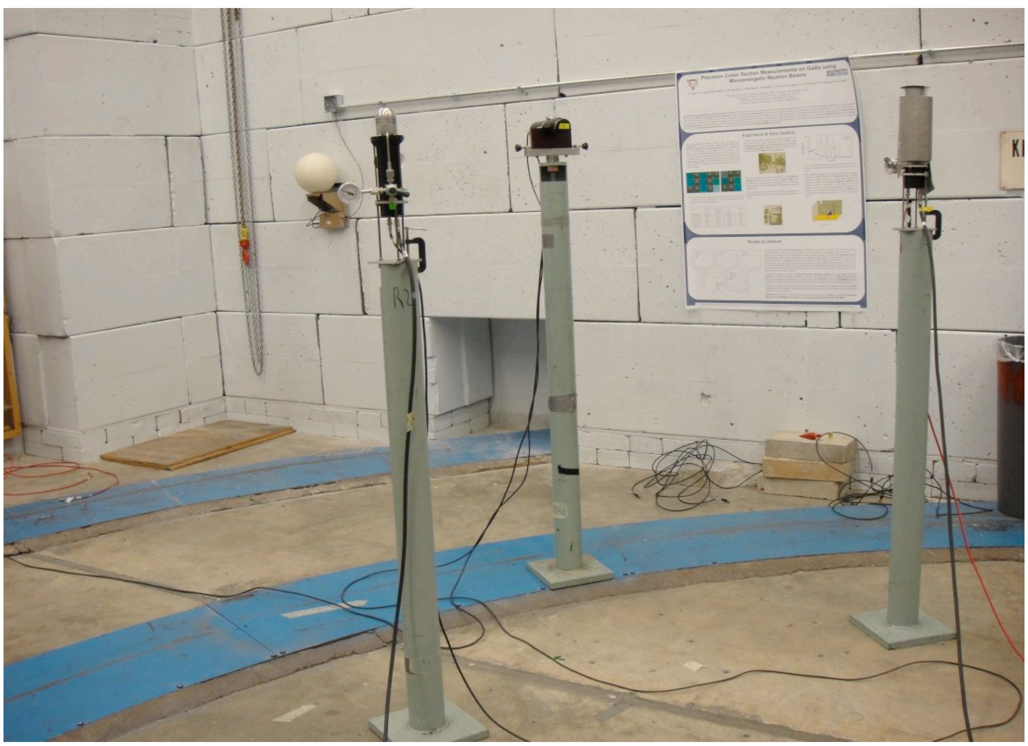


Fig. 2. Neutron detector in the middle and two identical ^{3}He gas scintillators positioned in the TUNL TOF room. The ^{3}He detector on the right is covered by 1.15 mm Cd sheet.

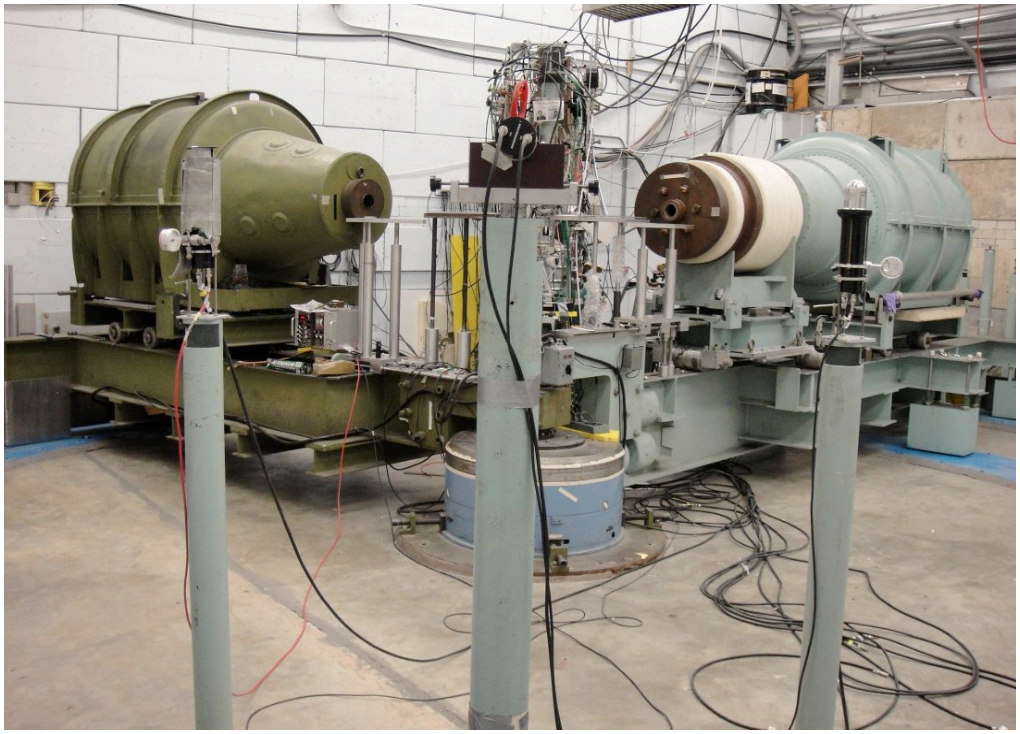


Fig. 3. TOF room. View from the neutron beam dump.
The average beam current on the gas cell was about 1.5 μA and remained constant during the TOF measurements. The TOF spectra from the 0-degree neutron monitor and one of the 3-He counters are shown in Fig. 4 and Fig. 5, respectively. A very good PSD discrimination between neutrons and gammas is shown in Fig. 6. The table below shows the count rates from the two ^{3}He counters with and without Cd cover.

^{3}He counters with and without Cd cover.

Detector #	# counts without Cd	# counts with Cd	Ratio (no Cd/Cd)
1 (left)	145999 (460)	132307 (414)	1.10
2 (right)	123667 (374)	112463 (442)	1.10

Since the Cd cover of the ^{3}He detectors was 1.15 mm, neutron attenuation in the Cd sheet has to be taken into account. A neutron transmission-efficiency factor τ_{eff} was therefore determined via MCNP simulation. The simple relation between the attenuation and the transmutation efficiency is given by:

$$A = 1 - \tau_{eff}$$

For example, the attenuation of the 8.7 MeV neutron beam in 1.15 mm Cd sheet is 4.0%.

At the end of the TOF measurements the position of the Compton edge on the 0-degree neutron-monitor was determined by counting two gamma sources: ^{137}Cs and ^{22}Na. From these source measurements effective threshold of the neutron-monitor can be determined.

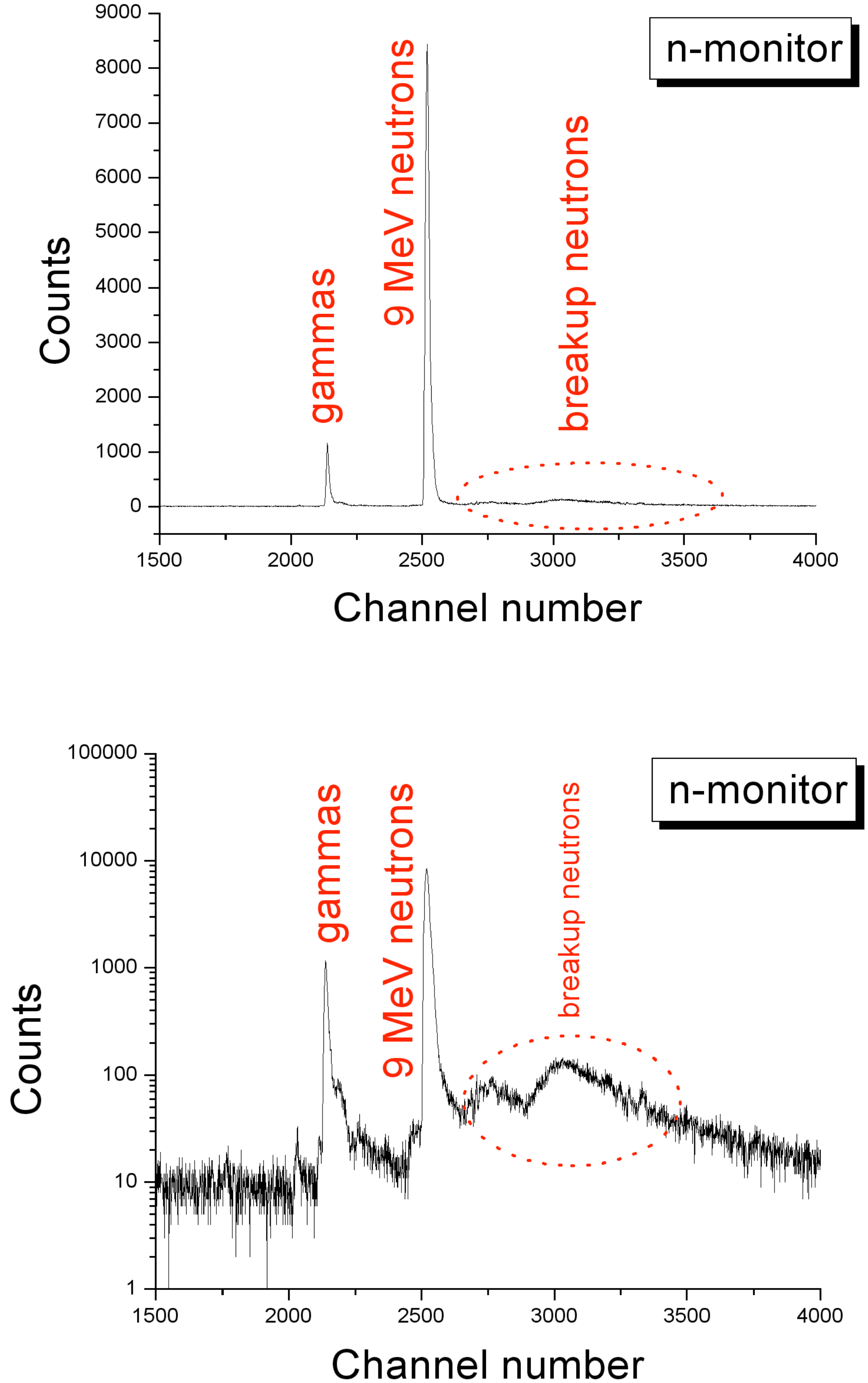


Fig. 4. TOF spectrum from the 0-degree neutron monitor. The top spectrum is in linear scale, the bottom is in log scale.

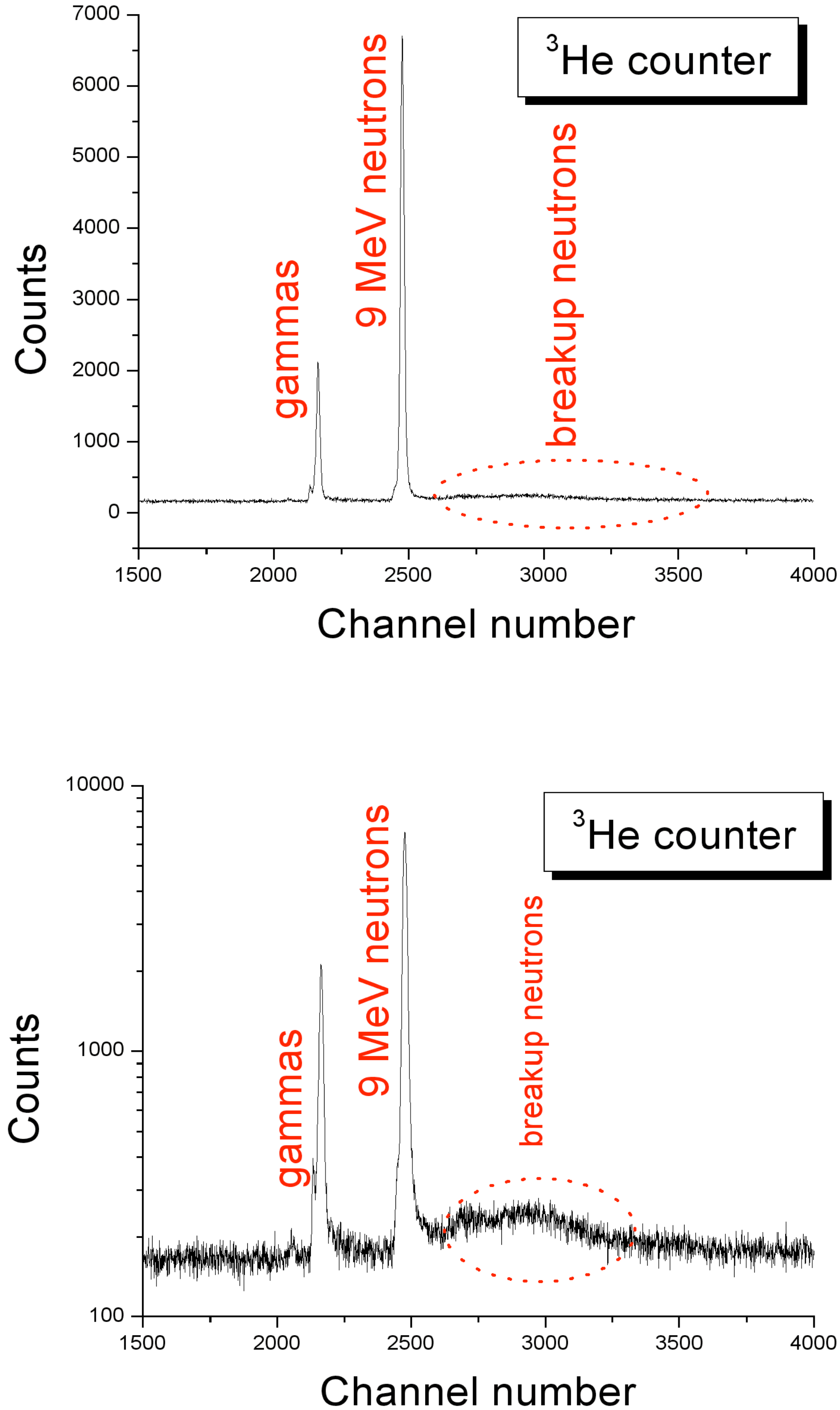


Fig. 5. TOF spectrum from the ^{3}He counter. The top spectrum is in linear scale, the bottom is in log scale.

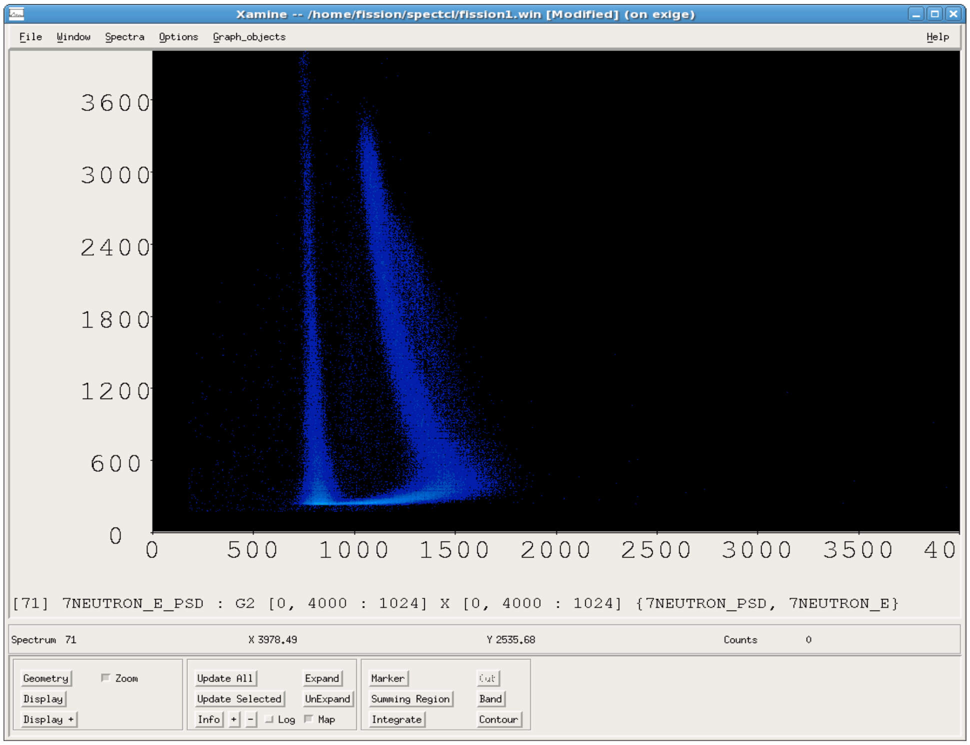


Fig. 6. Pulse shape discrimination (PSD) spectrum from the 0-degree neutron monitor.

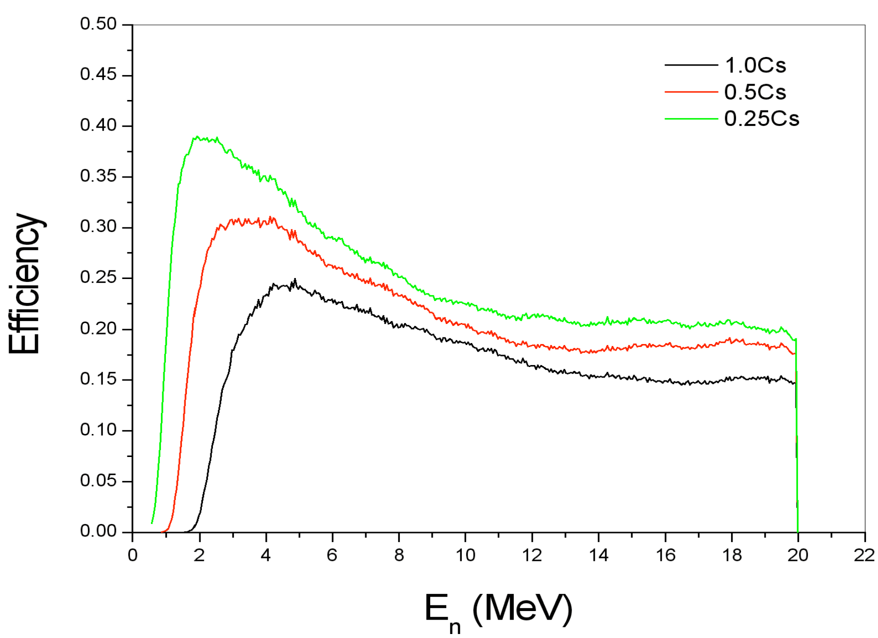


Fig. 7. Simulated neutron-detection efficiency including the threshold-induced systematic uncertainties as a function of neutron kinetic energy.

Background Issues

One of the major objectives of this run was to address the effect of background, room return neutrons. The long term goal of the experimental program is to investigate thermally fissile nuclei (^{235}U and ^{239}Pu) at a variety of incident neutron energies. These nuclei have very large fission cross sections for low energy neutrons and are thus vulnerable to scattered neutrons. To study this effect we mounted a series of monitor foils away from the primary beam axis. Some of these foil packages we wrapped in 0.5 mm of Cd foil. ^{113}Cd has a large neutron absorption edge located at 30 meV that very effectively absorbs thermal neutrons. We measured (n,γ) reactions on In and Au and the (n,f) reaction on ^{235}U in Cd and non Cd wrapped targets. The masses and location of these foils have been presented in the above "Run" tables. In total there were 16 different off-axis foils measured. One manner of presenting this data is to transform the observed γ-rays into the effective thermal neutron fluxes that would be required to produce the observed γ-intensities. These are presented in the next Table and Fig 8 below:

Effective Thermal Neutron Flux for Off Axis Targets

Target	g-Energy (keV)	σ-thermal (barns)	Run	Location (cm)	Cd Wrap?	Calc Flux n/s-cm^2	σ-flux (%)
In-2	1294	162	Mon	22.77	No	1.93E2	4.3
In-3	1294	162	Mon	22.77	Yes	0.82E2	4.2
In-6	1294	162	Prod	22.77	No	2.38E2	12
In-7	1294	162	Prod	22.77	Yes	1.29E2	13
In-8	1294	162	Prod	54.21	No	2.49E2	7.3
In-9	1294	162	Prod	54.21	Yes	0.85E2	9.9
Au-1	412	98.65	Prod	22.77	No	4.50E2	4.2
Au-2	412	98.65	Prod	22.77	Yes	2.44E2	5.8
Au-3	412	98.65	Prod	54.21	Yes	2.13E2	5.7
Au-4	412	98.65	Prod	54.21	No	3.61E2	4.7
U-36A-^{133}I	530	39.2	Mon	22.77	No	4.81E2	6.0
U-36A-^{135}I	1260	36.8	Mon	22.77	No	4.66E2	17.0
U-79B-^{133}I	530	39.2	Mon	22.77	Yes	3.16E2	5.9
U-79B-^{135}I	1260	36.8	Mon	22.77	Yes	3.70E2	9.0
U-79A-^{133}I	530	39.2	Prod	54.21	Yes	1.17E2	7.1
U-79A-^{135}I	1260	36.8	Prod	54.21	Yes	4.14E2	11.7

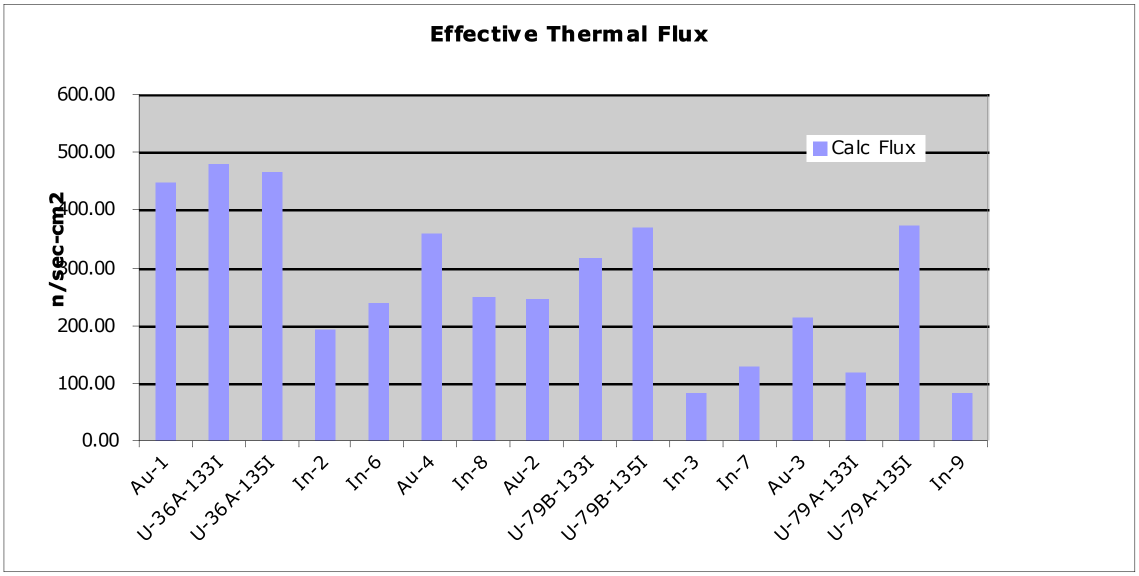


Fig 8. Effective "thermal" neutron flux for various off-axis monitor foils. The abscissa is labeled with the particular foil (from the table above). The ordering has been changed so that the foils that were wrapped in Cd are on the right side of the figure (starting with "Au-2").

From this analysis there are several features worth noting:

• This simple transformation to represent the observed γ-ray intensities as the result of thermal neutron capture gives a fairly large spread of "effective" thermal neutron fluxes (a range of 82-481 n/s-cm^2). However, this is still over 10^5 times smaller than the primary beam flux on target.

[a] The next feature is that the Cd wrapped foils all have lower extracted fluxes than do those that were bare – by about a factor of 2. Again, this implies there is a significant flux of thermal neutrons that we can suppress with Cd shielding. However, the Cd wrapped foils still show substantial activation. This points out the total "background" flux is not just thermal.

• The effective of distance. If the irradiation room were simply filled with a neutron gas then the background rate should be independent of location. From the above table when we look at the effect of increasing the distance (going from 22.7 to 54.2 cm from the production gas target) we see that the Au and In rates change by less than 20%. The fission products are somewhat harder to interpret. ^{133}I (when Cd wrapped – the only 54.2 cm measurement we made with this monitor) decreases by 60% while the two ^{135}I results agree within 10%. The far distance Cd wrapped ^{133}I appears to be clearly in error since it does not have the consistent ratio to the ^{135}I yields seen in the other ^{235}U measurements. It should be pointed out that this analysis is done with fairly weak peaks riding on a large background caused by the high intrinsic ^{235}U target decay rate. The values reported here are all from a single measurement. It will be necessary to follow the decays of these activities to ensure that the correct half-lives are obtained and that there are no other photon background effects obscuring the peaks we are trying to analyze.

• Some of the Cd wrapped activation is coming from neutrons directly produced in the d,d reaction. For a system producing 9 MeV neutrons at 0^0 then at 80^0 to the beam axis the flux goes down from the 0^0 value of 80 mb/sr to 6.4 mb/sr . Also, from kinematics, the neutron beam energy is lowered from 9 MeV to ~ 4.5 MeV. This still represents an appreciable flux of high energy neutrons. We have attempted to observe this effect by doing additional measurements on the "off-axis" In foils - the same ones used for measuring the "thermal" flux via the $^{115}In(n,\gamma)^{116}In$ reaction. In this case we use the $^{115}In(n,n')^{115m}In$ reaction that has a threshold of 336 keV, and is thus well suited for measuring these higher energy reaction produced neutrons. The results from this analysis are:

Neutron Flux for Off Axis In(n,n') Reactions

Target	γ-Energy (keV)	σ-(n,n') (barns)	Location (cm)	Cd Wrap?	Calc Flux (n/s-cm^2)	Production flux (n/s-cm^2)	σ-flux (%)
In-6	336	0.325	22.77	No	1.30E5	4.77E7	4.7
In-7	336	0.325	22.77	Yes	1.15E5	4.23E7	4.7
In-8	336	0.325	54.21	No	2.15E4	4.49E7	12.0
In-9	336	0.325	54.21	Yes	1.25E4	2.61E7	14.8

As seen, the calculated flux at the target location was ~ 1.2E5 n/s-cm^2 at the close distance and 5-10 times smaller at the further distance. For the close distance the extracted flux was, as it should be, essentially independent of the Cd wrapping. At the far distance the Cd wrapped foil was a factor of 2 less than the non Cd wrapped foil. This is unexpected but based on analysis of fairly weak intensity photopeaks (fitting uncertainty was 14.8%). When the extracted flux is transformed to represent the predicted "Production Flux" on target (i.e. corrected for target geometry and the (d,d) angular distribution) the values go in to the mid x10^7 n/s-cm^2 which is encouragingly consistent with the value extracted from the in beam monitor foils.

• The absolute value of the extracted "thermal" flux is quite modest. Even for the highest observed flux measured the value was ~ 480 n/s-cm^2. The flux on the target is ~ 4.5x10^7 n/sec/cm^2 – a factor of 10^5 greater. Even if we scale up the effect by the relative (n,f) cross sections (585 b for E_{th} and 1.79b for E = 9 MeV) the total background contribution would be less than 0.4%. If we use the more realistic Cd shielded values (we will shield the production targets with Cd) then the effective contribution for background events falls to around 0.2-0.3%. At this level the background effects will not be a major perturbation to the desired experimental accuracy of 1%.

We have also begun an effort to study the room return neutrons using Monte Carlo techniques. The neutron reaction room has been crudely modeled and we have used MCNP to estimate the effects of neutron scattering. Preliminary results from this analysis are shown in Figures 9 and 10.

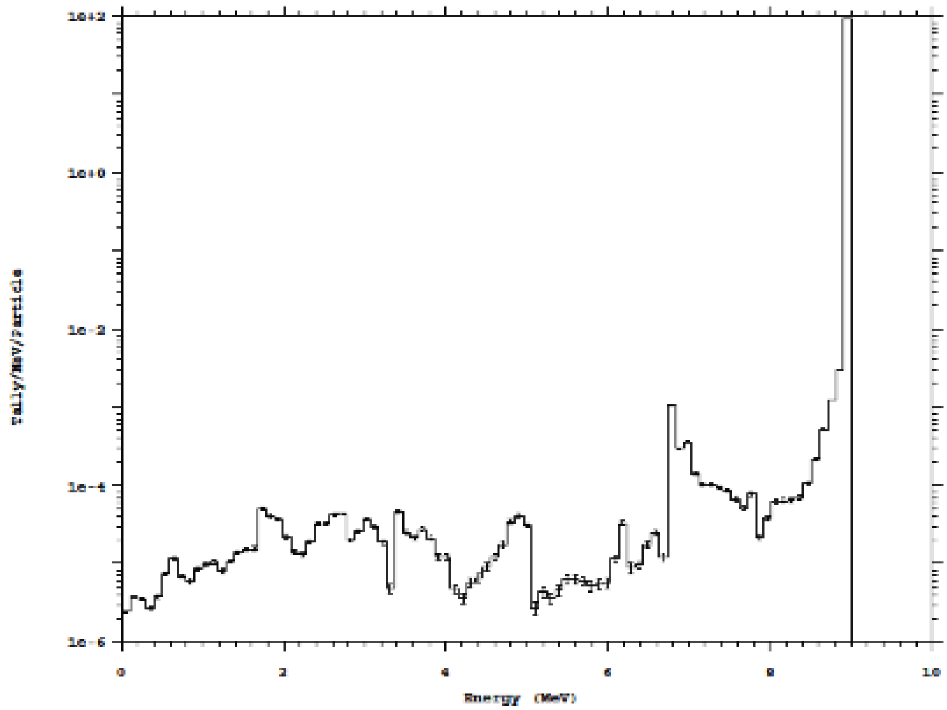


Figure 8. MCNP calculations of the neutron distribution in the reaction room near the irraditation target. The main beam is at 9 MeV.

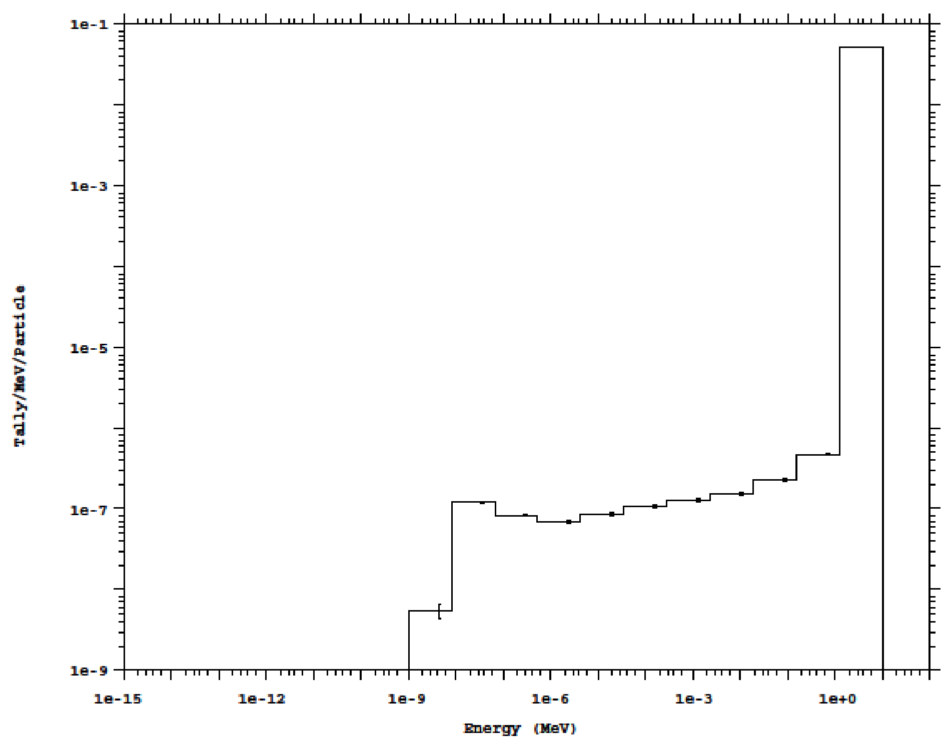


Figure 9. Similar to Figure 8 but with the neutron energy scale presented logarithmically.

The encouraging feature of this analysis is that it shows production of neutrons down to the thermal region. The yields of these low energy neutrons are 5-6 orders of magnitude below the primary beam peak – in qualitative agreement with the off-axis monitor foil analysis presented above.

Fission product yields

After the activation the two uranium foils were positioned in thin aluminum containers and the induced activity of the fission product yields, after β^- decay, was measured (and is still being measured) using two high-resolution (FWHM = 1.3 – 1.8 keV at 1.333 MeV) HPGe detectors. The measurement cycles were gradually increased from 30 minutes during the first day after the end of the irradiation to one day after two weeks following the activation. The duration between the cycles was 0 seconds. This counting procedure allows us to follow very closely the experimental half-lives of all fission products and account for any gamma-ray interference between them. The analysis of the experimental half-lives in comparison with the literature data is shown in Appendix A. The first preliminary results of the fission product yield ratios from ^{238}U and ^{235}U at E_n=9.0 MeV are shown in Table below. The fission product yields are normalized to the ^{99}Mo fission fragment. ^{99}Mo was chosen because it has convenient half-life, resulting in high-count rate, and its fission product yield has minimal variability with incident neutron energy.

Yield ratio of ^{99}Mo (E_γ=140.5keV) with respect to ^{140}Ba, ^{143}Ce and ^{147}Nd fission fragments.

Elements	**Yield ratio** ^{238}**U**	^{235}**U**
^{99}Mo (140.5)/^{140}Ba(537.3keV)	0.678	0.682
^{99}Mo (140.5)/^{143}Ce(293.3keV)	2.696	2.106
^{99}Mo (140.5)/^{147}Nd(531.0keV)	1.593	1.916

The statistical uncertainty on these fission product yield ratios is less or equal to 2%.

The present fission product yield experiments are providing complementary information on the ^{238}U(n,2n) reaction cross section using monoenergetic neutron beams. The first preliminary results at E_n=9.0 MeV using the most intense gamma lines in ^{237}U are very encouraging. Consistency of the ^{237}U yield produced in the (n,2n) reaction as determined using the 59.4, 208, and 267.5 keV characteristic gamma lines is very good. Obtaining the cross section of the ^{238}U(n,2n) is under way.

Yield of ^{238}U (n, 2n) ^{237}U for 59.54 keV, 208.01 keV and 267.54 keV transitions.

Energy (keV)	Yield
59.54	3.187(74)E-16
208.01	3.193(45)E-16
267.54	3.301(37)E-16

Conclusion

The first activation measurements at TUNL using thick uranium foils achieved the first goal of this joint LANL-LLNL-TUNL collaboration to obtain greater than 2% precision in the fission product yield ratios. This objective was achieved in both ^{235}U and ^{238}U targets at En=9.0 MeV. This precision is consistent with the 2010-year activation measurements on ^{238}U at En = 14.5 MeV [9]. Repeated measurements as a function of time will provide additional information regarding different isotopes and also permit determination of characteristic decay properties of different fission species.

The run was successful. We showed that using a variety of different measurements we were able to extract a consistent value for the neutron flux on target.

Probably the most important outcome from this run is that background issues associated with room return neutrons are below levels (< 0.4%) that will perturb the intended high precision experiment that has been proposed.

Our next step is aimed to determine the incident energy dependence of fission product yields over the energy region from 1 to 14.5 MeV. For this reason we manufactured a new dual fission ionization chamber that will provide high fidelity fission normalization and will be used in all future production experiments. The first feasibility experiment of using this dual fission chamber is scheduled for the week of September 19, 2011.

References

1) “Modernizing the Fission Basis”, R.S Rundberg et.al., LA-UR-10-05073:2010

2) Collaboration

LANL	LLNL	TUNL
E. Bond	B. Bandong	J. Kelley
T. Bredeweg	J. Becker	A. Tonchev
M. Fowler	S. Carman	W. Tornow
R. Rundberg	C. Hagmann	G. Rusev
D. Vieira	J. Kenneally	C. Arnold
J. Wilhelmy	T. Luu	C. Bhatia
	R. Macri	M. Gooden
	C. Ryan	B. Fallen
	S. Sheets	A. Crowell
	M. Stoyer	C. Howell

3) A.P. Tonchev et.al., Phys. Rev**.** **C77**, 54610 (2008).

4) R. Raut, et.al., Phys. Rev. **C 83,** 044621 (2011).

5) A. P. Tonchev, et.al., Phys. Rev. **C**, **82**, 054620 (2010).

6) “Wahl Yield Calculations” t2.LANL.database:
http://t2.lanl.gov/publications/yields/apxA.txt

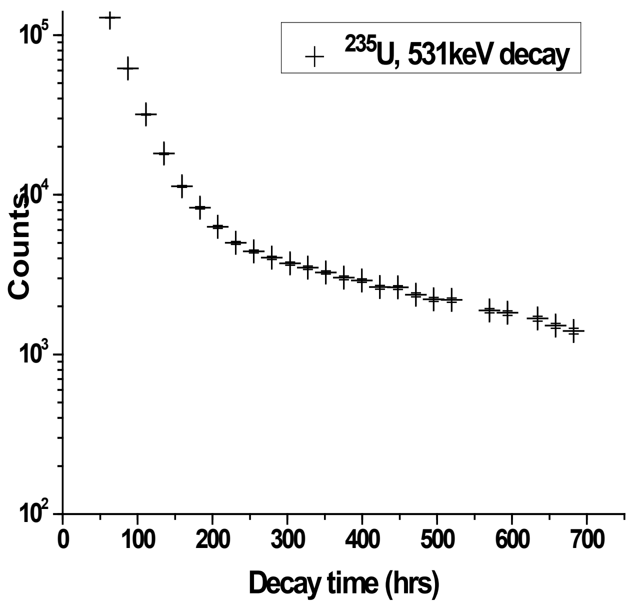
7) W. Tornow, et.al., Phys Lett. B **702**, 121 (2011).

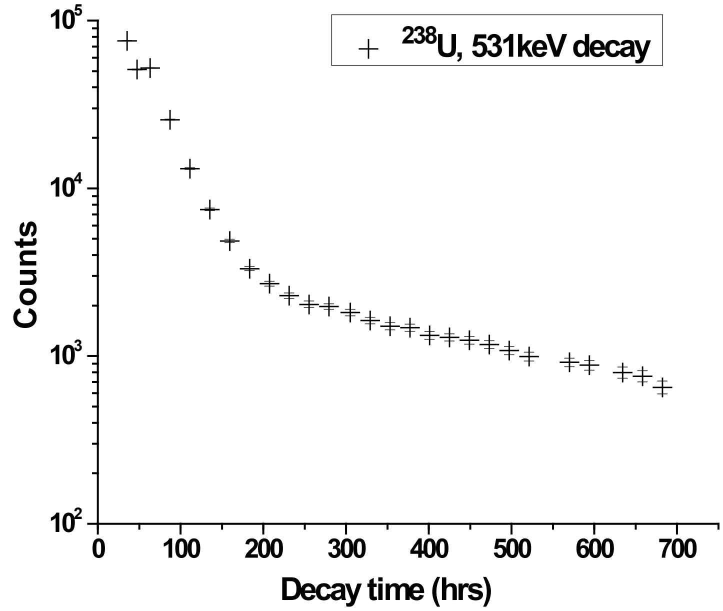
8) W. Tornow et al.. Nucl. Inst. and Meth. **A** 647, 86 (2011).

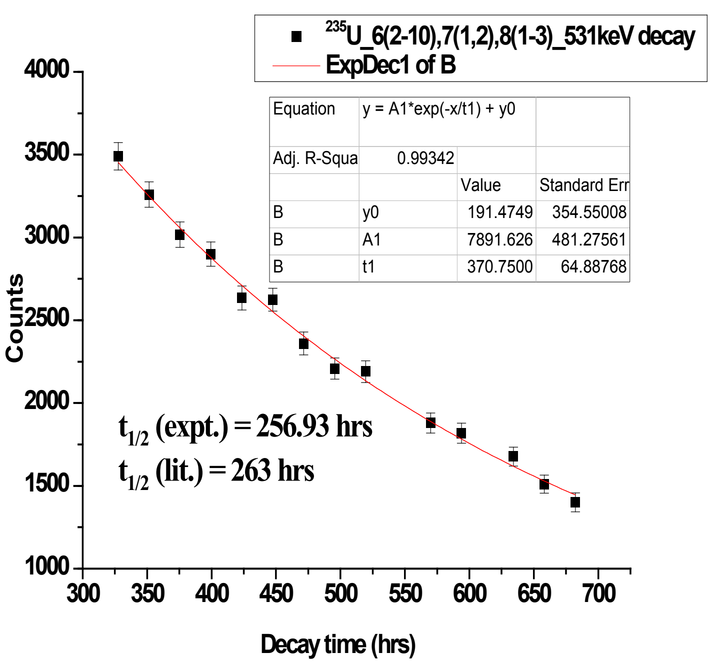
9) A. Tonchev at al. TUNL progress report, 2010.

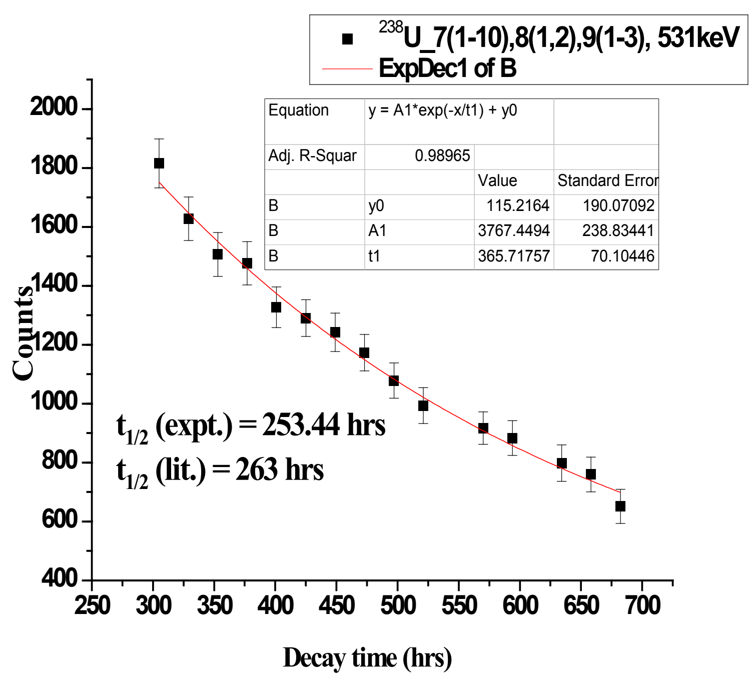
Appendix A)

Analysis of fission product decays.



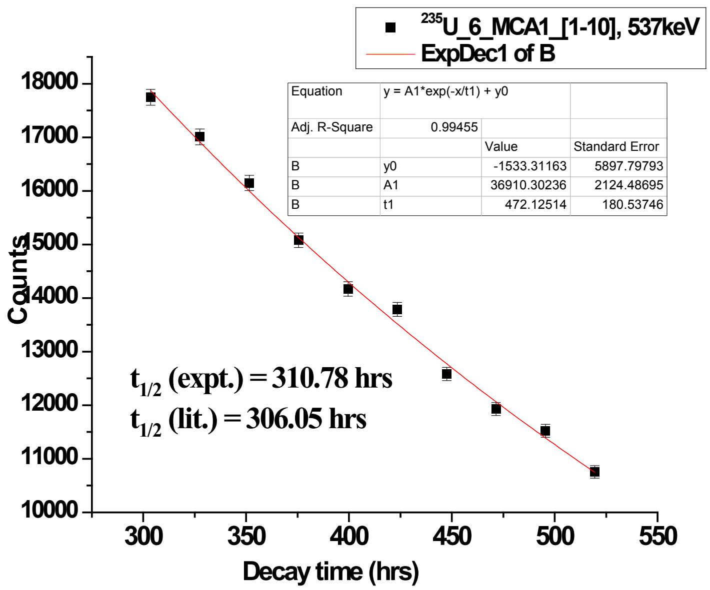


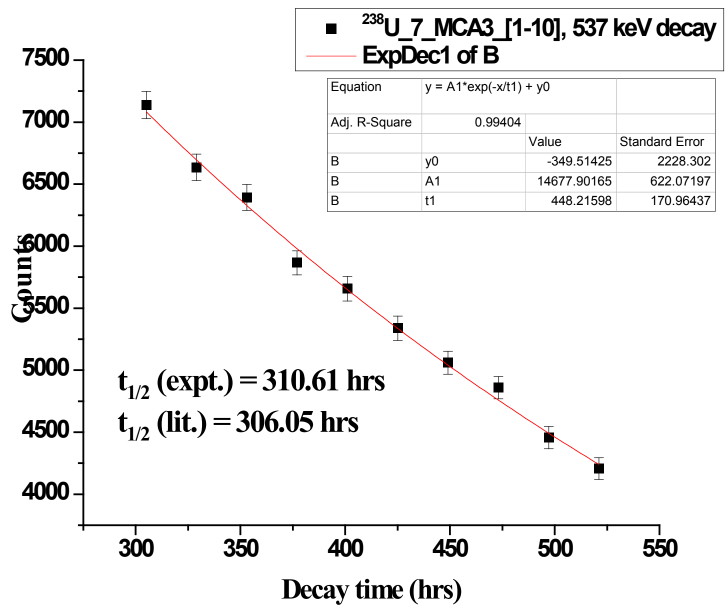




238U - % error in $T_{1/2}$ = 2.31 %

235U - % error in $T_{1/2}$ = 3.63 %



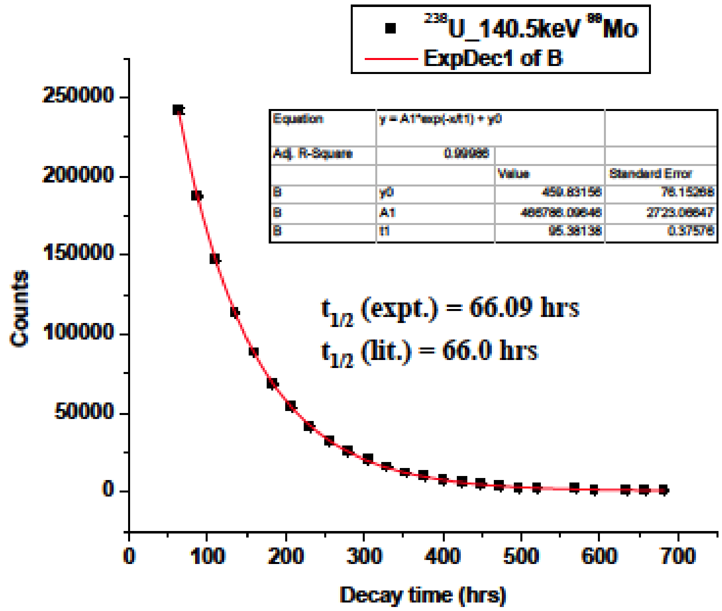


238U - % error in $T_{1/2}$ = 1.56 % **235U - % error in $T_{1/2}$ = 1.47 %**

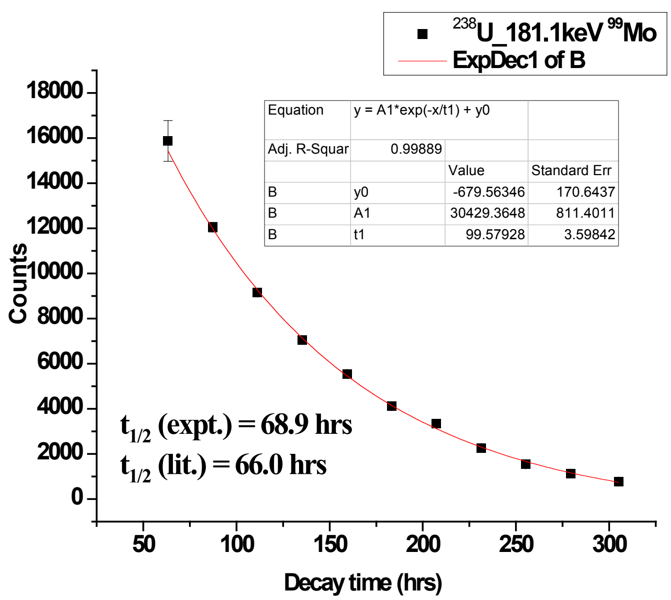
Spectrum & cycles	E_γ (keV)	$T_{1/2}$ (literature) (hrs)	$T_{1/2}$ (expt.) (hrs)	% error
235U_ 6(2-10),7(1,2), 8(1-3)	531	263	256.93	2.31
235U_6_MCA1_[1-10]	537	306.05	310.78	1.56
238U_7(1-10),8(1,2),9(1-3)	531	263	253.44	3.63
238U_7_MCA1_[1-10]	537	306.05	310.61	1.49

Fiss ion

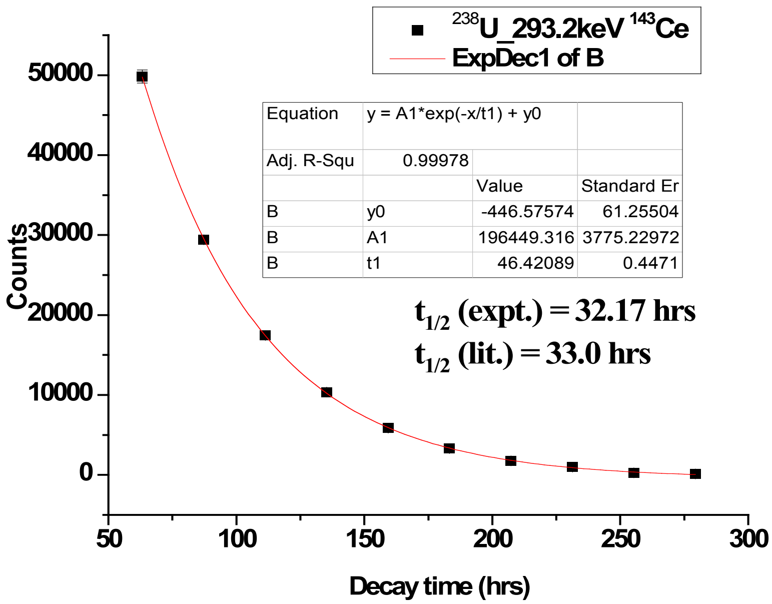
yield ratio ^{235}U ($^{140}Ba/^{147}Nd$) (at t = 327.57 hrs) = 2.827 ± 235
Fission yield ratio ^{238}U ($^{140}Ba/^{147}Nd$) (at t = 327.57 hrs) = 2.365 ± 199



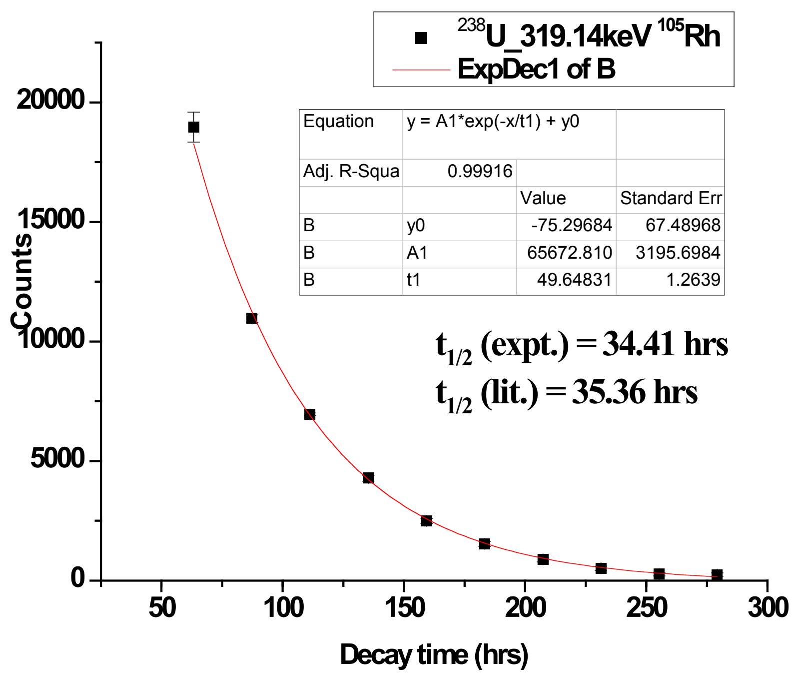
% error = 0.14%



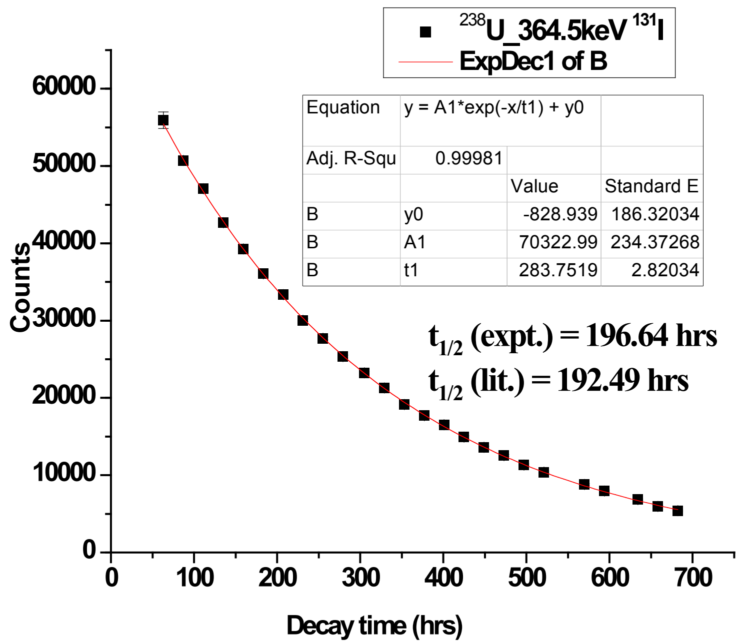
% error = 4.47 %



% error = 2.52 %

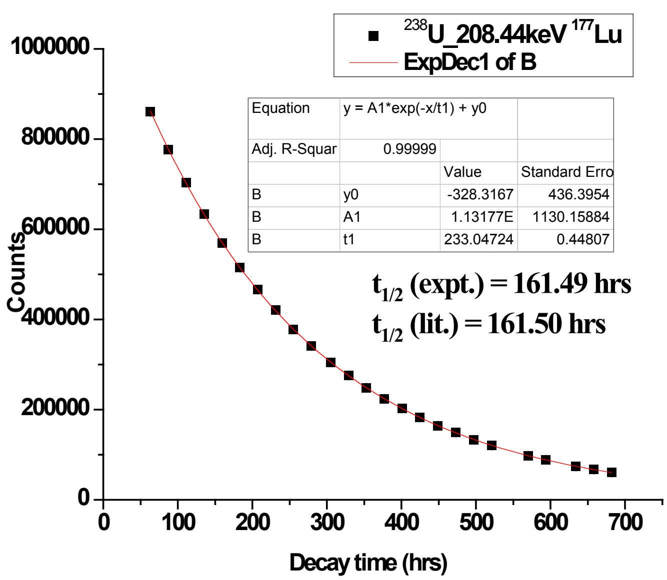


% error = 2.68 %

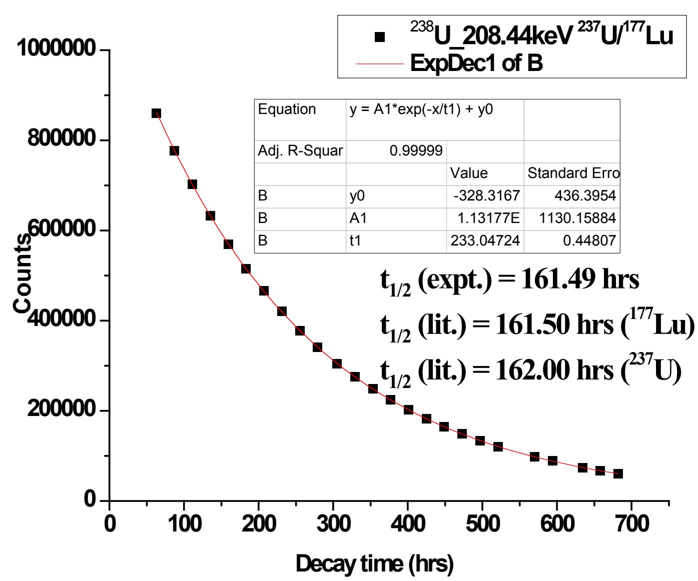


238U_364.5keV 131I
ExpDec1 of B
Equation
y = A1*exp(-x/t1) + y0
Adj. R-Squ
0.99981
Value
Standard E
B
y0
-828.939
186.32034
B
A1
70322.99
234.37268
B
t1
283.7519
2.82034
t1/2 (expt.) = 196.64 hrs
t1/2 (lit.) = 192.49 hrs
Counts
Decay time (hrs)

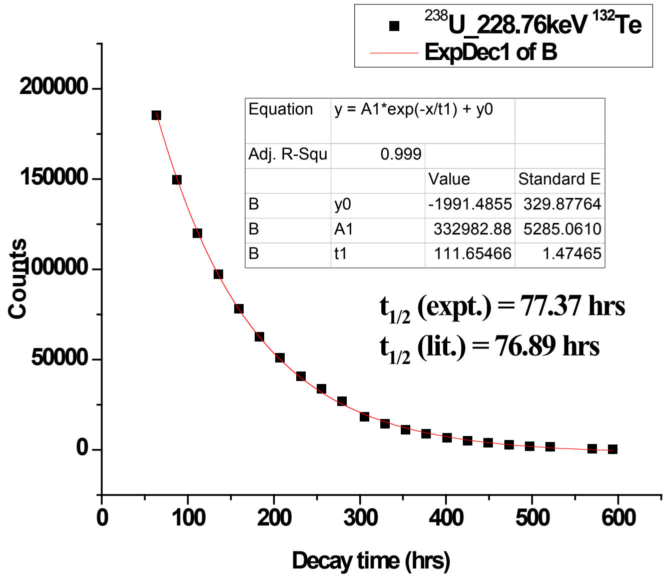
% error = 2.16 %



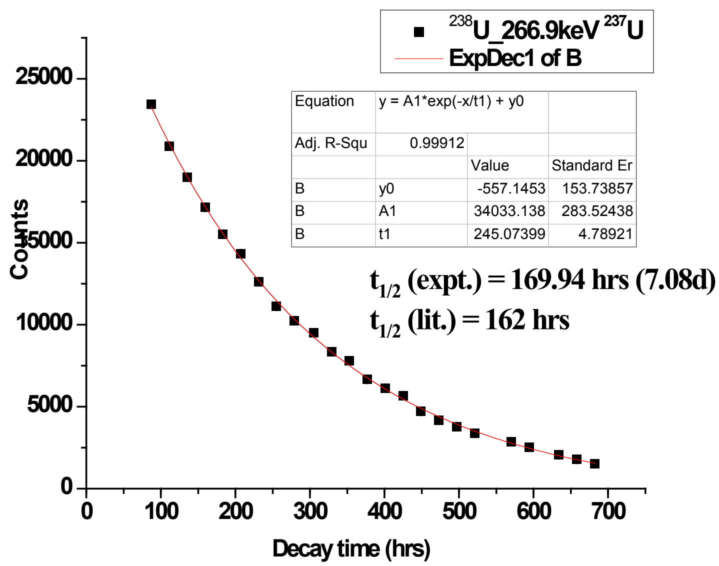
238U_208.44keV 177Lu
ExpDec1 of B
Equation
y = A1*exp(-x/t1) + y0
Adj. R-Squar
0.99999
Value
Standard Erro
B
y0
-328.3167
436.3954
B
A1
1.13177E
1130.15884
B
t1
233.04724
0.44807
t1/2 (expt.) = 161.49 hrs
t1/2 (lit.) = 161.50 hrs
Counts
Decay time (hrs)



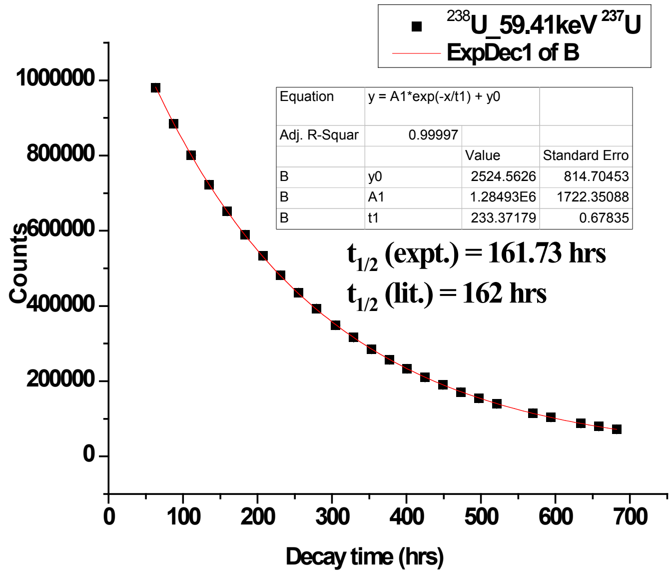
238U_208.44keV 237U/177Lu
ExpDec1 of B
Equation
y = A1*exp(-x/t1) + y0
Adj. R-Squar
0.99999
Value
Standard Erro
B
y0
-328.3167
436.3954
B
A1
1.13177E
1130.15884
B
t1
233.04724
0.44807
t1/2 (expt.) = 161.49 hrs
t1/2 (lit.) = 161.50 hrs (177Lu)
t1/2 (lit.) = 162.00 hrs (237U)
Counts
Decay time (hrs)



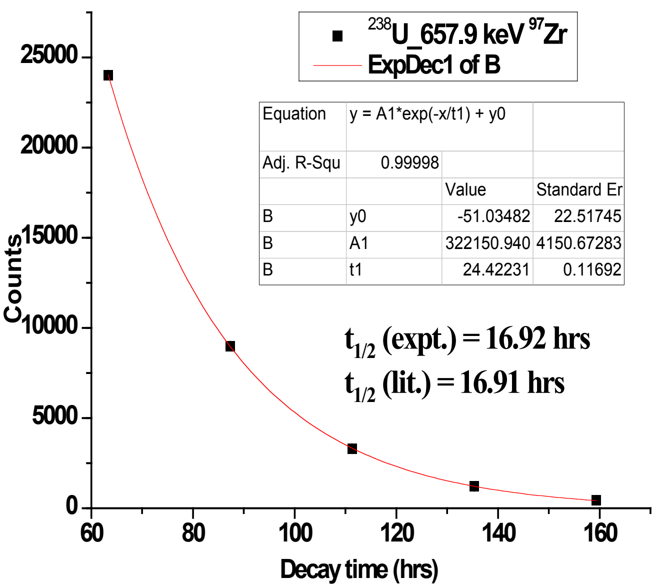
% error = 0.62 %



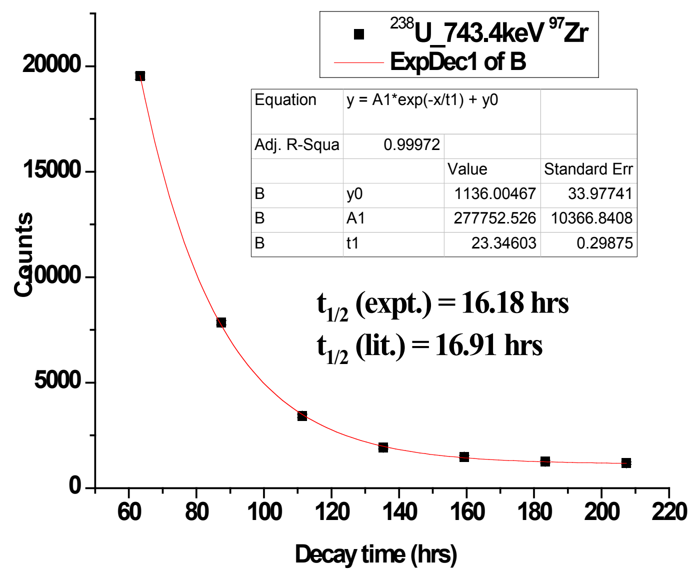
% error = 4.90 %



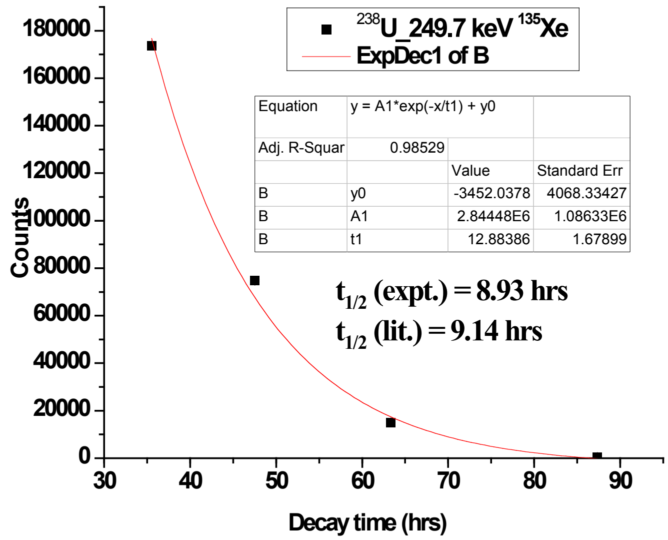
% error = 0.16 %



% error = 0.059 %



% error = 4.31 %


238U_249.7 keV 135Xe
ExpDec1 of B
Equation
y = A1*exp(-x/t1) + y0
Adj. R-Squar
0.98529
Value
Standard Err
B
y0
-3452.0378
4068.33427
B
A1
2.84448E6
1.08633E6
B
t1
12.88386
1.67899
t1/2 (expt.) = 8.93 hrs
t1/2 (lit.) = 9.14 hrs
Counts
Decay time (hrs)
180000
160000
140000
120000
100000
80000
60000
40000
20000
0
30
40
50
60
70
80
90

% error = 2.35 %