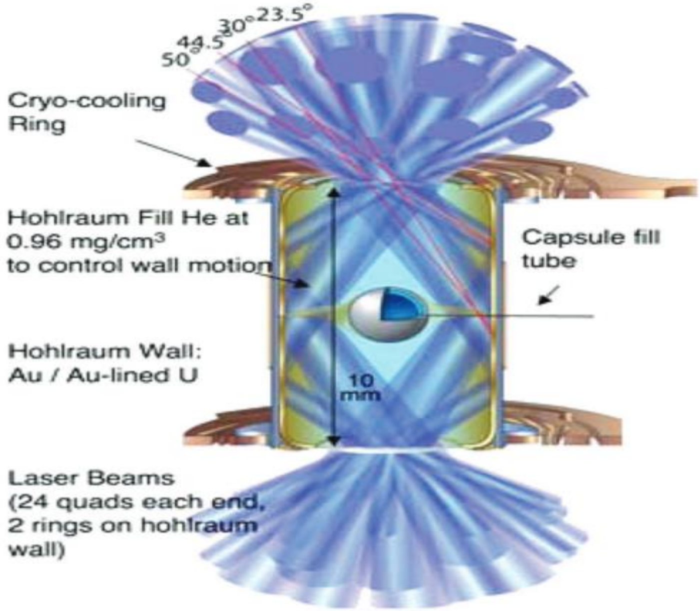
^{124}Xe(n,γ)^{125}Xe and ^{124}Xe(n,2n)^{123}Xe Measurements for National Ignition Facility

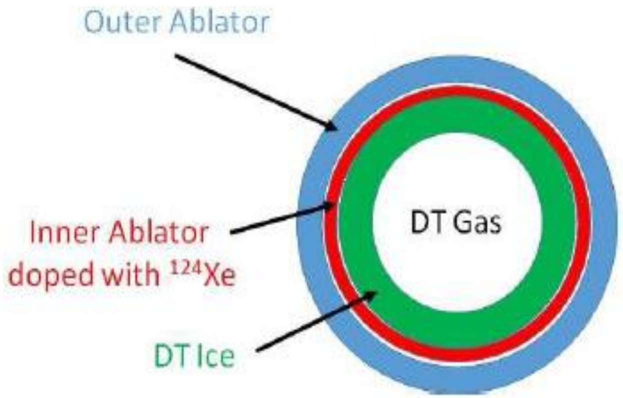
Megha Bhike
Werner Tornow
(Duke University and TUNL)

Nurin Ludin
(REU student, University of Denver)

Fusion Energy Research at National Ignition Facility (NIF)

- Efforts are underway at LLNL to accurately measure neutron energy distribution obtained in DT shots
- NIF irradiates a small D-T capsule inside a cryogenically cooled hohlraum with 192 laser beams
- Peak Power ~500 TW and up to 1.85 MJ of UV light deposited
- Radius of the capsule = 200-400 μm



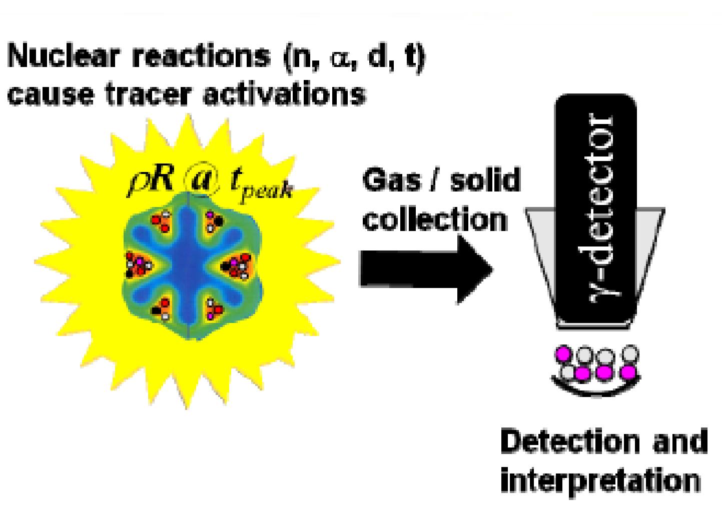


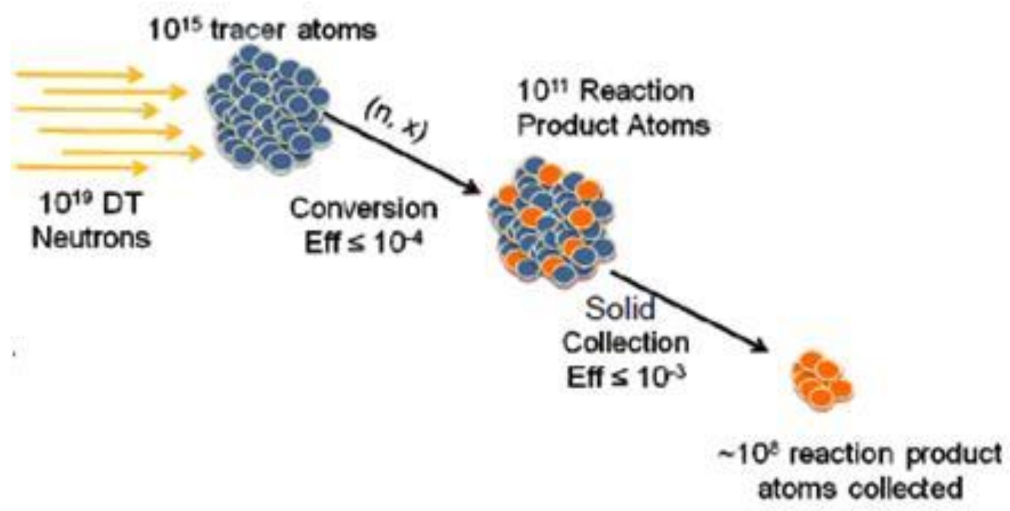
Schematic of D-T capsule

Based on simulations $\leq 10^{15}$ dopant atoms can be loaded without interfering the implosion performance (C. Cerjan, LLNL-TR-472595)

RADIOCHEMICAL APPARATUS FOR GASEOUS SAMPLES (RAGS)

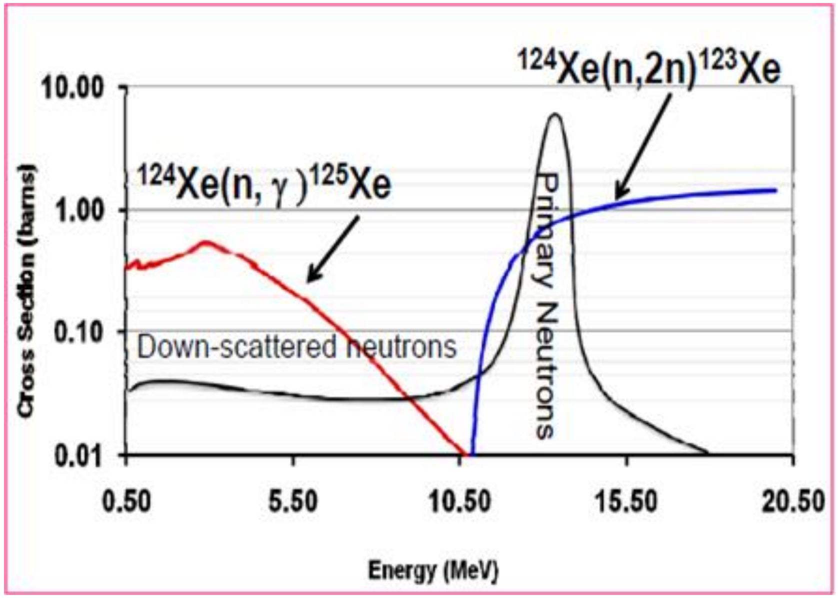
- RAGS designed for collection and analysis of gaseous samples produced during ignition following a NIF shot
- After collection, the activated products counted via gamma spectroscopy
- Noble gases are suitable dopants





^{124}Xe for Fuel Density (ρR) Diagnostics

- In the presence of DT neutrons ^{124}Xe undergoes both (n,γ) and (n,2n) reactions
- In case of neutron induced reactions, collection efficiency cancels out
- Isotopic ratio ^{125}Xe/^{123}Xe ratio related to areal density ρR of the fuel.
- to benchmark the capsule performance



^{124}Xe reactions

Probes primary down scattered low energy neutrons

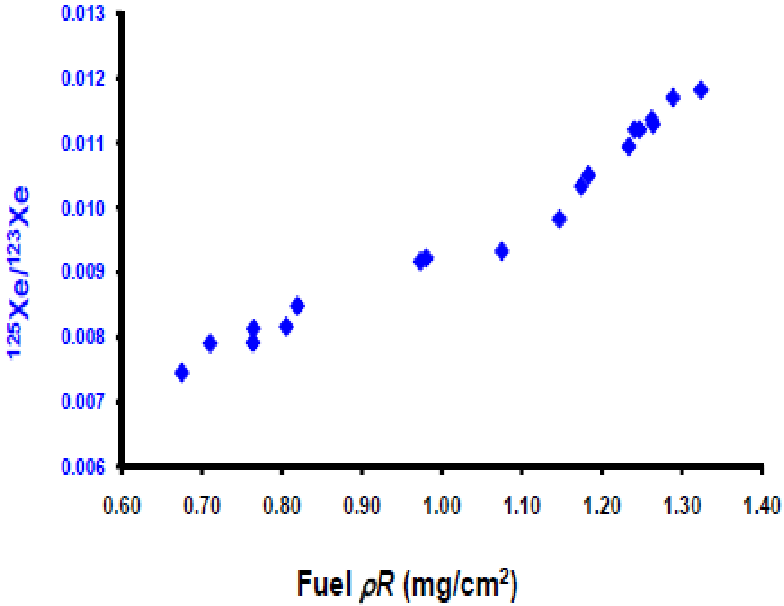
$$^{124}\mathrm{Xe} + n \rightarrow {}^{125}\mathrm{Xe} + \gamma$$

No threshold

Probes primary 14 MeV DT neutrons

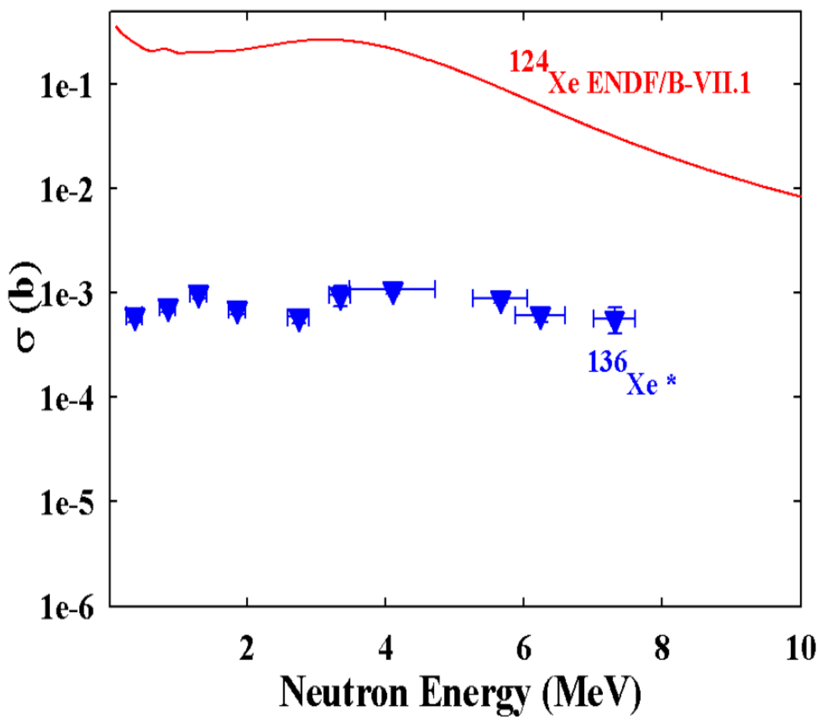
$$^{124}\mathrm{Xe} + n \rightarrow {}^{123}\mathrm{Xe} + 2n$$

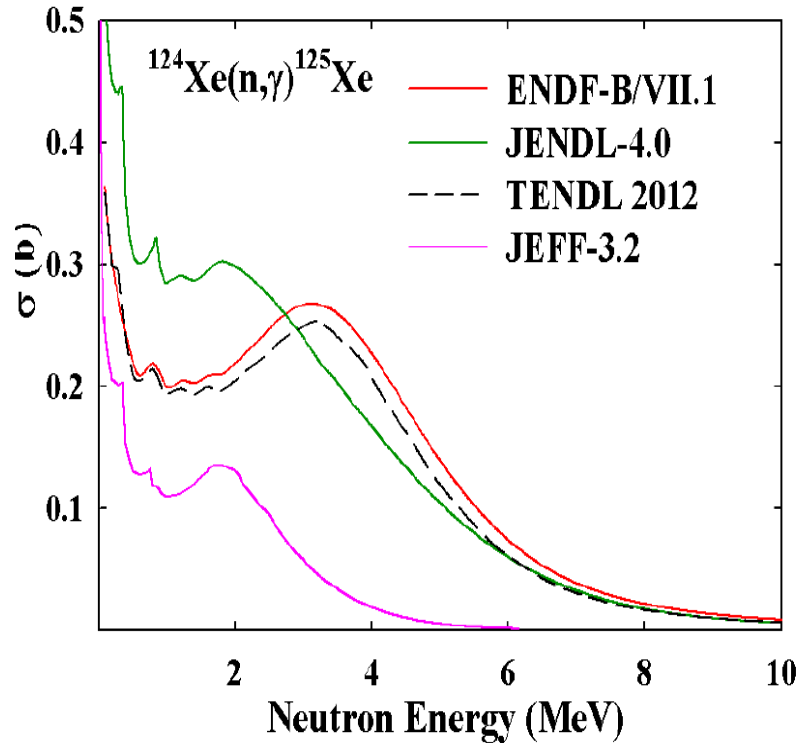
$$E_{th} = 10.569 \text{ MeV}$$



PRESENT STATUS OF ^{124}XE(N,γ) CROSS SECTION DATA

A NIF shot on a 2.1 mm diameter spherical glass shell filled with a 1:1 DT mixture and a small amount of ^{124}Xe was performed in February 2012 for commissioning of the RAGS



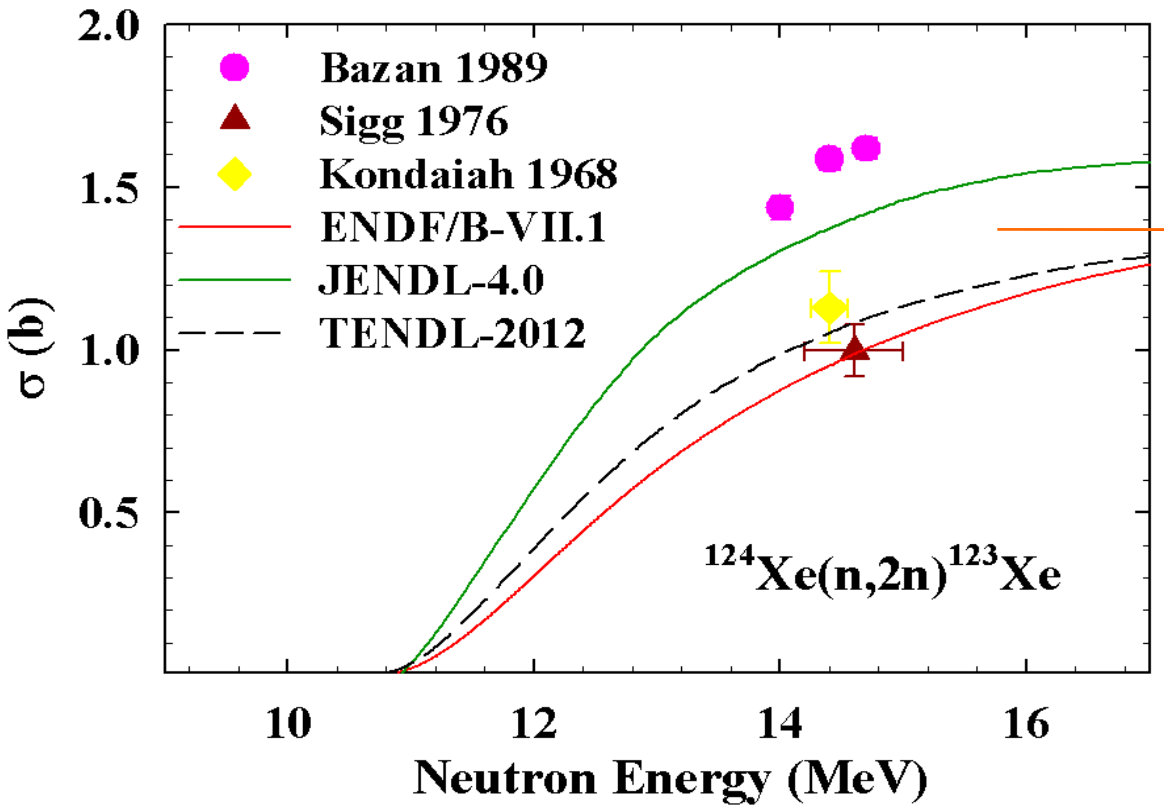


*M. Bhike et al., PRC 89, 031602(R) (2014)

Obtaining new data is an important step to interpret the activation measurements at NIF

PRESENT STATUS OF ^{124}XE(N,2N)^{123}XE CROSS SECTION DATA

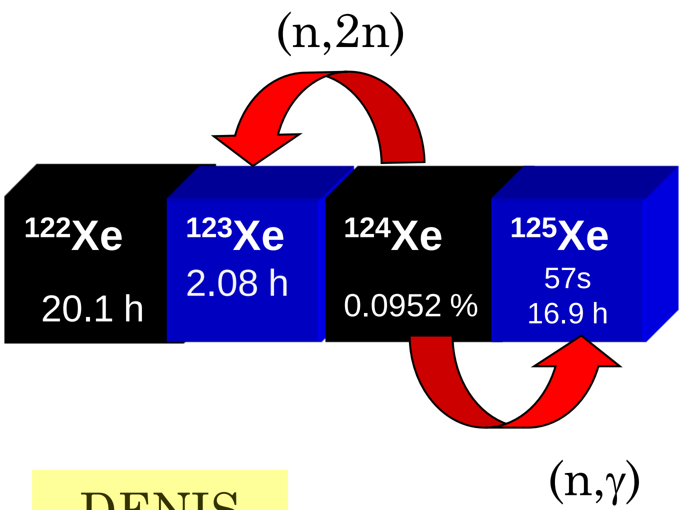
A NIF shot on a 2.1 mm diameter spherical glass shell filled with a 1:1 mixture and a small amount of ^{124}Xe was performed in February 2012 for commissioning of RAGS system



Large scatter

Obtaining new data is an important step to interpret the activation measurements at NIF

ACTIVATION MEASUREMENTS @ TUNL

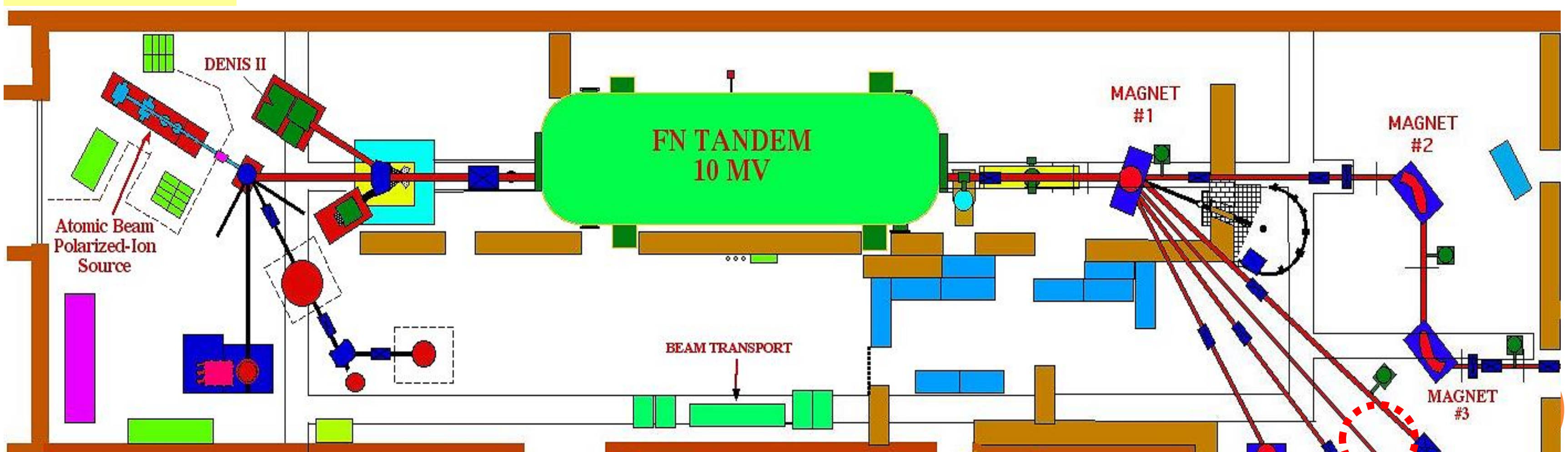


- 3 neutron sources :

Neutron source	Q-value (MeV)	Energy range
^{3}H(p,n)^{3}He - PT	-0.764	0.37 -3.8 (n,γ)
^{2}H(d,n)^{3}He - DD	3.269	4.5-7.3 (n,γ) 11.3-14.5 (n,2n)
^{3}H(d,n)^{4}He - DT	17.589	14.8 (n,2n)

- Ip/d = 1.5 – 3.5 μA
- $\phi_n = 10^7$ n/cm^2/s

DENIS



10 MV accelerator at TUNL

TOF

^{124}Xe TARGET

- Xenon gas target

  contained in a stainless steel sphere of inner diameter 20 mm and wall thickness of 0.6 mm

  enriched to 99.9% in ^{124}Xe

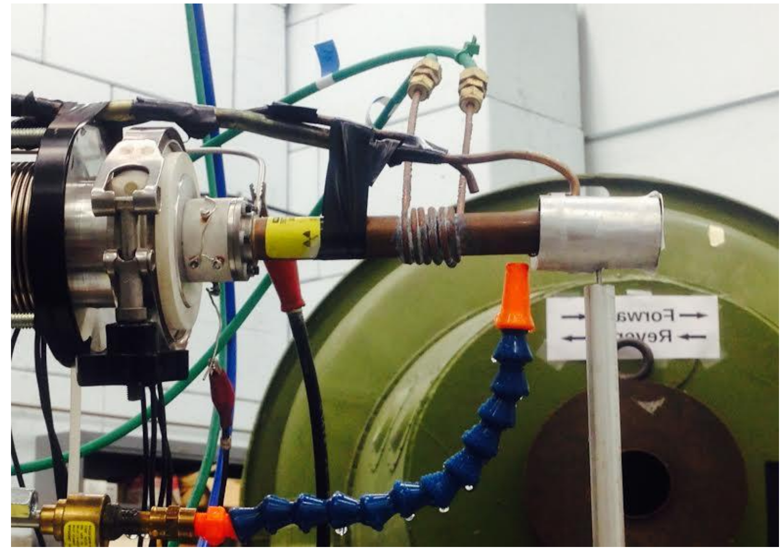
  mass = 2.697 g

  pressurized to 120 atm
- Can be recycled
- In and Au monitor foils for flux measurement

  diameter 20 mm and thickness 0.1 mm attached upstream and downstream faces of the sphere for neutron fluence determination
- Identical empty sphere used to check contamination in the energy region of interest

EXPERIMENTAL SETUP FOR (N,γ) MEASUREMENTS

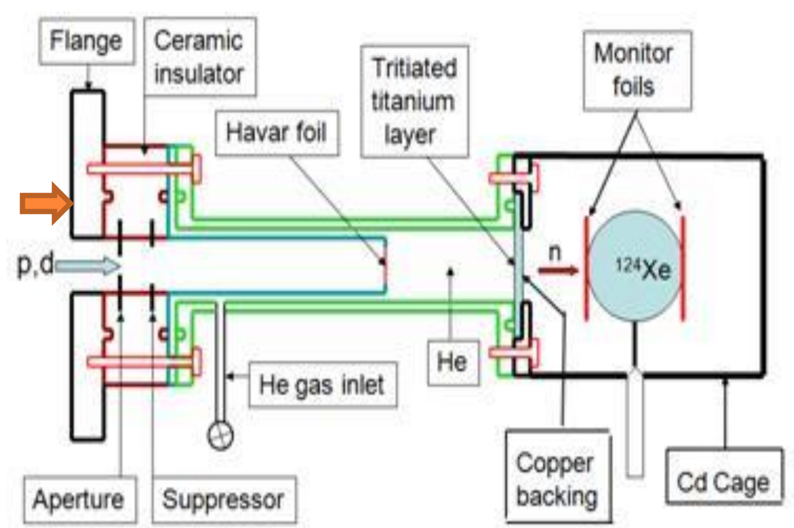
Neutron source	E_n (MeV)	Monitor Reaction
$^{3}H(p,n)^{3}He$	0.37	$^{115}In(n,\gamma)^{116m1}In$
	0.86,1.86 2.73,3.65	$^{115}In(n,n')^{115m}In$
$^{2}H(d,n)^{3}He$	4.48, 5.31 6.31,7.25	$^{115}In(n,n')^{115m}In$



- $^{3}H(p,n)^{3}He$-PT
  2.1 Ci tritium loaded into a 2.2 mg/cm^2 of Ti of 16 mm diameter evaporated on a 0.4 mm thick Cu backing separated from by a 6.5 μm havar foil from accelerator vacuum

- $^{2}H(d,n)^{3}He$-DD
  3 cm long gas cell pressurized to 3 atm of deuterium gas separated by a 6.5 μm havar foil from accelerator vacuum

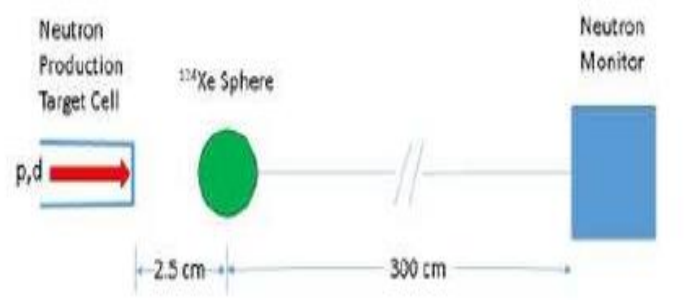
- Distance between target and sphere = 10 mm
- Irradiation time = 2 hrs



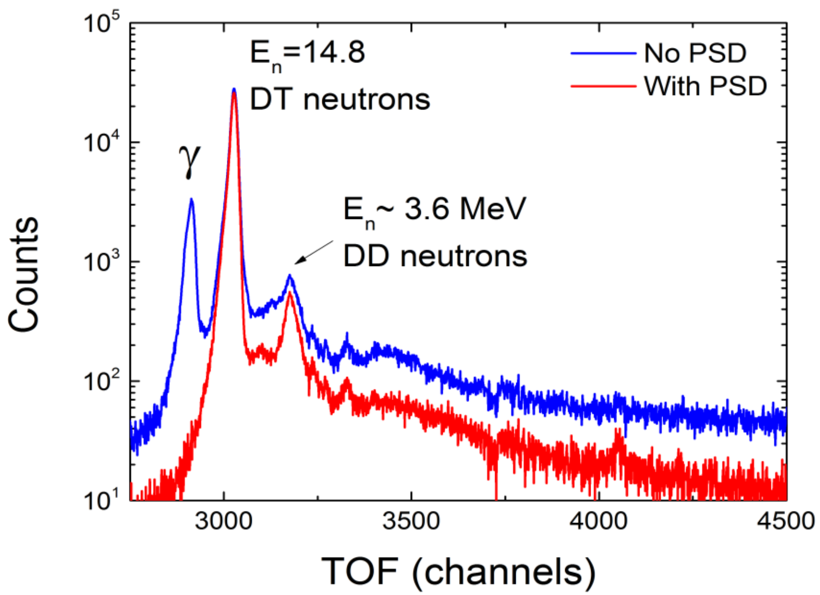
Tritiated target schematic

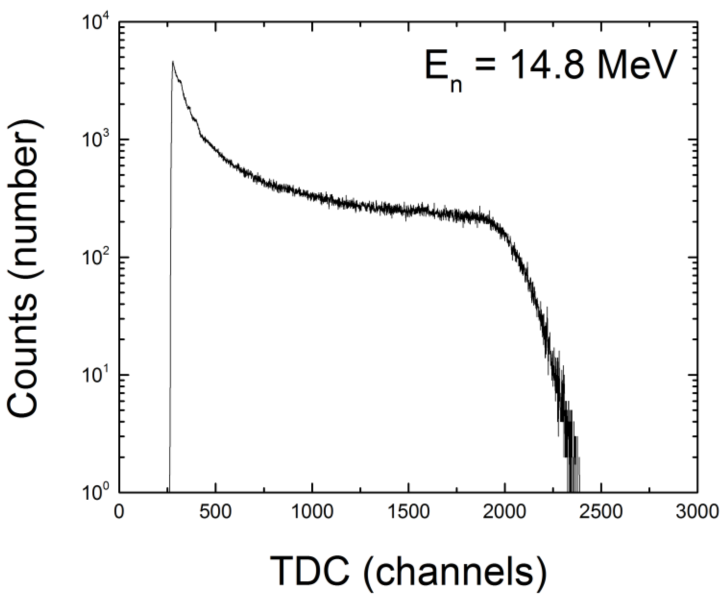
TIME OF FLIGHT AND ENERGY SPECTRA

- Liquid scintillator-based neutron detector
  (Bicron 501A, 1.5″x1.5″) positioned at 3 m from neutron production target
- Incident beam pulsed at 2.5 MHz with overall time resolution 2.5 ns
- Monitoring of neutron flux
- Determination of mean neutron energy and its spread



Schematic of experimental setup

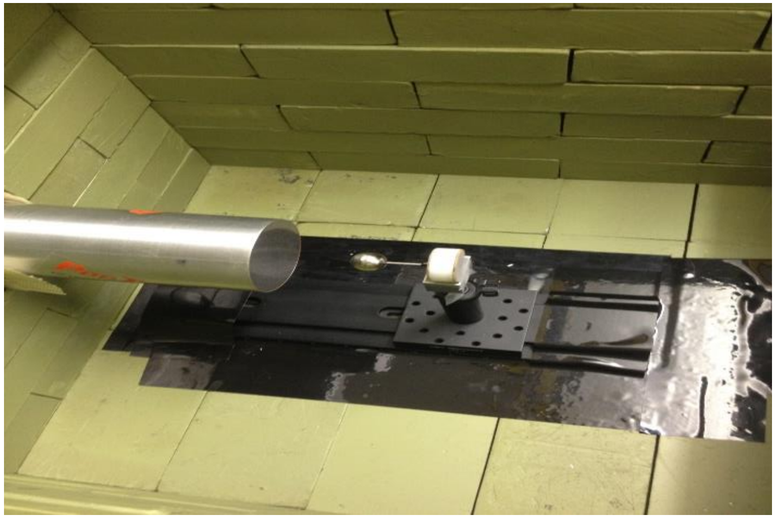


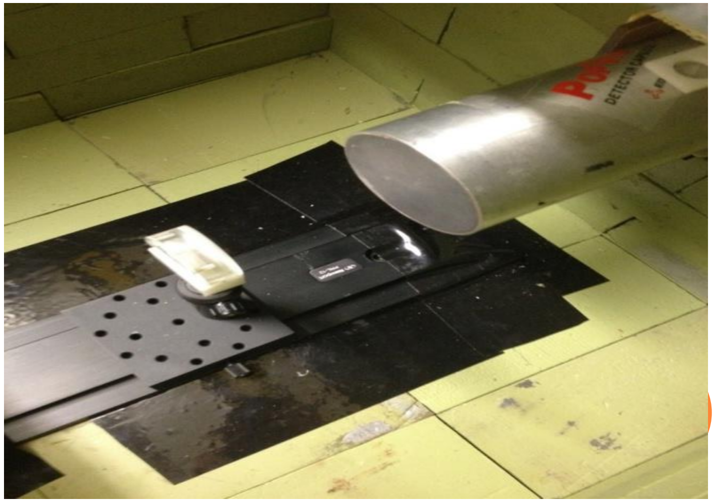


TOF and Energy spectra for En = 14.8 MeV

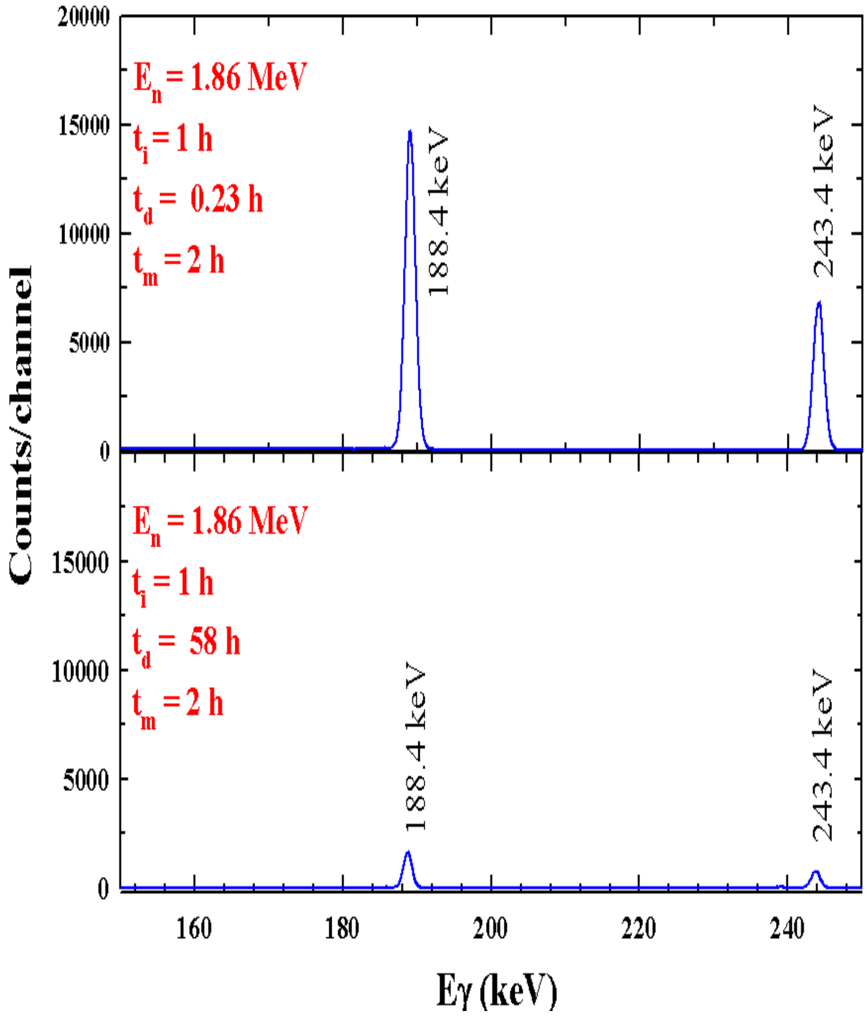
OFF-LINE γ-RAY COUNTING WITH HPGE DETECTORS

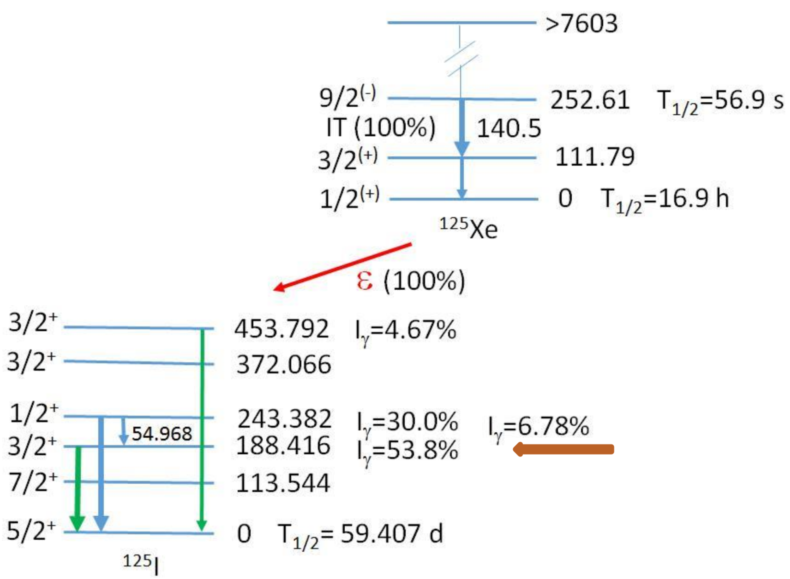
TUNL's low background counting facility





γ RAY SIGNATURE FROM ^{124}XE(N, γ)^{125}XE REACTION



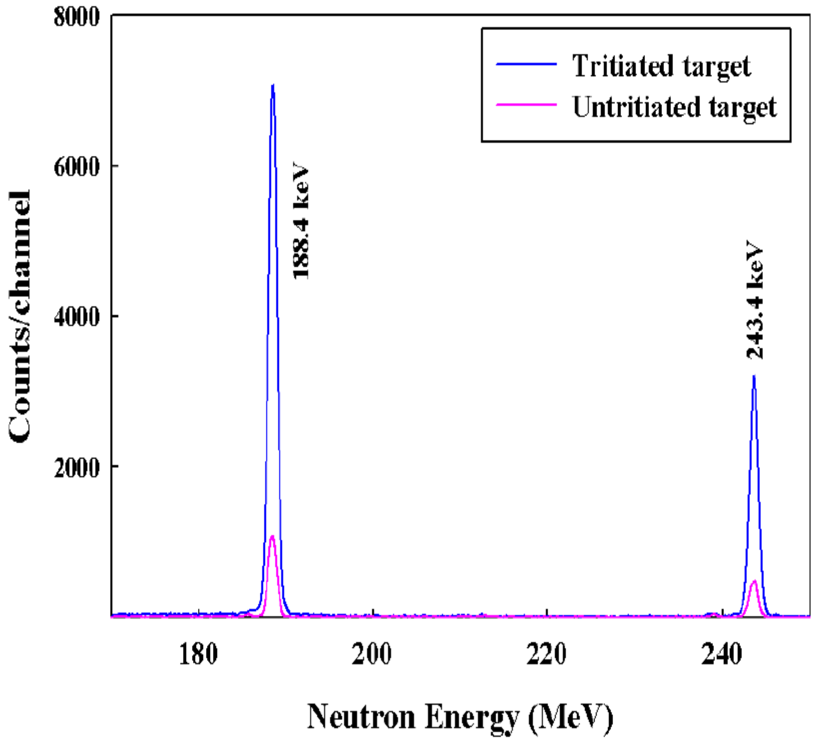


E_γ = 188.4 keV; I_γ = 53.8 %; $T_{1/2}$ = 16.9 h

- Measured 9 energies between 0.3 - 14.8 MeV.

AUXILIARY MEASUREMENTS - $^{3}H(p,n)^{3}He$ REACTION

- For Ep > 2.8 MeV i.e. E_n > 2 MeV
  primary neutrons from $^{3}H(p,n)^{3}He$ accompanied by low-energy neutrons from (p,n) reactions on tritium target backing (Cu and Ti)
- Auxiliary measurements performed with an untritiated but identical target
  Two individual measurements are normalized to the accumulated proton charge (BCI)



Correction factors for background neutrons for $^{3}H(p, n)^{3}He$ reaction

E_n (MeV)	C_{In}(%)	C_{Xe}(%)
2.73	13.55	16.36
3.6	18.73	27.94

AUXILIARY MEASUREMENTS – $^{2}H(d,n)^{3}He$ REACTION

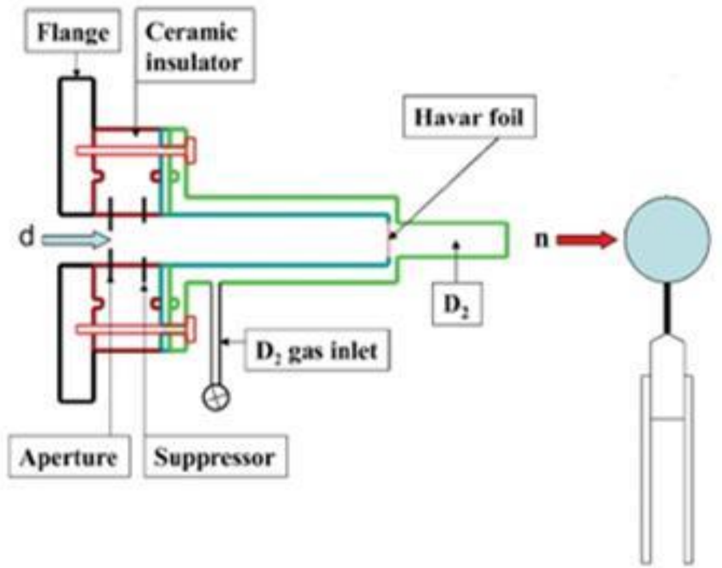
$Q = (^{2}H + d - {}^{3}He - n) = +3.3$ MeV

- The deuteron break up on beam line components has Q = -2.2 MeV
  - Implies the break up neutrons come at ~ 5.5 MeV less than the neutron energy

- Any Energy Higher than 5.5 MeV therefore HAS breakup neutrons

- Auxiliary measurements performed with the deuterium gas pumped out.

- Two individual measurements are normalized to the accumulated deuteron beam charge (BCI)



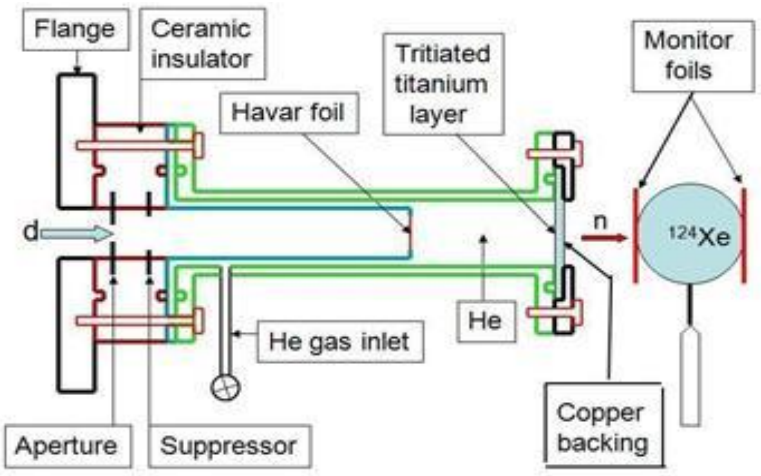
Correction factors for background neutrons from $^{2}H(d, n)^{3}He$ reaction

E_n (MeV)	C_{In}(%)	C_{Xe}(%)
5.31	1.58	0.9
6.33	2.02	10.02
7.25	5.99	37.23

With the experimental facility at TUNL, (n,γ) measurements between 8 and 14 MeV are not possible

Experimental Setup for (n,2n) Measurements

Source Reaction	Neutron Energy	Monitor Reaction
$^{2}H(d,n)^{3}He$	11.36, 11.86 12.36 12.85 13.35 13.85 14.35	$^{197}Au(n,2n)^{196}A$
$^{3}H(d,n)^{4}He$	14.80	

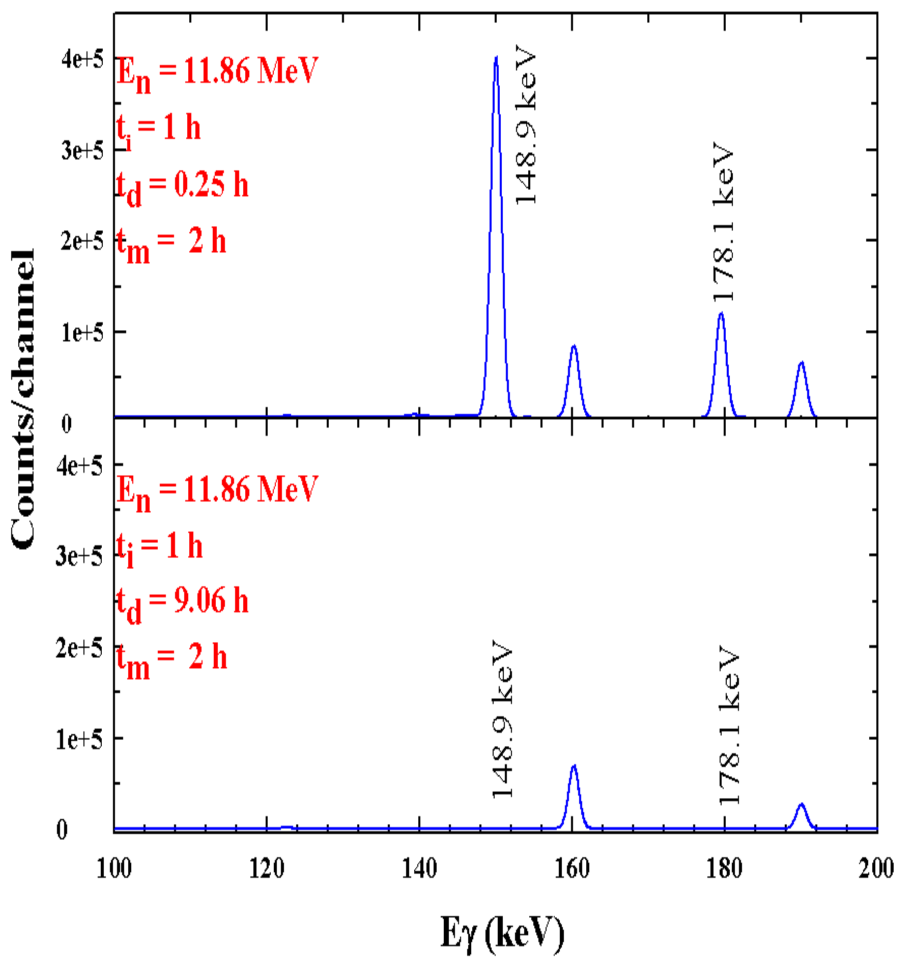


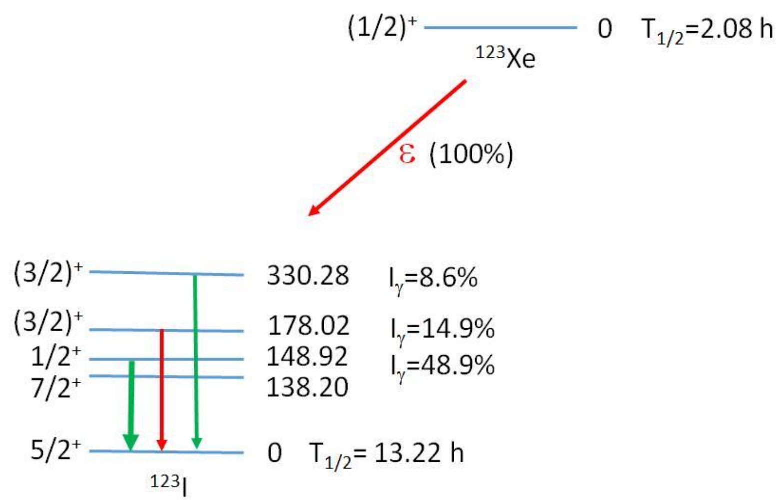
Schematic for (n,2n) measurements

- $^{2}H(d,n)^{3}He$ -DD
  3 cm long gas cell pressurized to 3 atm of deuterium gas separated from accelerator vacuum by a 6.5 μm havar foil

- $^{3}H(d,n)^{4}He$ -DT
  2.1 Ci loaded into a 2.2 mg/cm^2 of titanium of 16 mm diameter evaporated on a 0.4 mm thick copper backing separated from vacuum by 6.5 μm havar foil

γ RAY SIGNATURE FROM ^{124}XE(N,2N)^{123}XE REACTION





E_γ = 148.9 keV; I_γ = 48.9 %;
$T_{1/2}$ = 2.08 h

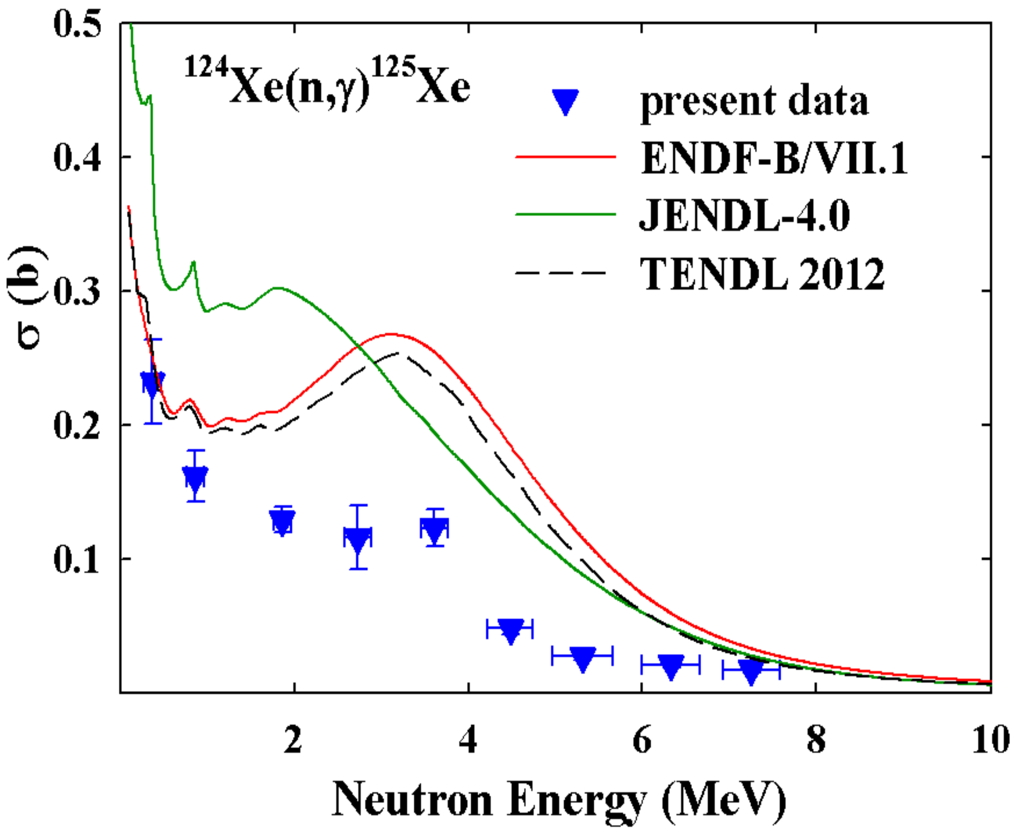
- Measured 9 energies between 11 and 14.8 MeV.

NEUTRON FLUX AND CROSS SECTION CALCULATION

$$\sigma = \frac{A\lambda}{N\epsilon\phi I_{\gamma}(1-e^{-\lambda t_{irr}})e^{-\lambda t_d}(1-e^{-\lambda t_c})}$$

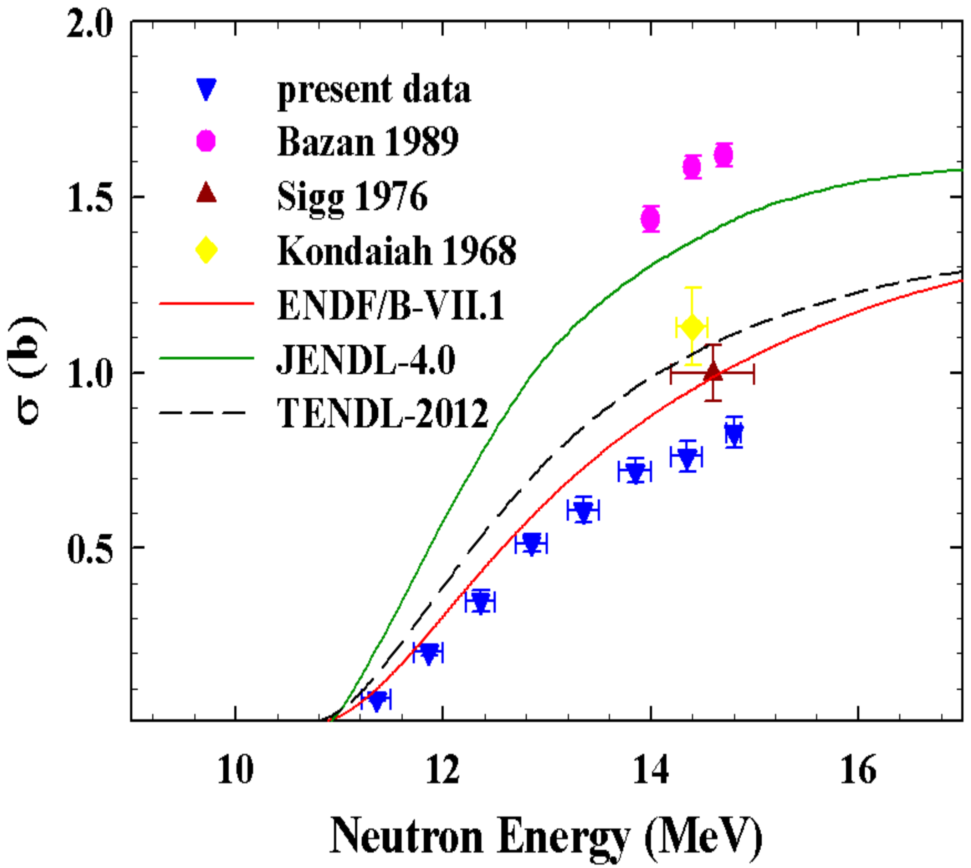
A = total yield in the photo peak
γ = decay constant
N = no of target nuclei
ε = Efficiency
ϕ = Neutron flux
I_γ = Emission probability
tirr = Irradiation time
t_d = delay time
tc = counting time

Preliminary results from $^{124}Xe(n,\gamma)^{125}Xe$ measurements at TUNL



- None of the evaluations are in agreement with the experimental data
- order of magnitude is well predicted

Preliminary results from $^{124}Xe(n,2n)^{123}Xe$ measurements



- ❑ TUNL data follows the predicted energy dependence but slightly lower in magnitude than the ENDF/B-VII.1 evaluation.
- ❑ Our data at 14 MeV slightly below the data of Sigg et al and Kondaiah et al.

SUMMARY

- $^{124}Xe(n,\gamma)^{125}Xe$ cross section has been measured between 0.3 and 7.25 MeV and $^{124}Xe(n,2n)^{123}Xe$ cross section data has been obtained from threshold to 14.8 MeV

- Present work provides for the first time an accurate basis for interpreting measurements of the $^{125}Xe/^{123}Xe$ intensity ratio performed at NIF in laser shots on ^{124}Xe loaded DT capsules.

- The extracted information on ρR of the inertial confinement of fusion plasma will help to make substantial progress towards break-even goal at NIF

Reaction rate at TUNL and NIF for $^{124}Xe(n,\gamma)^{125}Xe$

Parameter	TUNL	NIF
Activation time	1.8×10^4 s	$\sim 10^{-9}$ s
Decay time	1 min	1 min
Measurement time	1 min - hours	min - hours
Sample mass	2.7 g (1.3×10^{22} atoms)	~1μg (10^{15} atoms)
Neutron flux	7×10^6 n/cm^2/s	10^{14} n/ns
Neutron fluence	1.3×10^{11} n/cm^2	1×10^{18} n/cm^2
Fluence x sample mass	1.7×10^{33} n/cm^2 g	1×10^{33} n/cm^{2}g