Inertial Confinement Fusion as a Tool to Study Fundamental Nuclear Science

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Houghton College, 4/19/21

Introduction to Nuclear Science: Cross-Sections

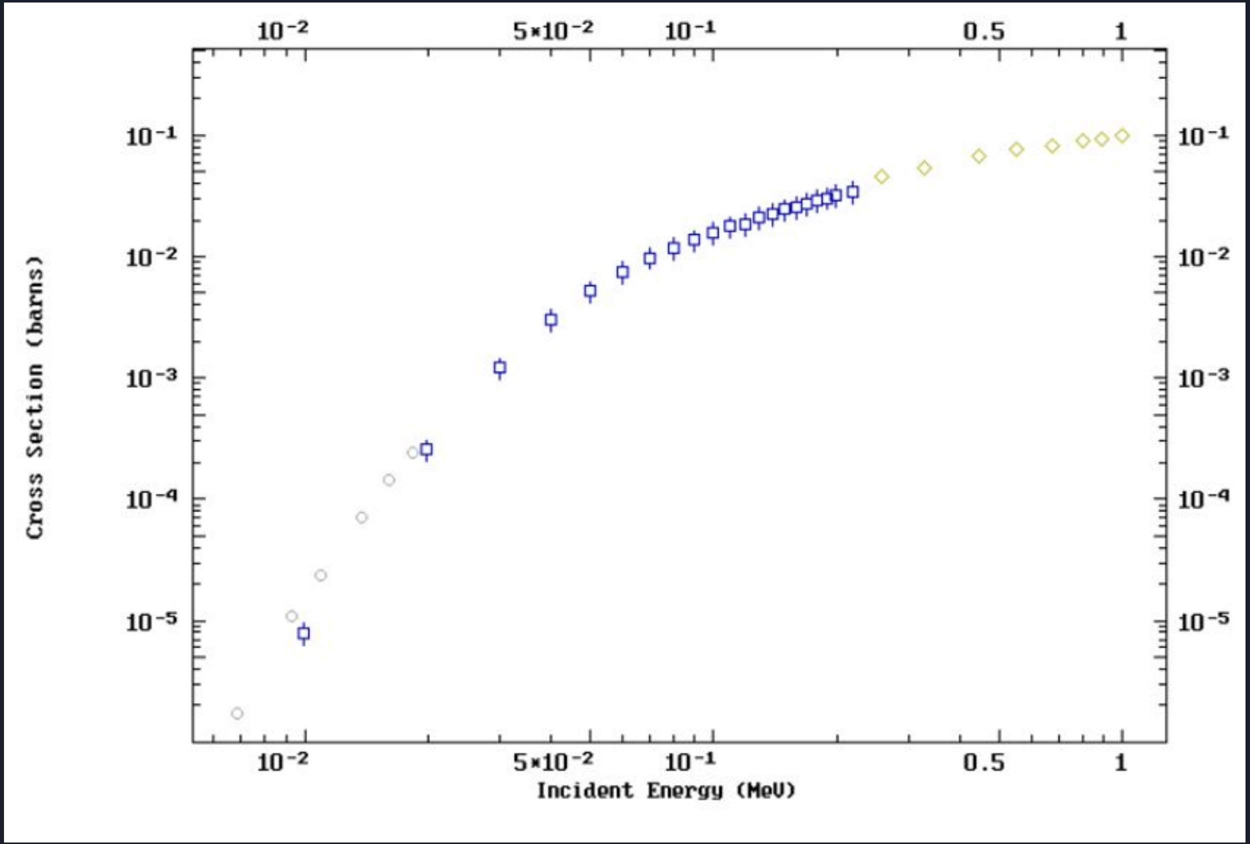
- Proportional to the probability of a given interaction occurring
  - Collisions and scattering
  - Nuclear interactions
  - Chemical Interactions

- Used as input data for models in
  - Astrophysics
  - Nuclear Energy
  - Early Universe/Big-Bang Physics

Introduction to Nuclear Science: Cross-Sections

$^{2}H(d,n)^{3}He$

Typically, light-ion fusion cross-sections decrease rapidly as energy decreases.

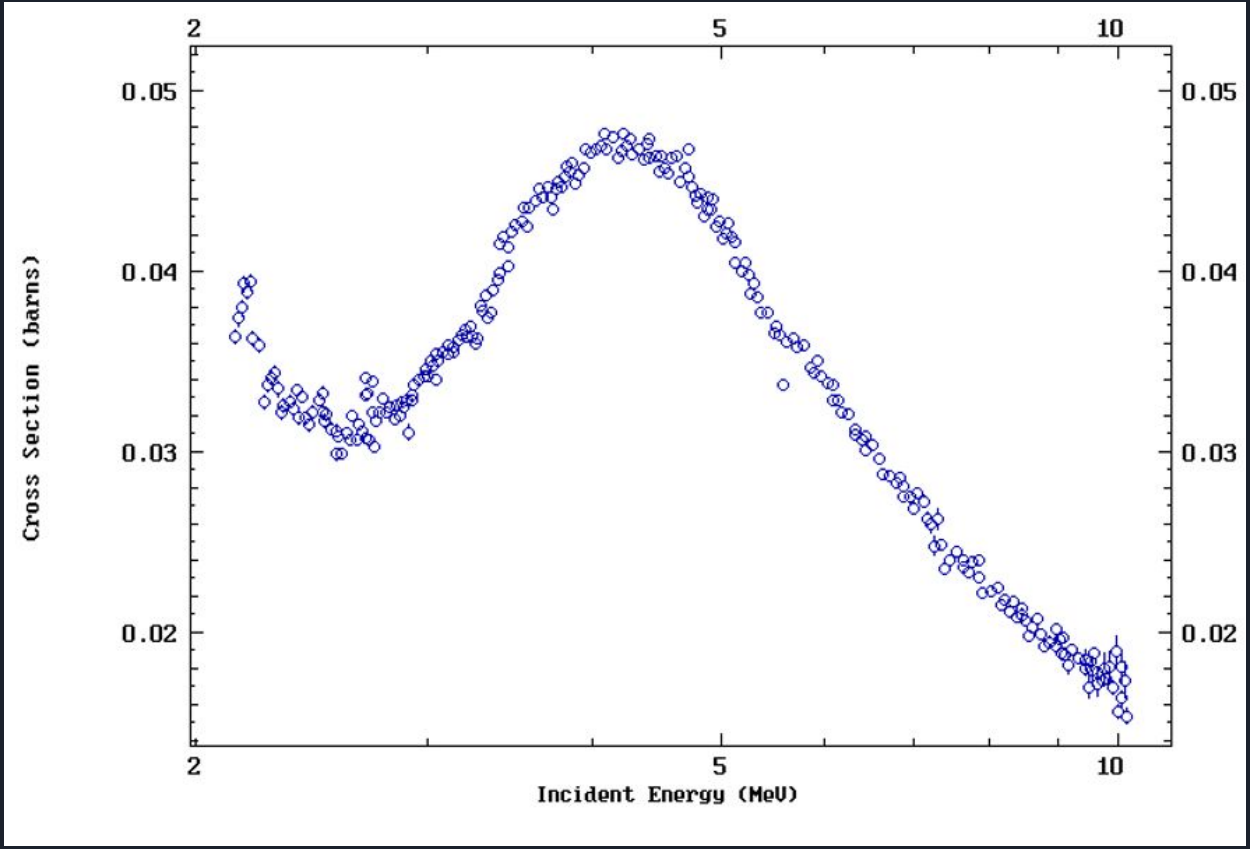


Plot constructed using www.nndc.bnl.gov and data from Ref. [1,2,3].

Introduction to Nuclear Science: Cross-Sections

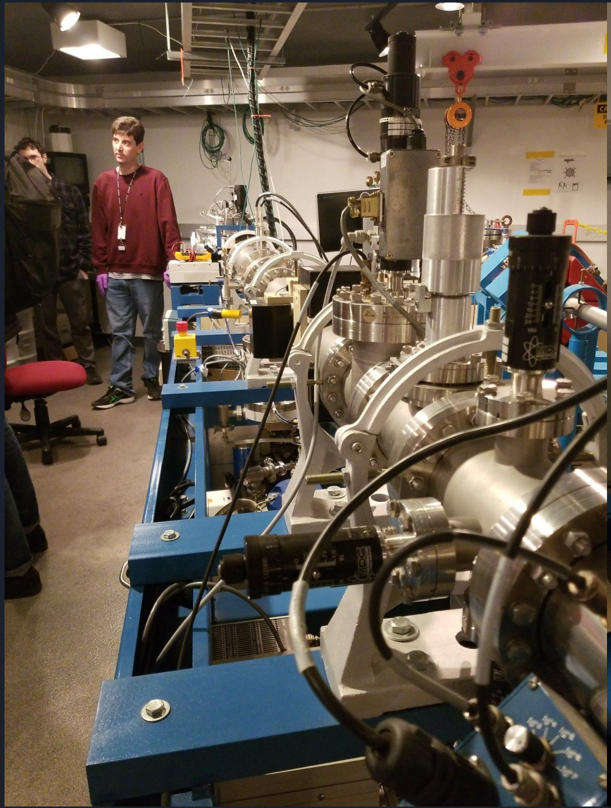
$^{6}Li(t,p)^{8}Li$

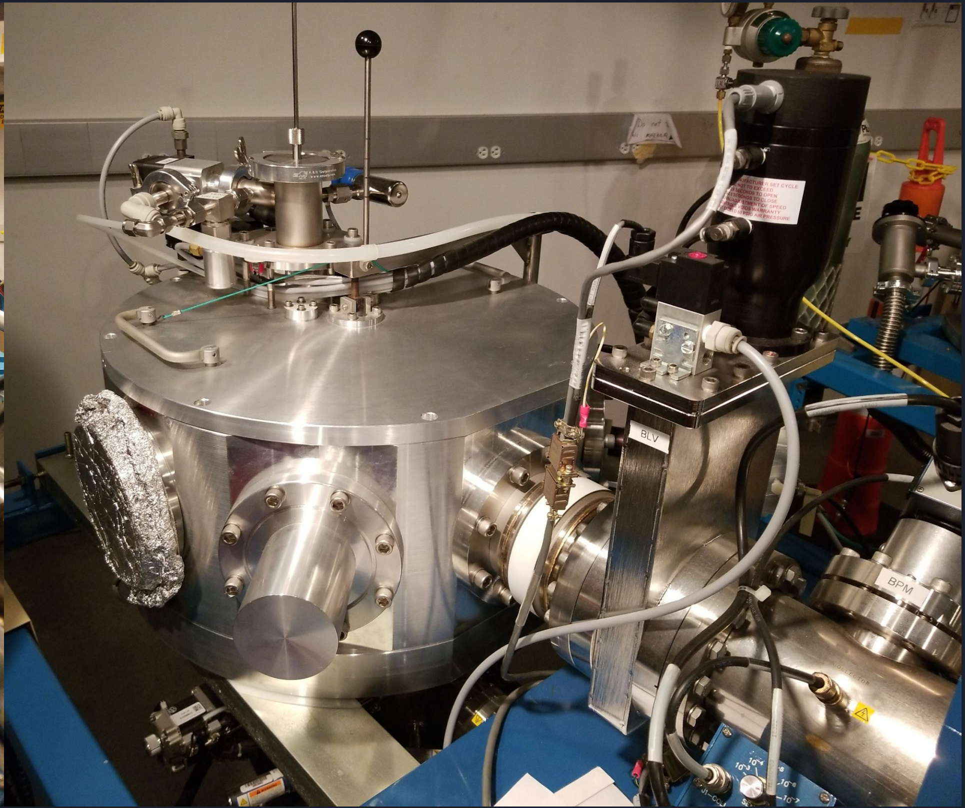
Where are the cross sections at lower energies?



Plot constructed using www.nndc.bnl.gov and data from Ref. [4].

Introduction to Nuclear Science: Accelerators





Assuming 1 μA beam current, measuring 1,000,000 $^{7}Li(t,\alpha)^{6}He$ reactions would take almost 2,800 years

Introduction to Nuclear Science: Thermonuclear Reactions

Controlled

Figure taken from Ref. [5].

Uncontrolle
d

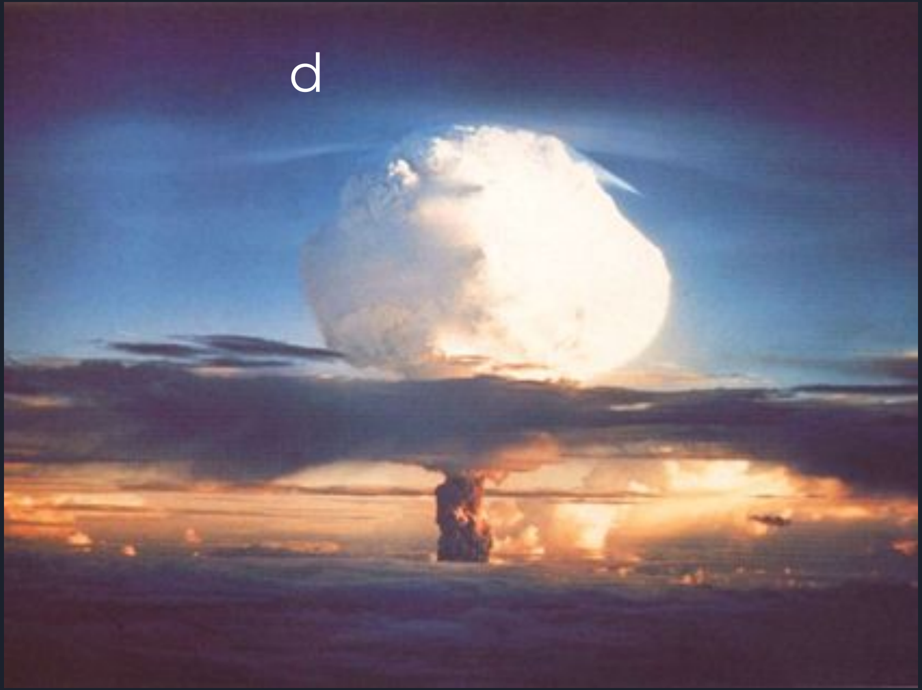
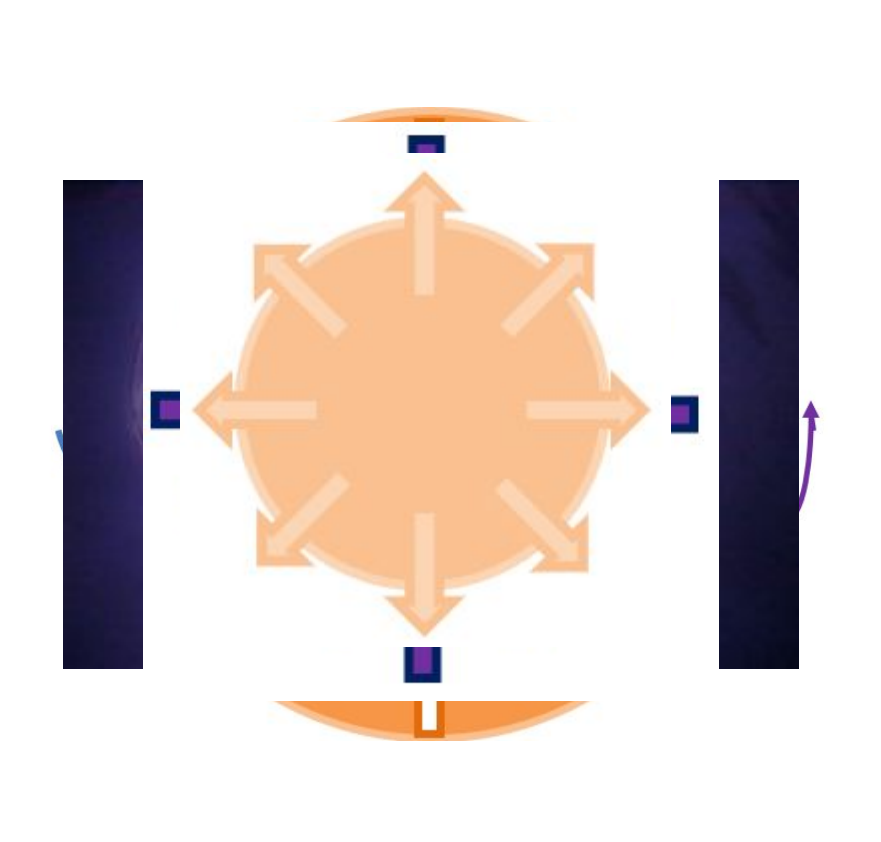


Figure taken from nuclearweaponarchive.org.

Introduction to Nuclear Science: Controlled Thermonuclear Reactions



- Types of controlled thermonuclear fusion
  - Gravitational Confinement Fusion
  - Magnetic Confinement Fusion (MCF)
  - Inertial Electrostatic Confinement Fusion (IEC)
  - Inertial Confinement Fusion (ICF)

Introduction to Nuclear Science: ICF

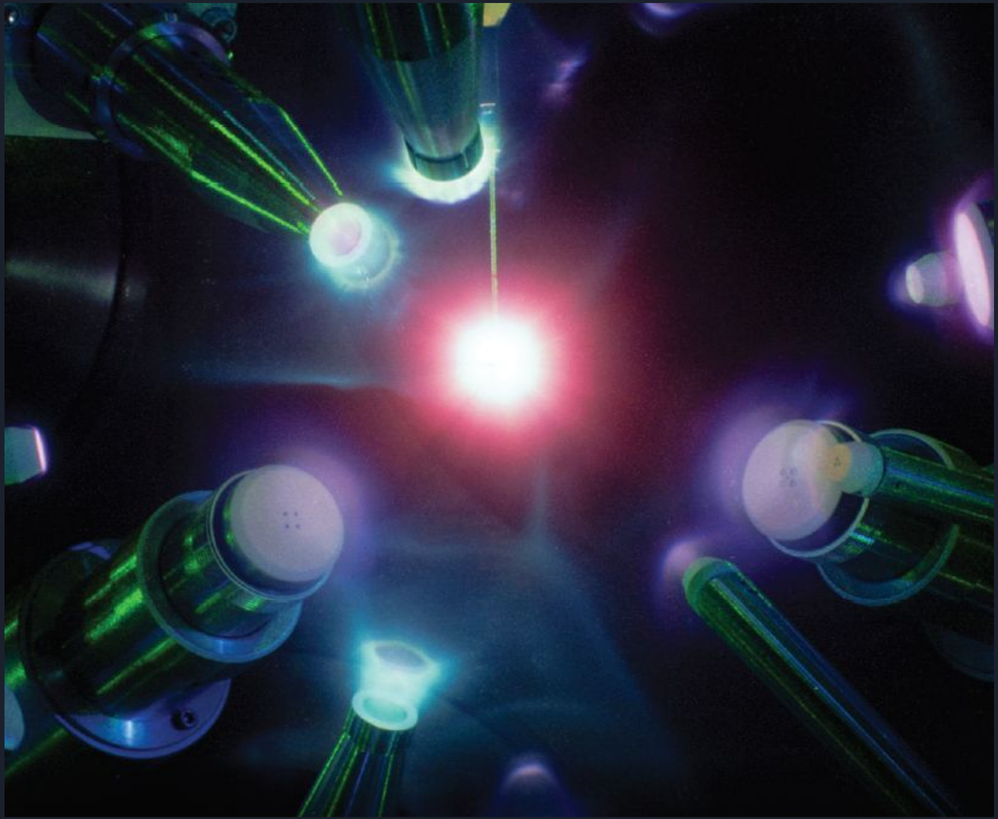
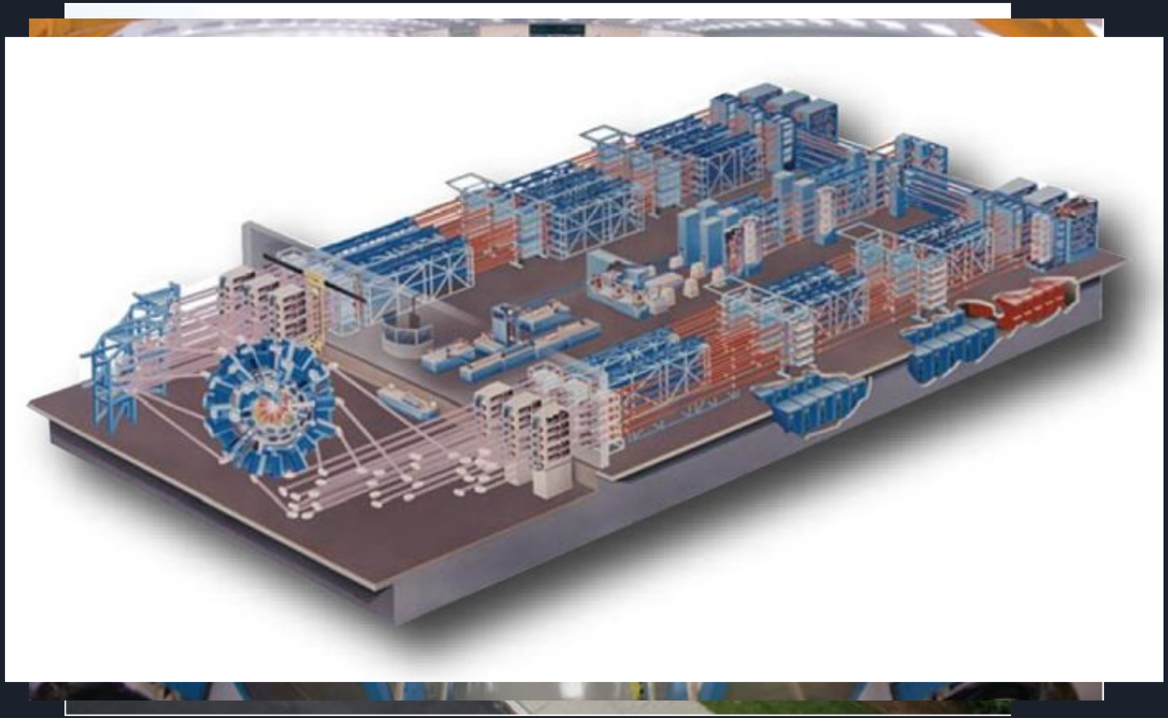


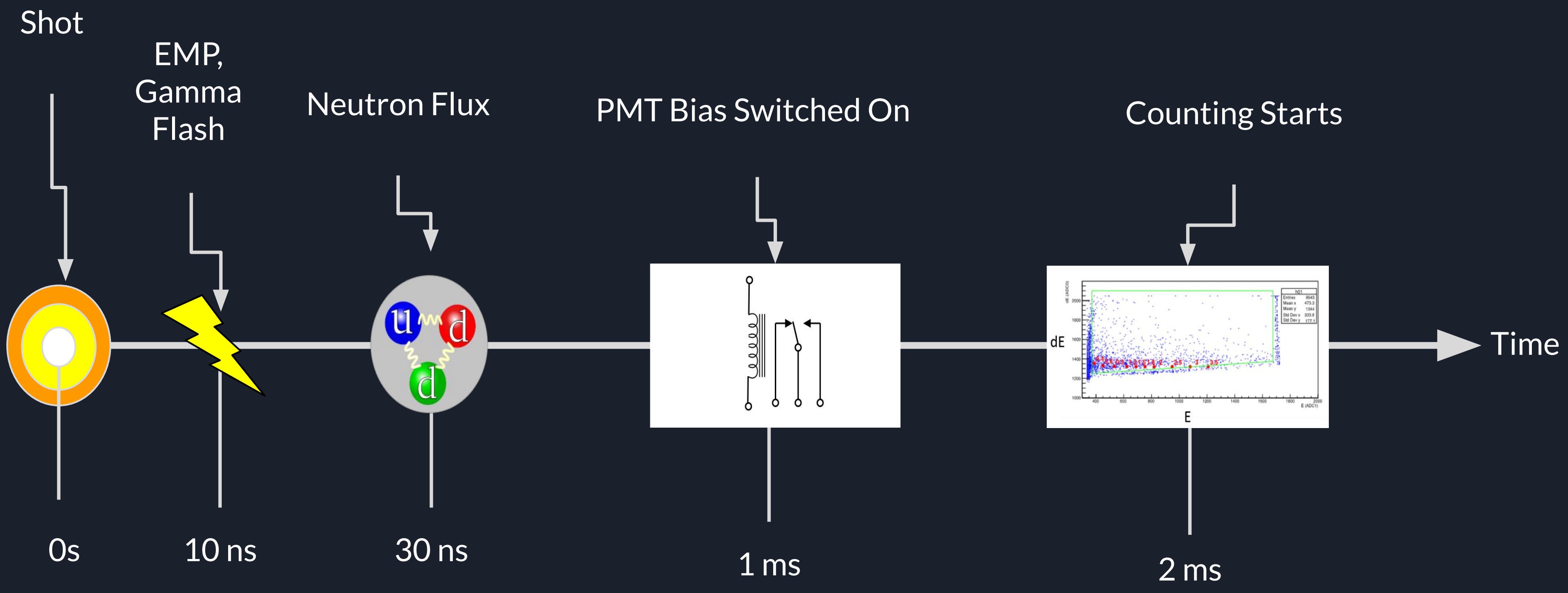
Figure taken from Ref. [6].

Introduction to Nuclear Science: ICF

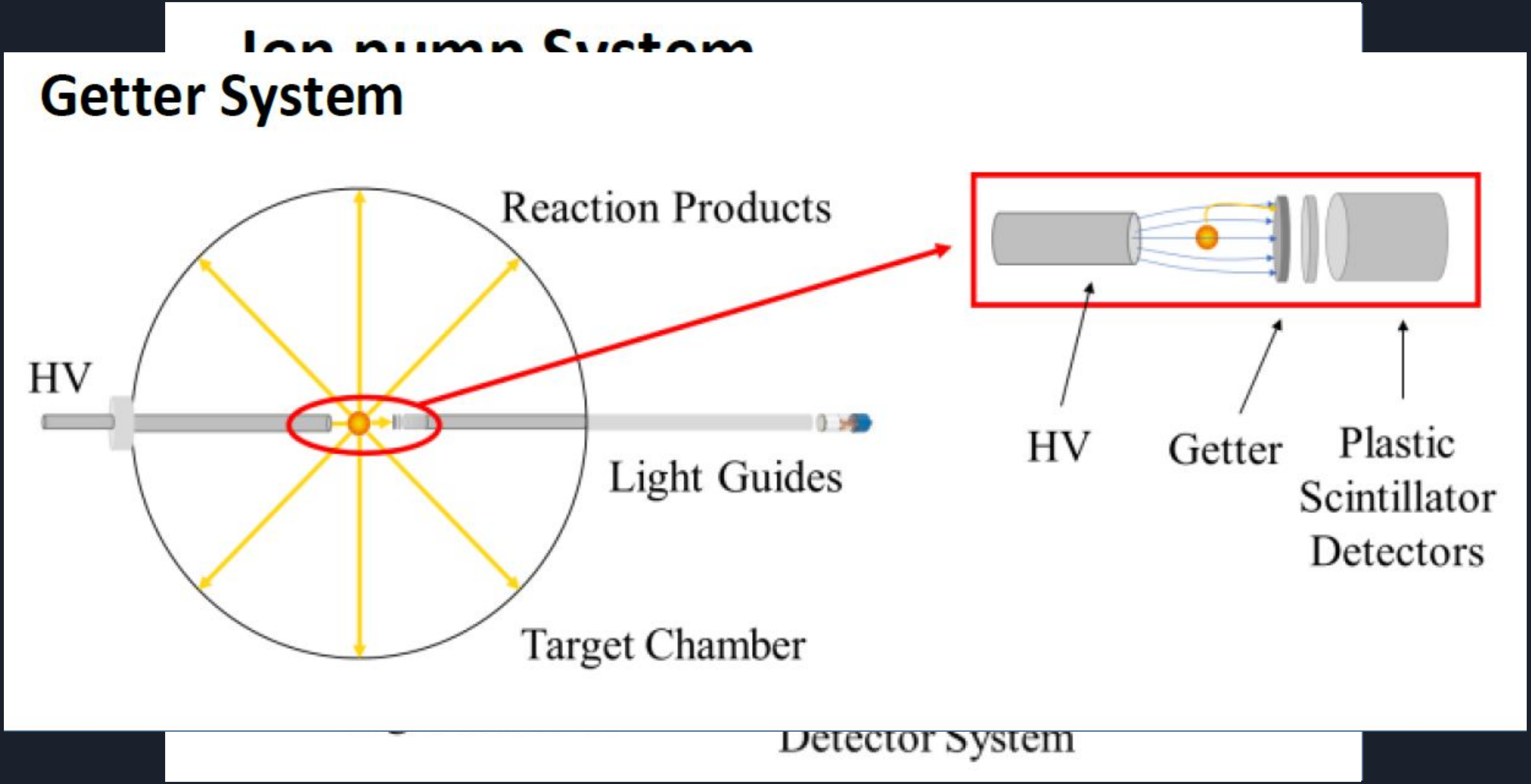
The targets are 0.8 mm in diameter, containing a mixture of deuterium, tritium, and possibly multiple dopants.



The Proposed Methodology: Experiment Timeline



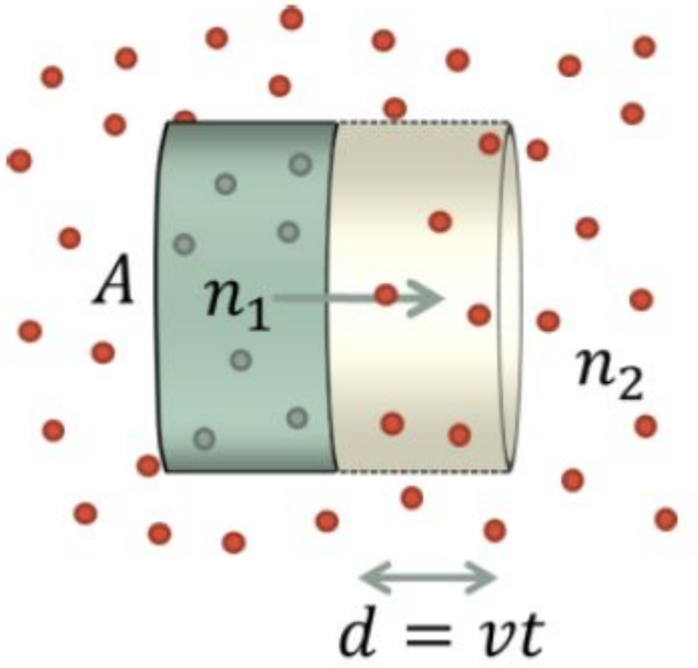
The Proposed Methodology: Collection Methods



The Proposed Methodology: Possible Isotopes

			Shot 39794 (50-50 DT, 11.8 keV)	Shot 77951 (1.5-98.5 DT, 18.3 keV)	
Reaction	Product Half-life	Reactant Abund.	Predicted Yield	Predicted Yield	Notes
$^{3}H(t,g)^{6}He$	807 ms	^{3}H fill	Branching ratio of ~10^{-7} to $^{3}H(t,2n)^{4}He$ gives	8 x10^{4}	To ^{6}He g.s. only, excited states decay by 2n
$^{6}Li(t,p)^{8}Li$	840 ms	7.6%	2-10´10^{5}	4-16 x10^{5}	TALYS + Abramovich et. al.
$^{7}Li(t,a)^{6}He$	807 ms	92.4%	1-3´10^{5}	1-4 x10^{5}	TALYS + Abramovich et. al. To ^{6}He g.s. only, excited states decay by 2n
$^{9}Be(t,a)^{8}Li$	840 ms	100%	2.3´10^{4}	8 x10^{4}	TALYS
$^{9}Be(t,g)^{12}B$	20.2 ms	100%	2.8	3.0	TALYS
$^{10}B(t,p)^{12}B$	20.2 ms	19.9%	78.3	923	TALYS
$^{11}B(d,p)^{12}B$	20.2 ms	80.1%	372	1735	TALYS
$^{15}N(d,p)^{16}N$	7.1 s	0.4%	0.10	2.0	TALYS

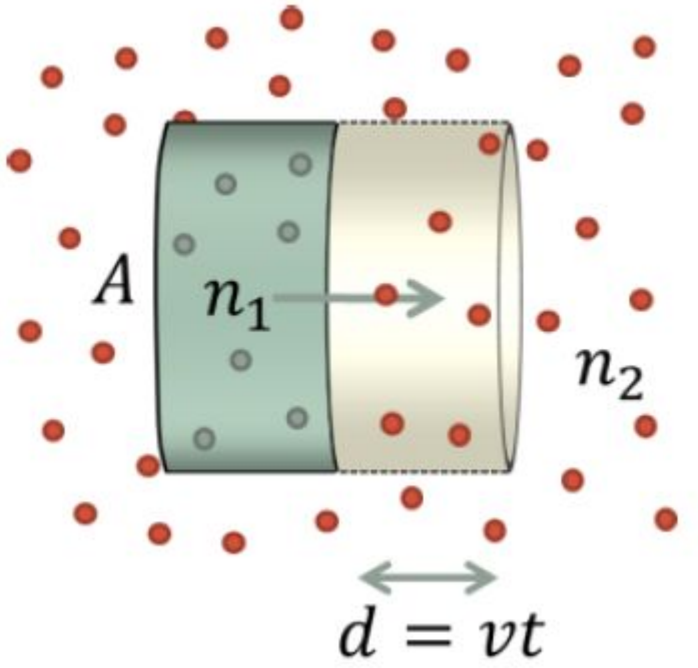
Theory: Nuclear Cross-Sections and Reaction Rate



$$N = \sigma \frac{N_1 N_2}{A} = \sigma(n_1 A d)(n_2 d)$$

$$R = \frac{N}{(Ad)t} = n_1 n_2 \sigma v$$

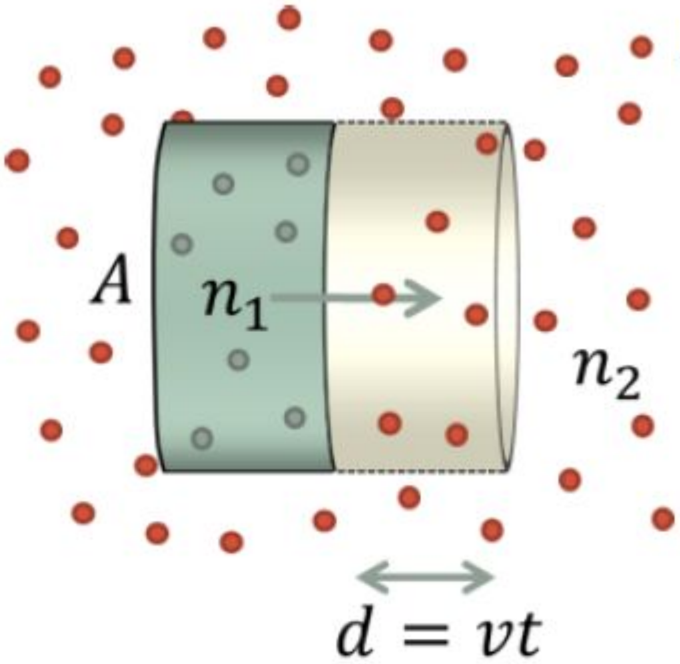
Theory: Maxwell-Boltzmann Distribution



$$dn = 4\pi n \left[\frac{m}{2\pi kT}\right]^{\frac{3}{2}} e^{-\frac{mv^2}{kT}} v^2 dv$$

$$dn = \frac{4n}{(2\pi M)^{\frac{1}{2}}(kT)^{\frac{3}{2}}} e^{-\frac{E}{T}} \left[\frac{E}{v}\right] dE$$

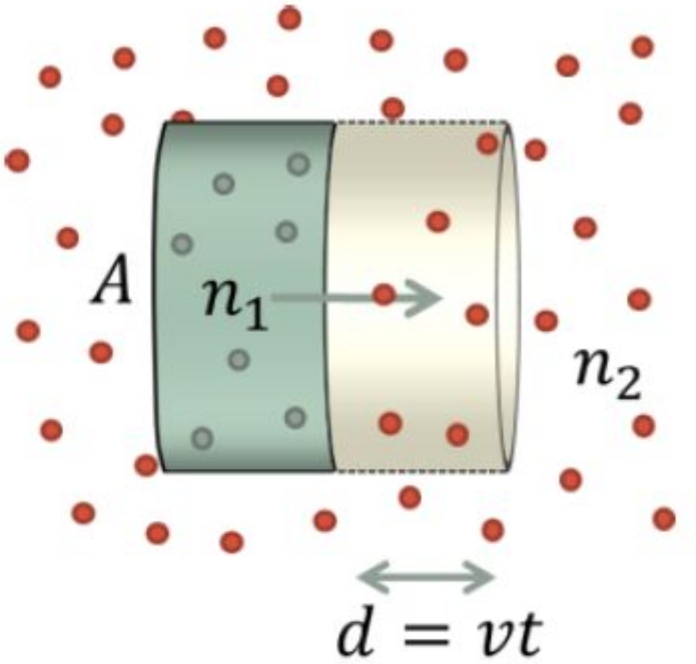
Theory: Average Reactivity



$$R = \int_0^\infty \sigma(E)\, n_2 [v\, dn_1] = \int_0^\infty \sigma(E) n_2 \frac{4 n_1}{(2\pi M A)^{\frac{1}{2}} (kT)^{\frac{3}{2}}} e^{-\frac{E}{kT}} E\, dE$$

$$\langle \sigma v \rangle = \frac{4}{(2\pi M A)^{\frac{1}{2}} (kT)^{\frac{3}{2}}} \int_0^\infty \sigma(E) e^{-\frac{E}{kT}} E\, dE$$

Theory: Yields



$$Y_{12} \propto R_{12} = f_1 f_2 \left(\frac{\rho}{\bar{m}}\right)^2 \langle \sigma v \rangle_{12}$$

$$\frac{Y_{12}}{Y_{34}} \cong \frac{f_1 f_2}{f_3 f_4} \frac{\langle \sigma v \rangle_{12}}{\langle \sigma v \rangle_{34}}$$

Theory: Calculating Cross-Sections

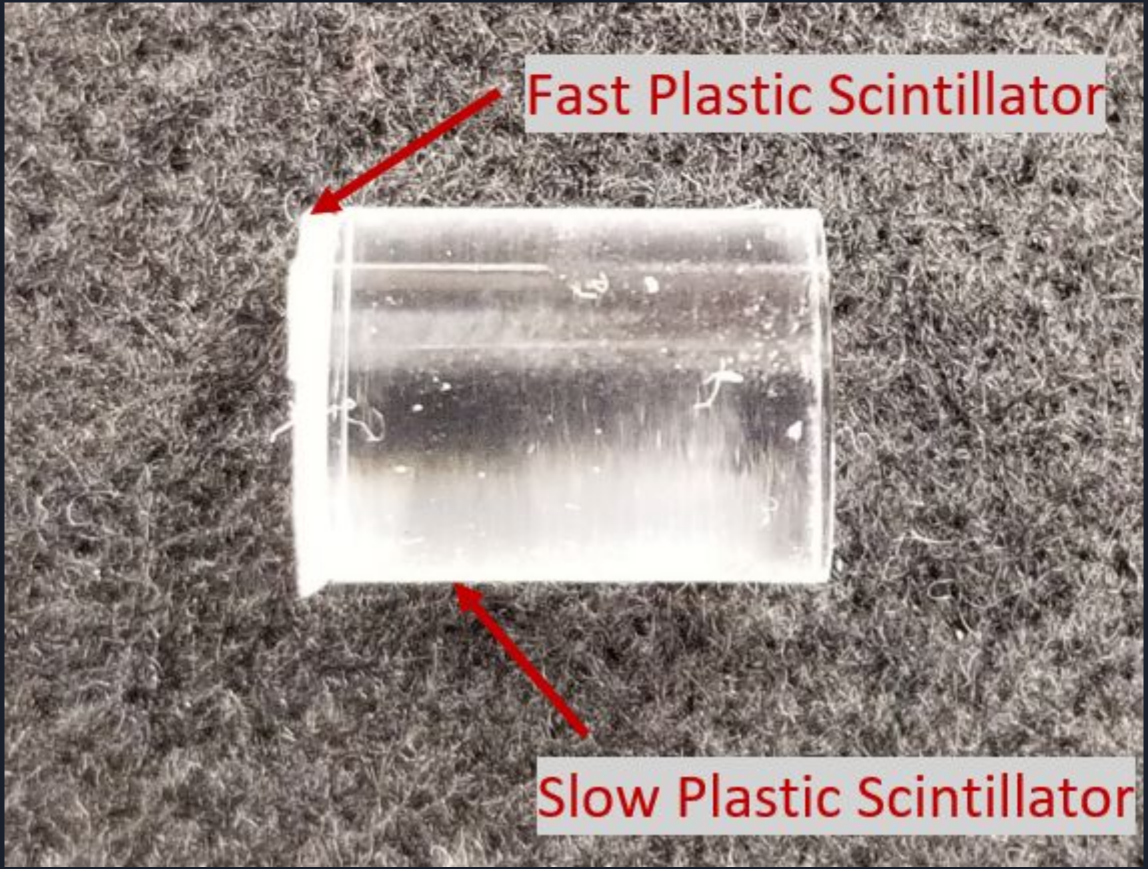
- S-Factor Extrapolation [7]

$$\sigma(E) = \frac{S(E)}{E} \exp\left(-\sqrt{\frac{E_G}{E}} \right)$$

- TALYS [8]
  - Includes many other relevant models

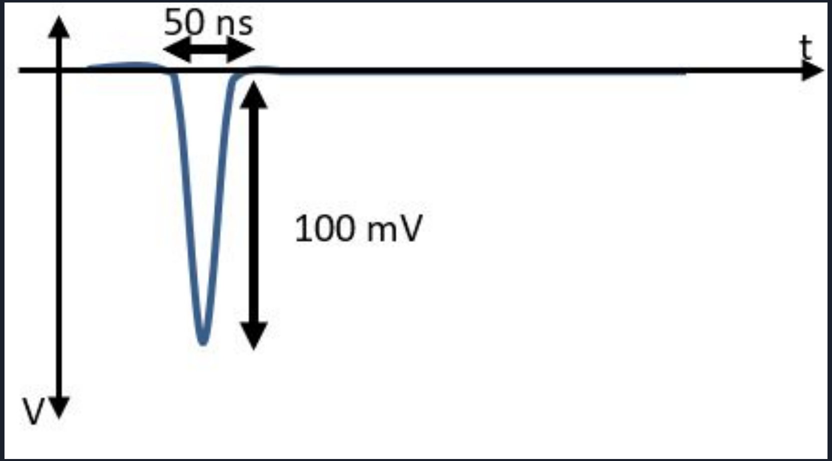
- R-Matrix Formalism [7]
  - Does not need data from cross-section of interest
  - Examines characteristics of other reactions that go through same compound nucleus

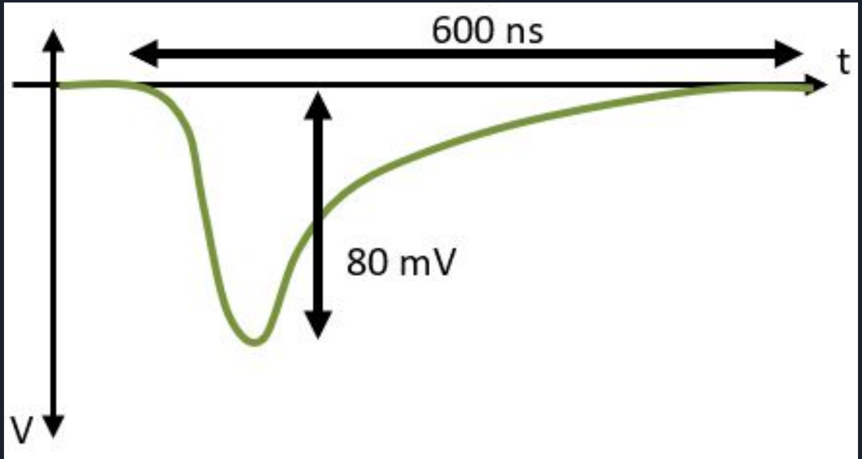
Experiment: Phoswich Detector

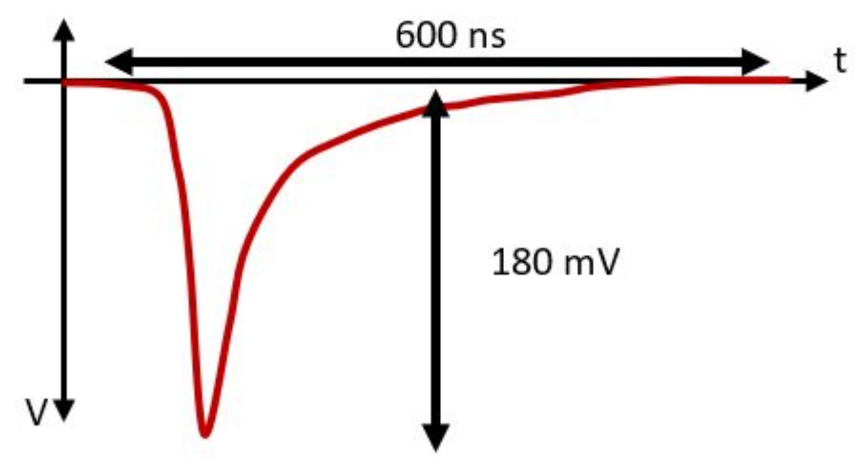


- Particle Identification
- Removes the need for a second detector in the small geometry of the apparatus
- Allows for complex detector geometry

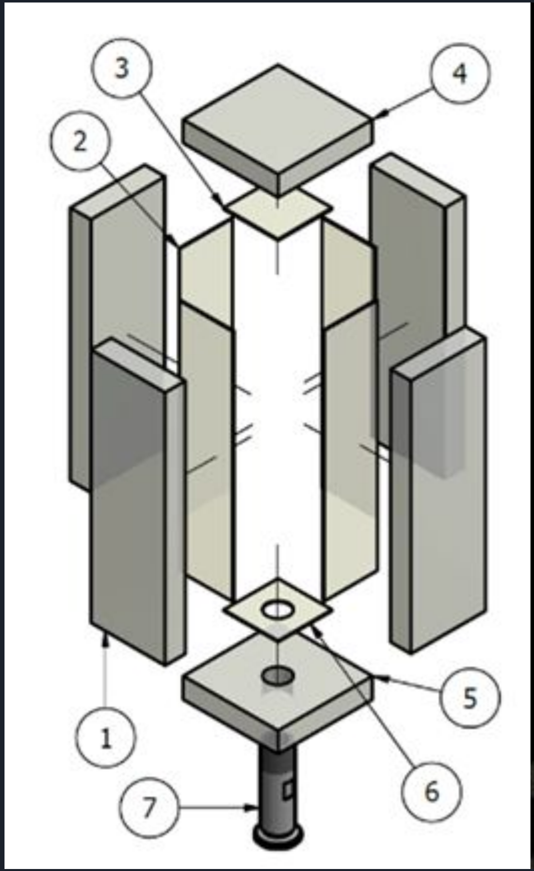
Experiment: Phoswich Detector





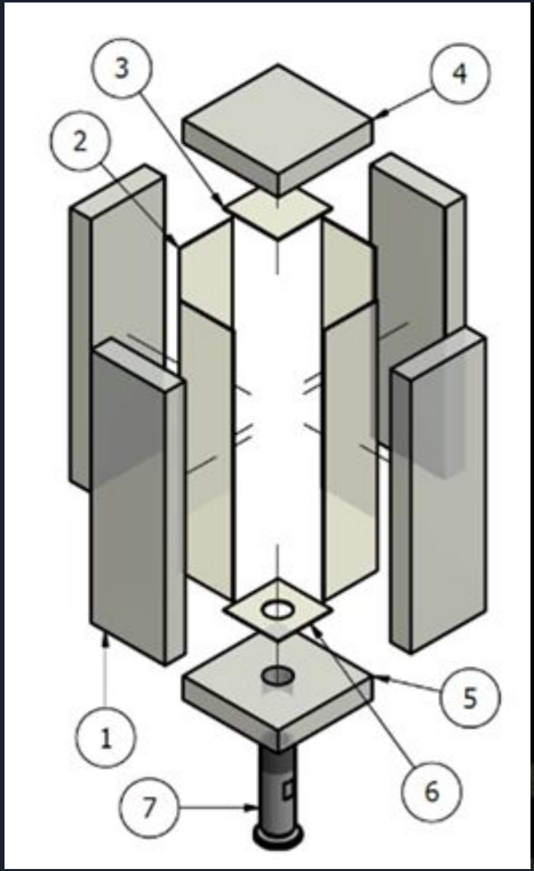


Experiment: 4π Phoswich Detector



- Large Internal Volume and solid angle for internal decays
- Can trap non-reactive products
- Total scintillator thickness of 18 mm

Experiment: 4π Phoswich Detector



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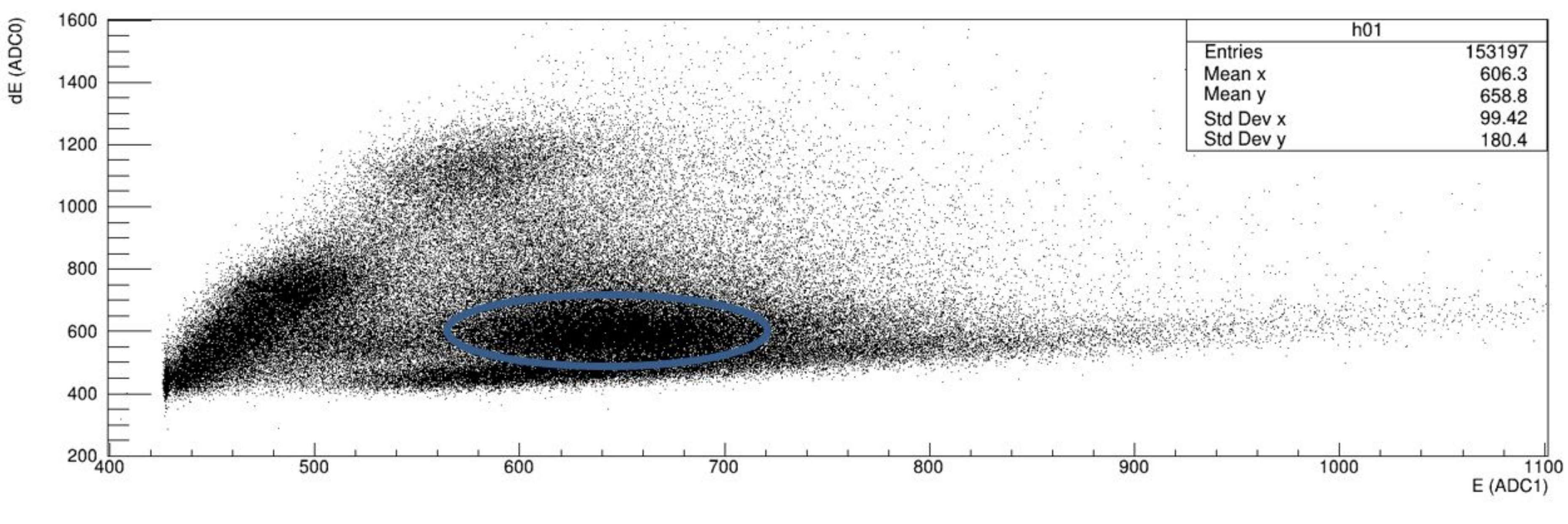
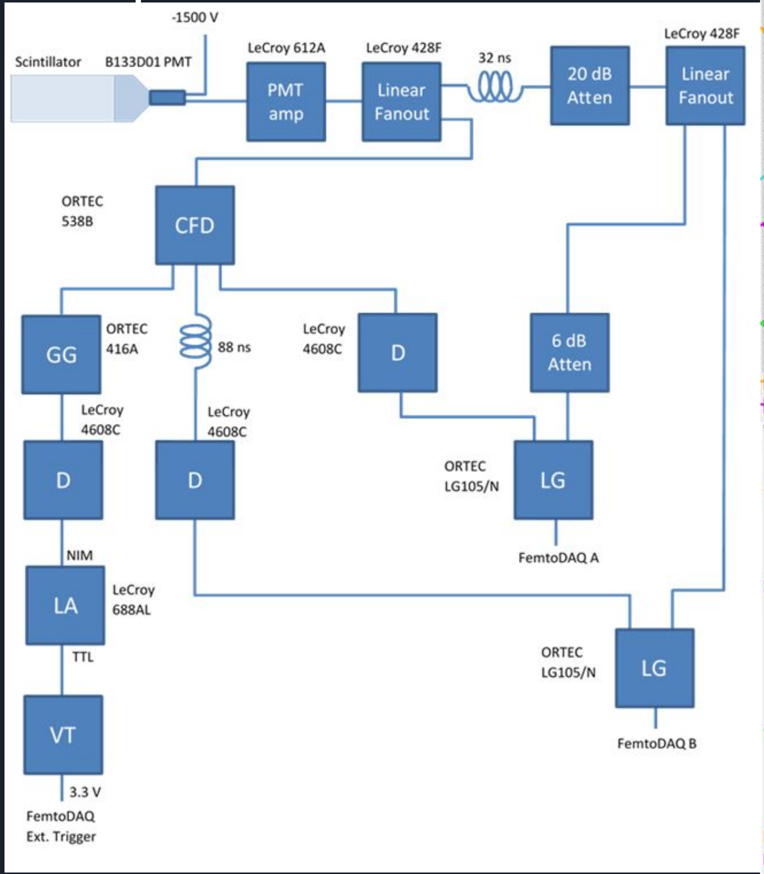
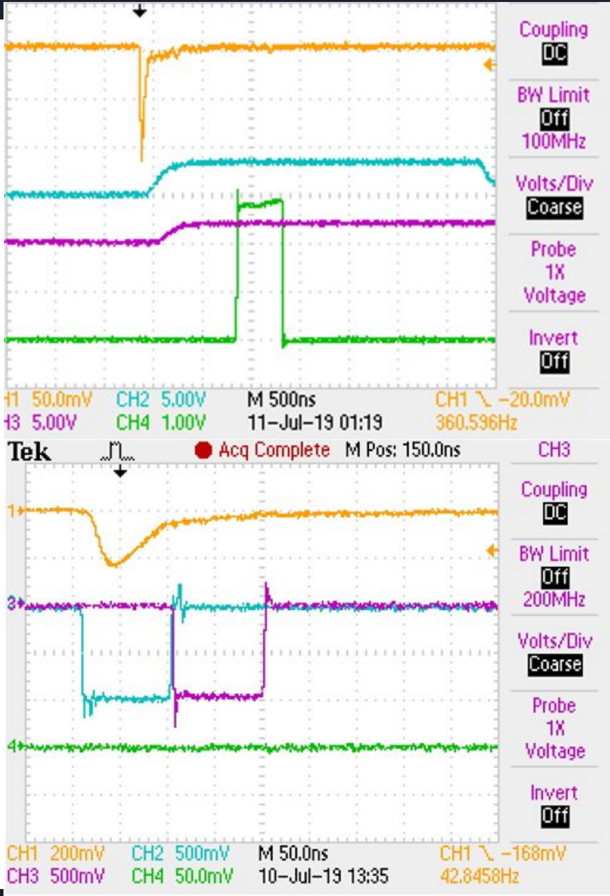


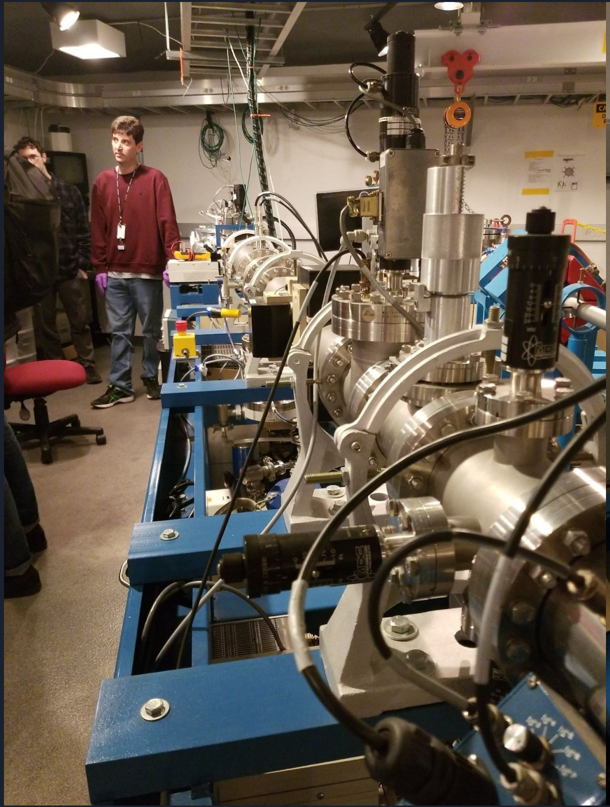
Experiment: Pulse Separation and Data Acquisition

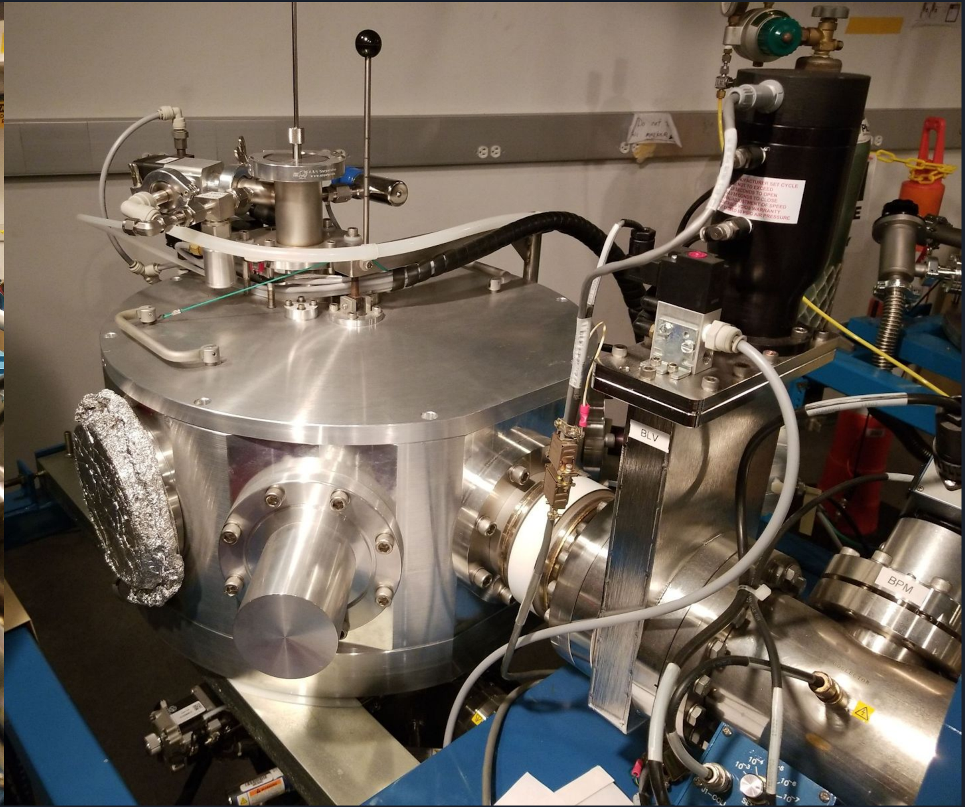




- Pulse separated into dE and E components
- Trigger for digitalization generated
- FemtoDAQ records pulse heights of each component when triggered

Experiment and Analysis: ^{41}Ar Experiment





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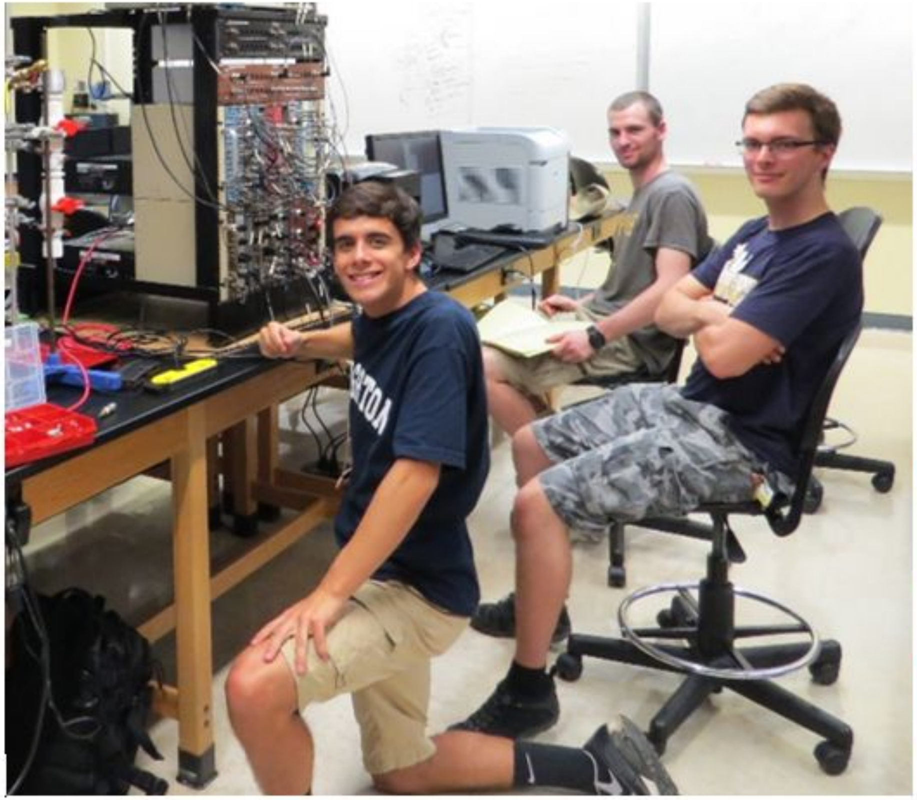

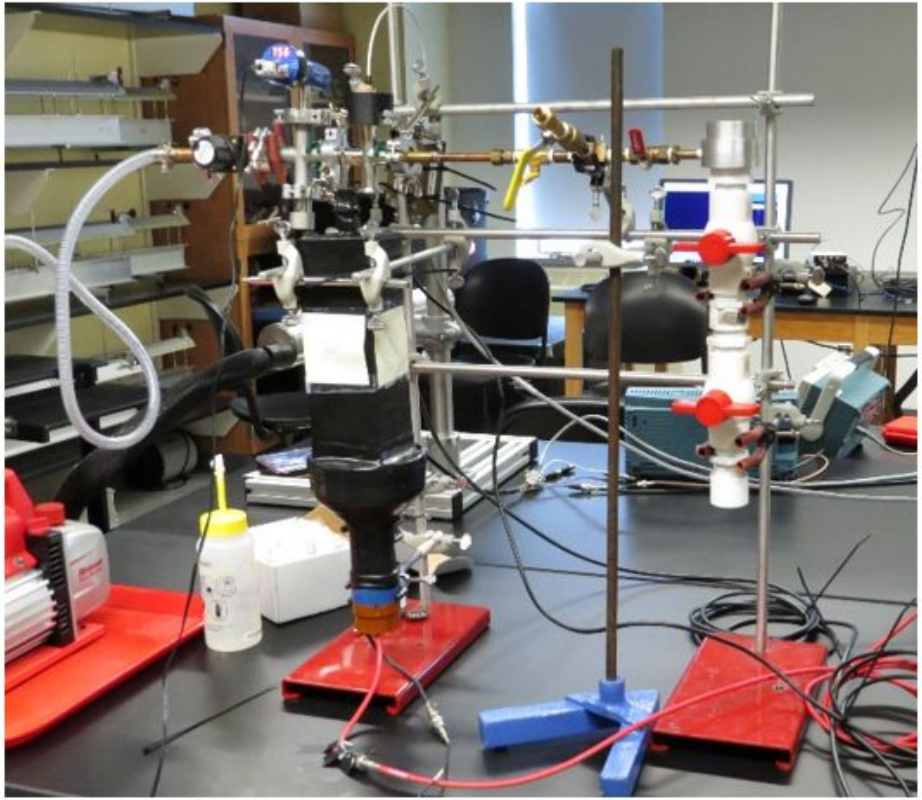

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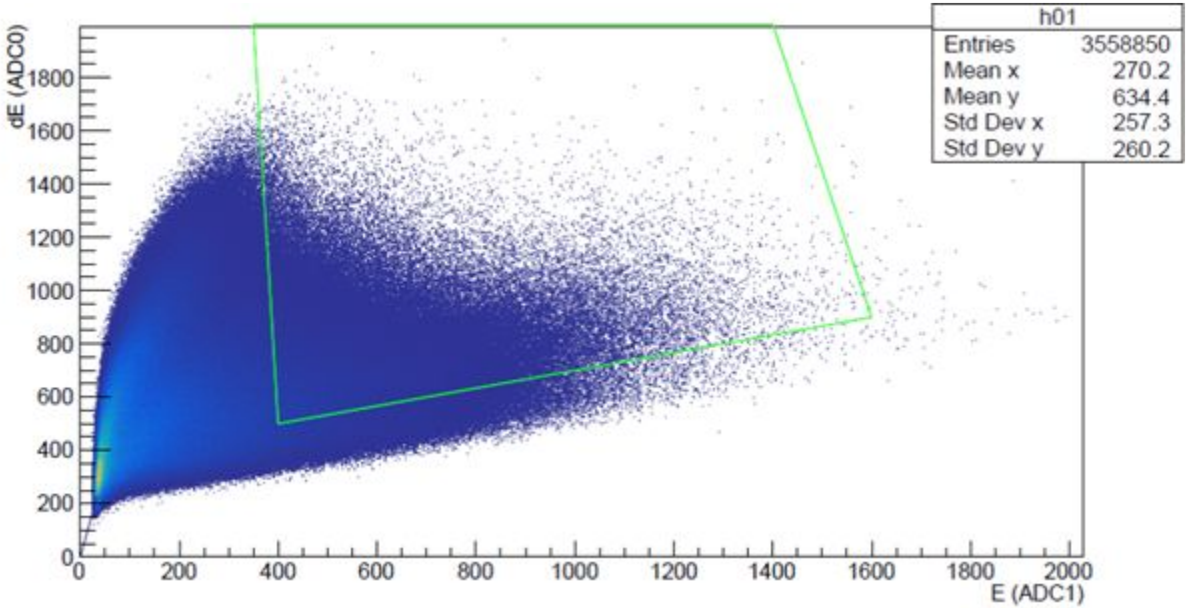
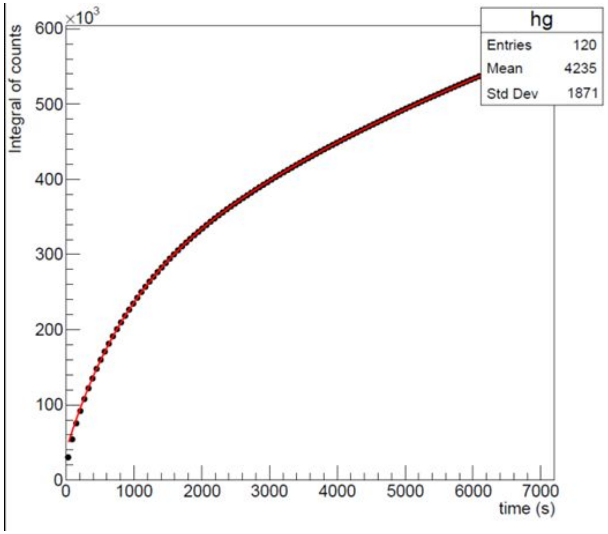
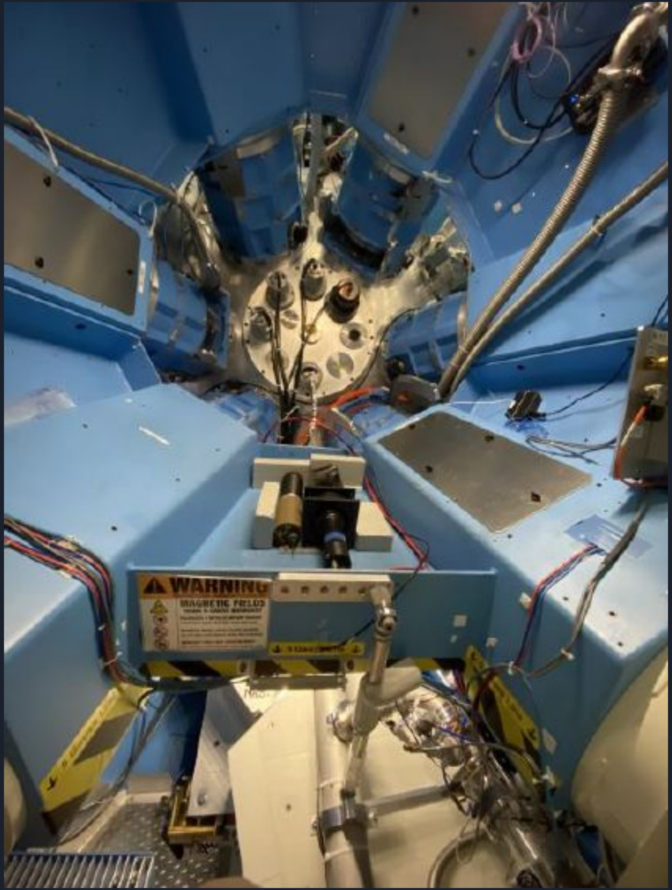


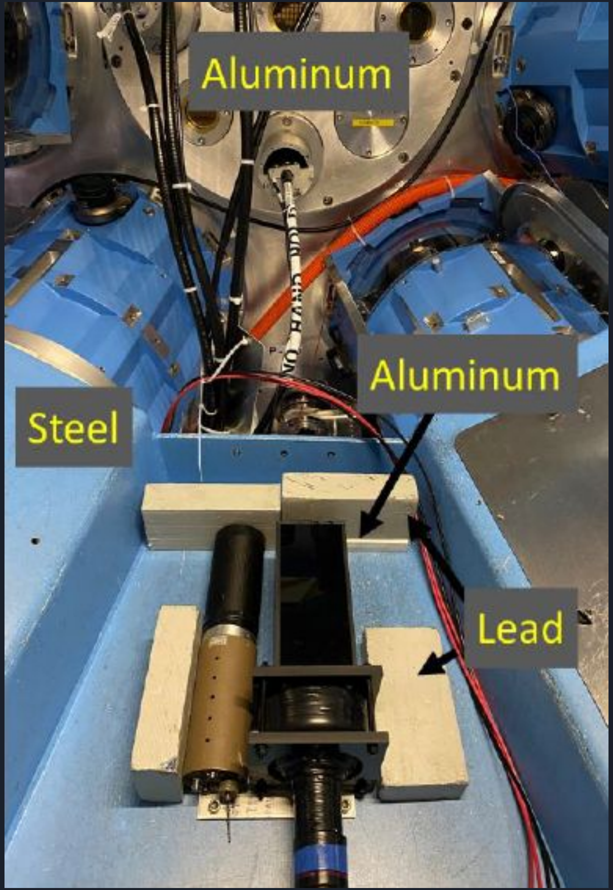


$$N(t) = A\left(1 - e^{-\lambda_{\mathrm{Ar-41}} t}\right) + B\left(1 - e^{-\lambda_{\mathrm{N-13}} t}\right) + Ct + D$$

^{41}Ar Half-life calculated agreed with the accepted value of 109.6 min

Experiment and Analysis: LLE Ride Along





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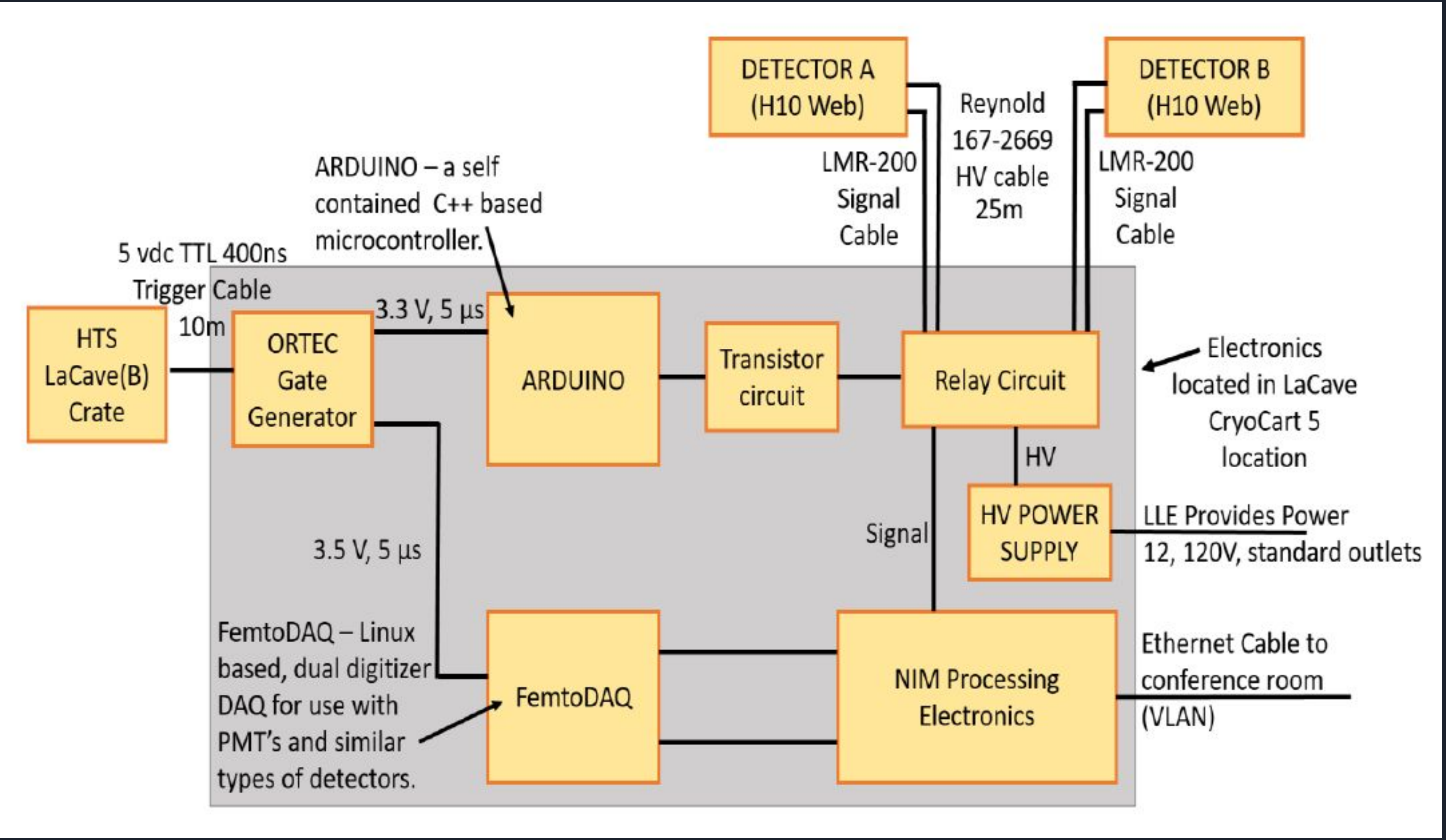
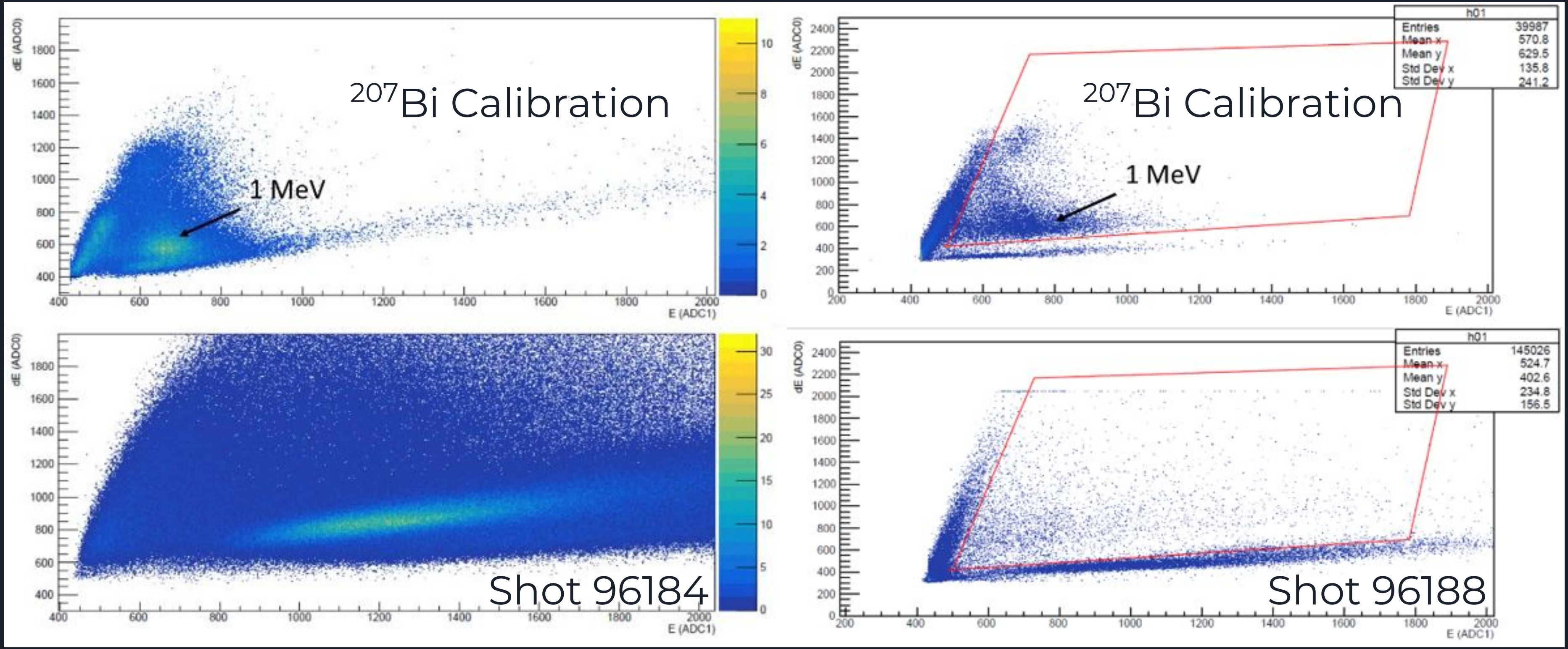


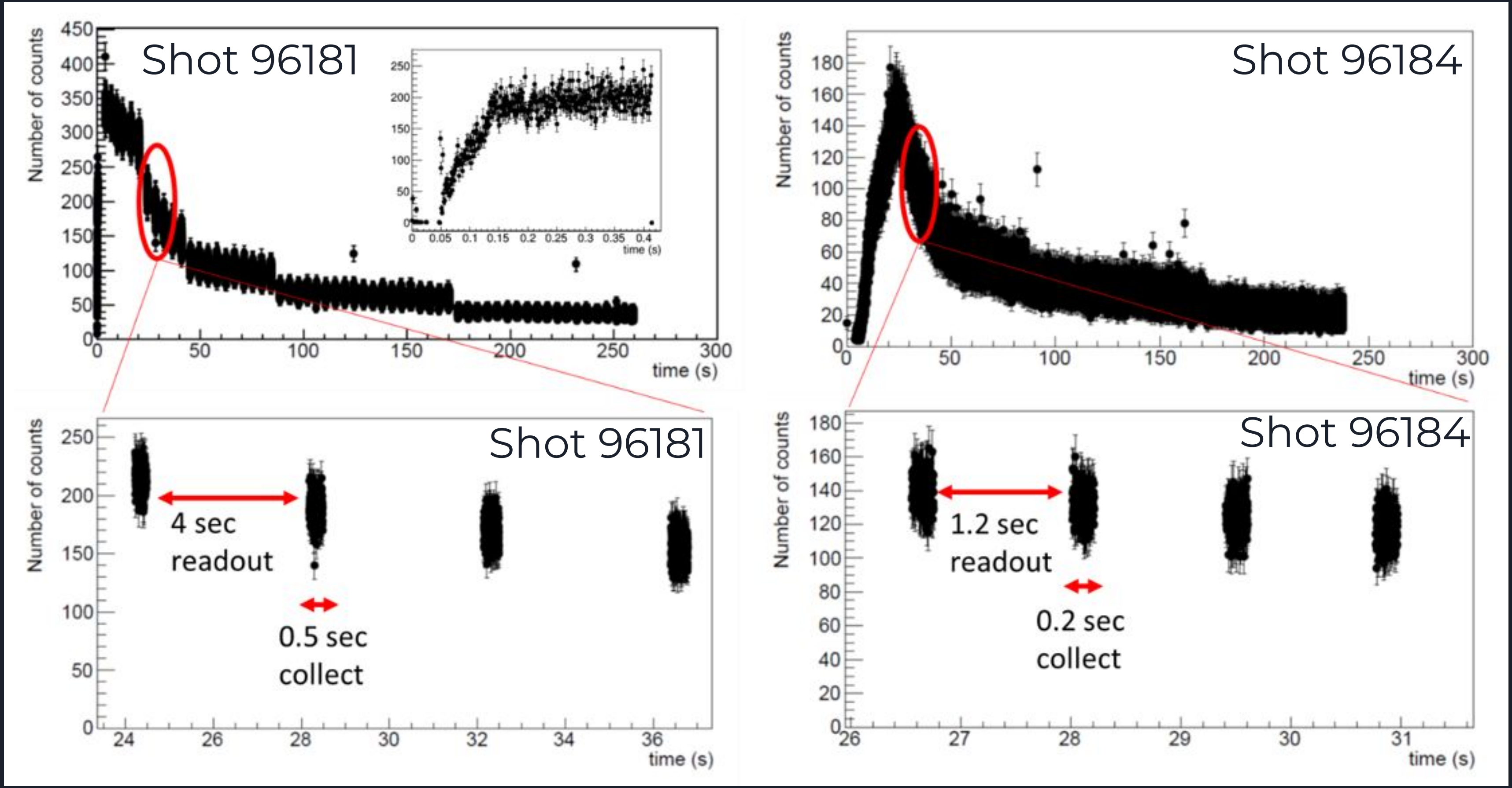
Experiment and Analysis: LLE Ride Along

Shot Number	Neutron Yield	T_{ion} (keV)	Detector	Shielding	FemtoDAQ Timeout	Note
96175	1.04×10^{14}	9.28	4π Phoswich			FemtoDAQ crashed
96178			4π Phoswich			Trigger test, null shot
96179	1.34×10^{14}	9.51	4π Phoswich			Relays failed to close
96180			4π Phoswich			Trigger test, null shot
96181	1.32×10^{14}	8.44	4π Phoswich	none	30 sec	Good
96183			4π Phoswich	none	30 sec	FemtoDAQ error
96184	1.56×10^{14}	10.64	4π Phoswich	none	0.2 sec	Good
96185	1.50×10^{14}	8.68	4π Phoswich	lead	0.2 sec	Good
96186			Getter Det.			No FemtoDAQ trigger
96187			Getter Det.			Trigger test, null shot
96188			Getter Det.	lead	30 sec	Good

Experiment and Analysis: LLE Ride-Along



Experiment and Analysis: LLE Ride-Along



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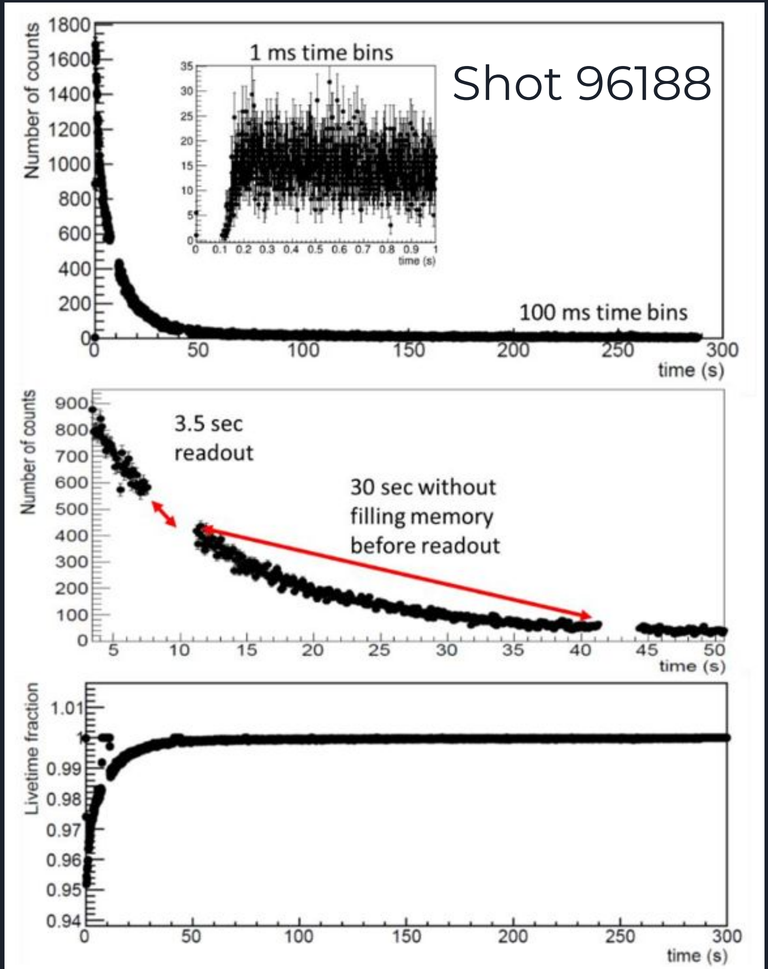
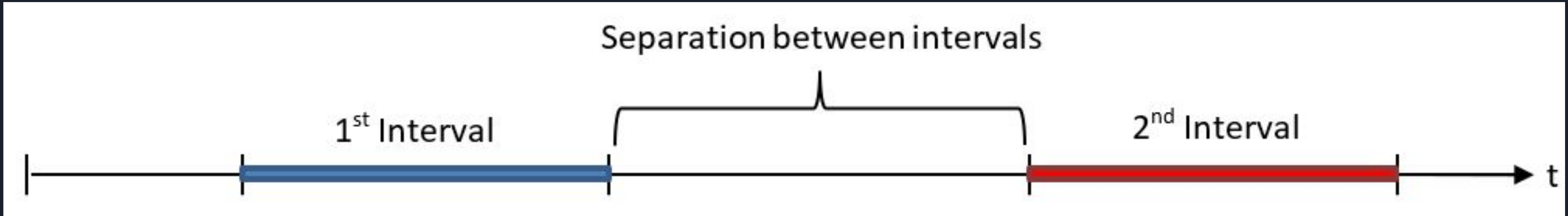
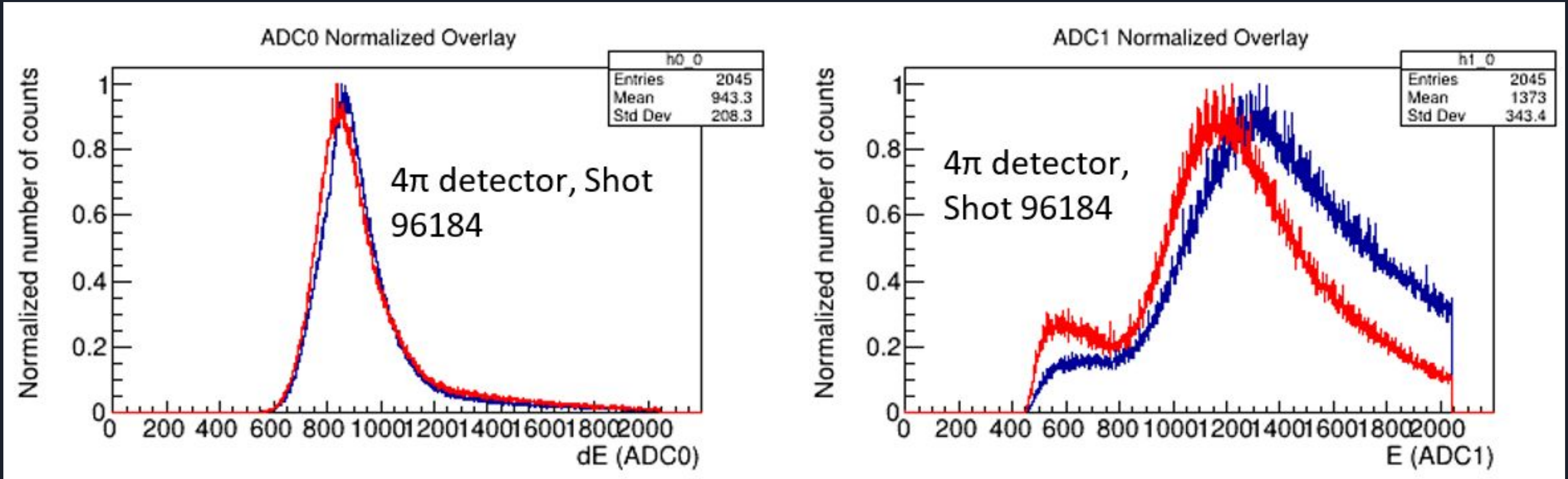


- Over 350,000 counts/s for 4π Detector
- Over 18,000 counts/s for Getter Detector

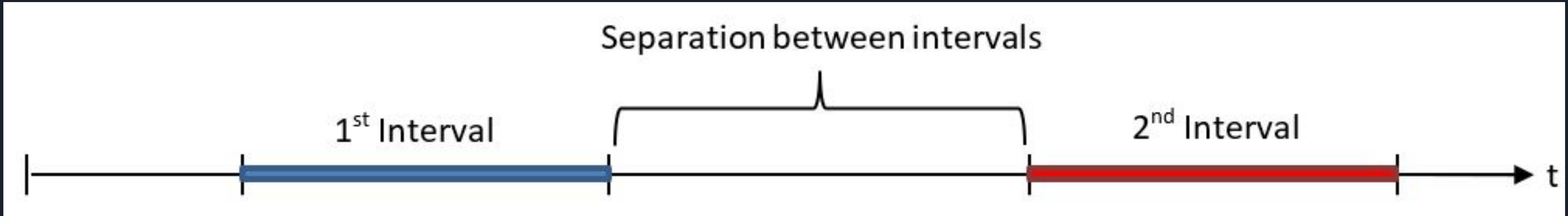
What issues are created by this high count rate?

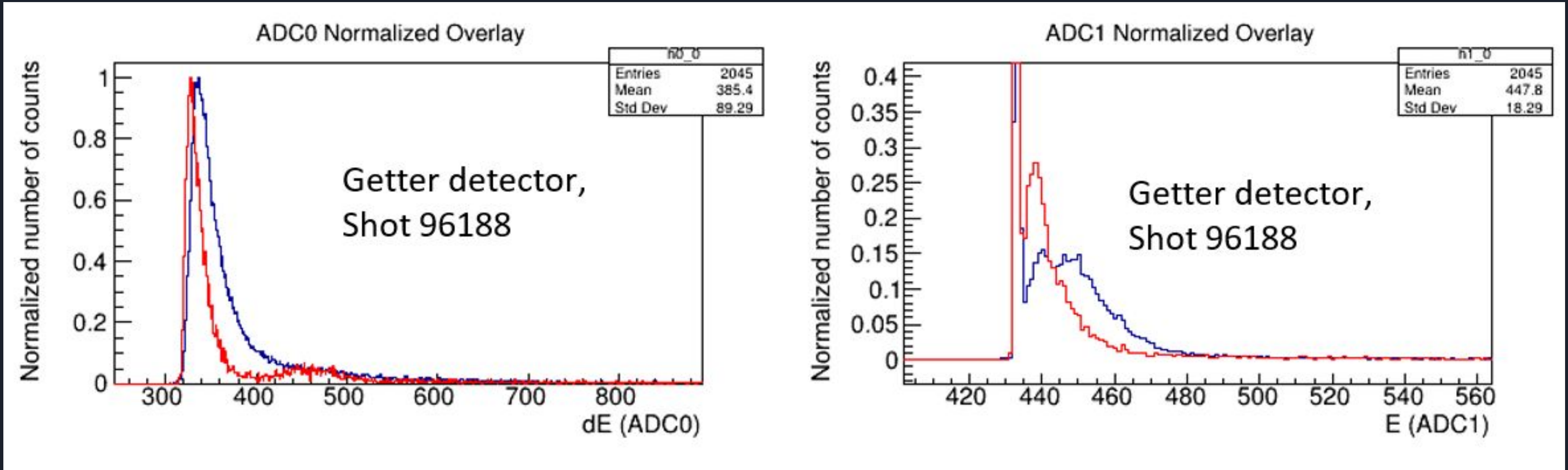
Experiment and Analysis: LLE Ride-Along



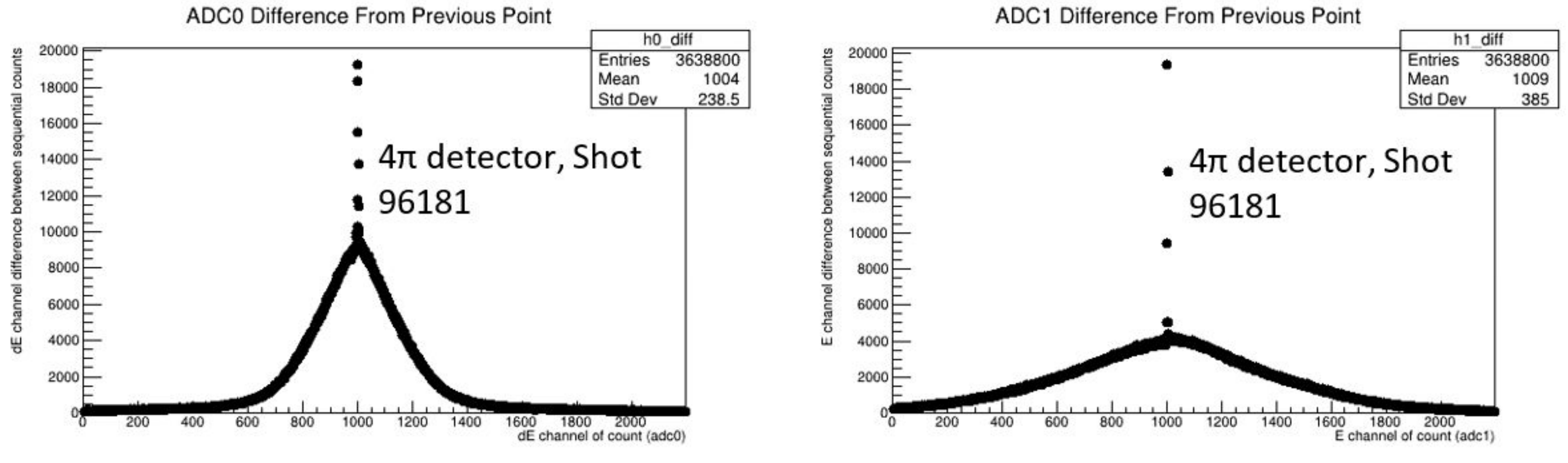


Experiment and Analysis: LLE Ride-Along





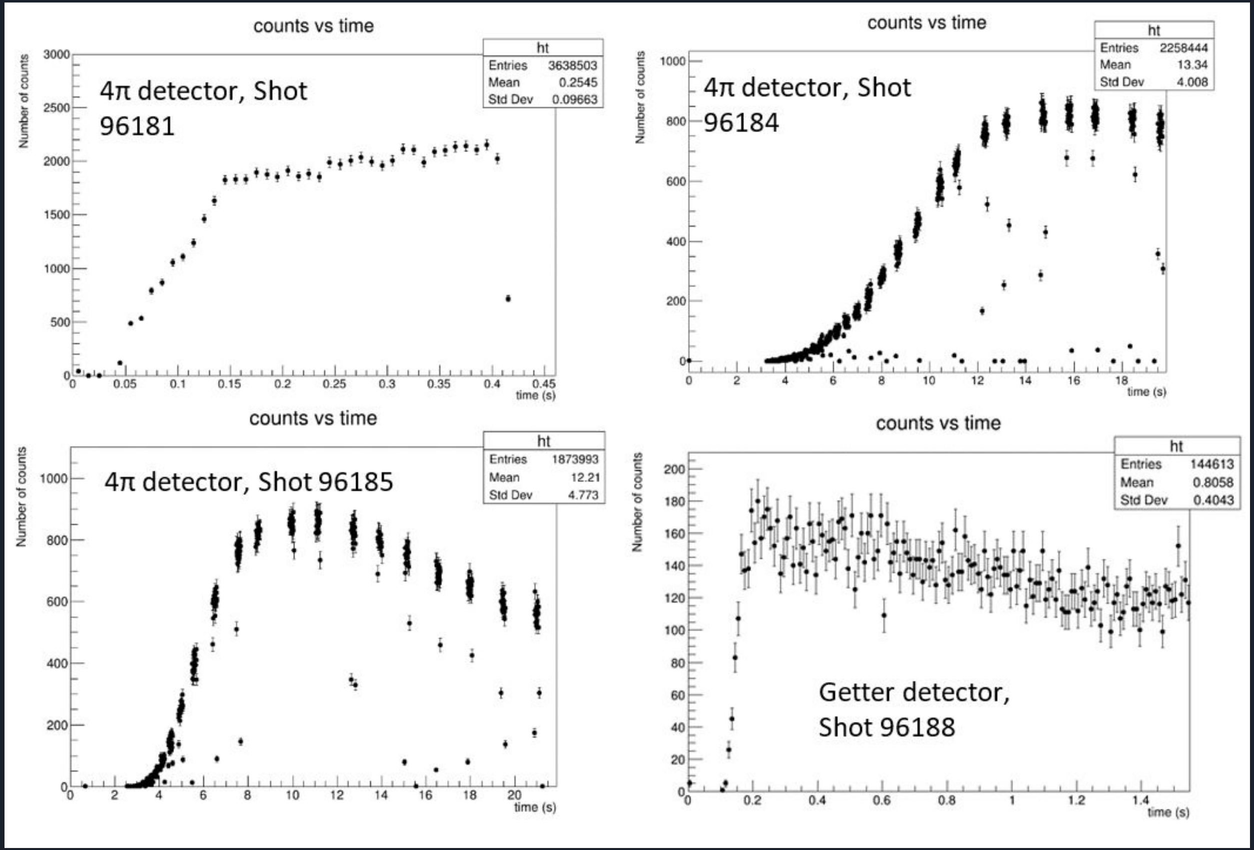
Experiment and Analysis: LLE Ride-Along



What does this mean?

How can we address this?

Experiment and Analysis: LLE Ride-Along

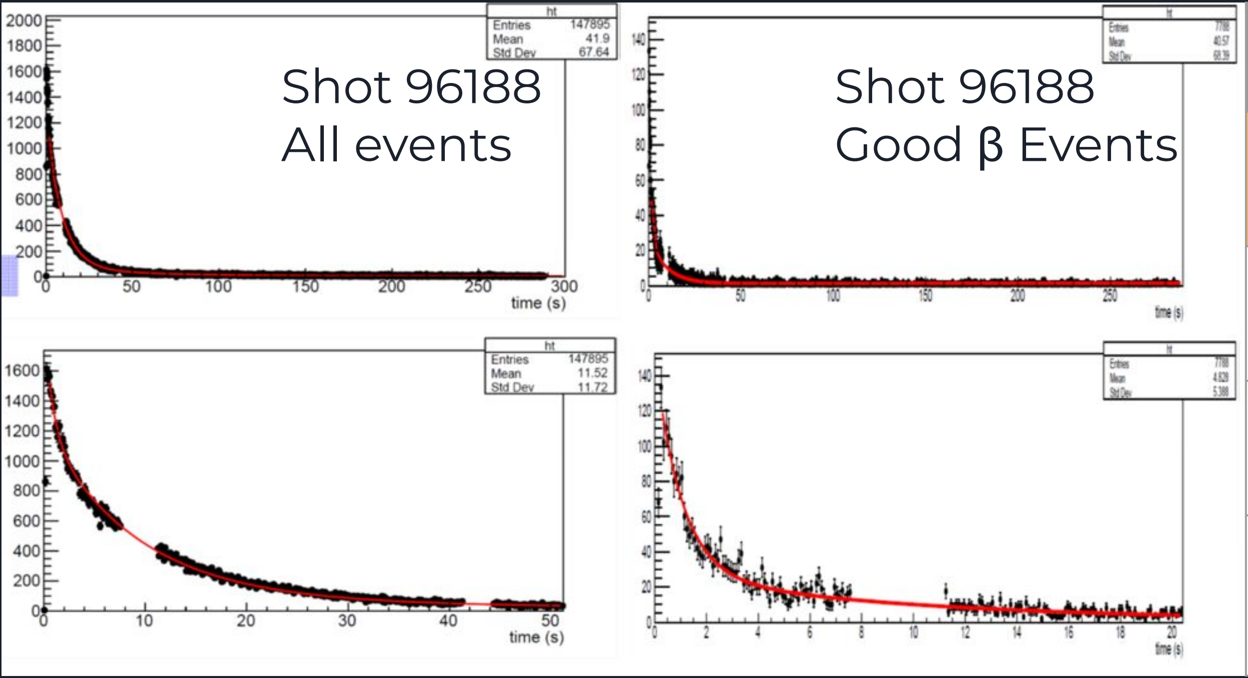


4π Detector:
4 - 4.5 sec

Getter Detector:
0.2 sec

What is causing the warm-up time to be this long?

Experiment and Analysis: LLE Ride-Along



All Counts		Good β	
$T_{1/2}$ (sec)	N	$T_{1/2}$ (sec)	N
0.76	728	0.73	115
7.13 (fixed)	1080	7.13 (fixed)	23
59	40	N/A	N/A

$$F(t) = N_0 e^{-\lambda_0 t} + N_1 e^{-\lambda_1 t} + N_2 e^{-\lambda_2 t} + B$$

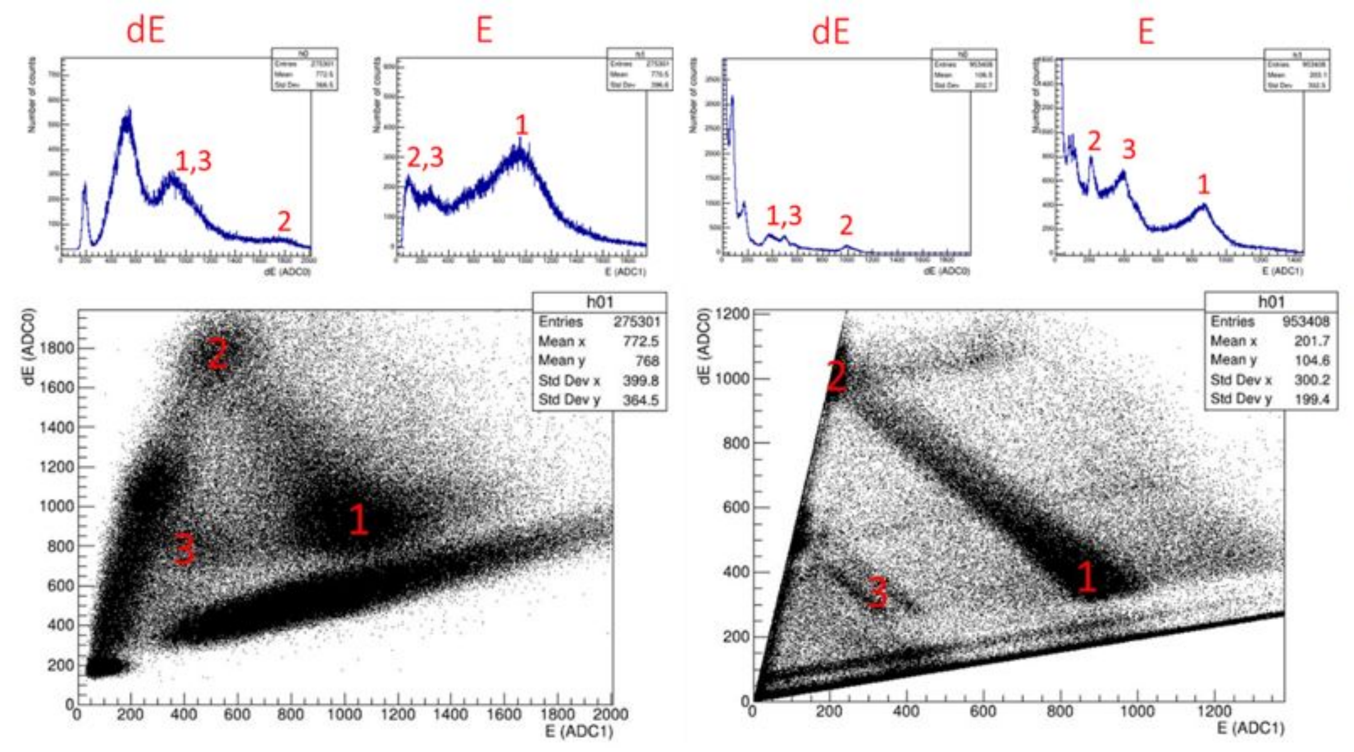
Experiment and Analysis: LLE Ride-Along

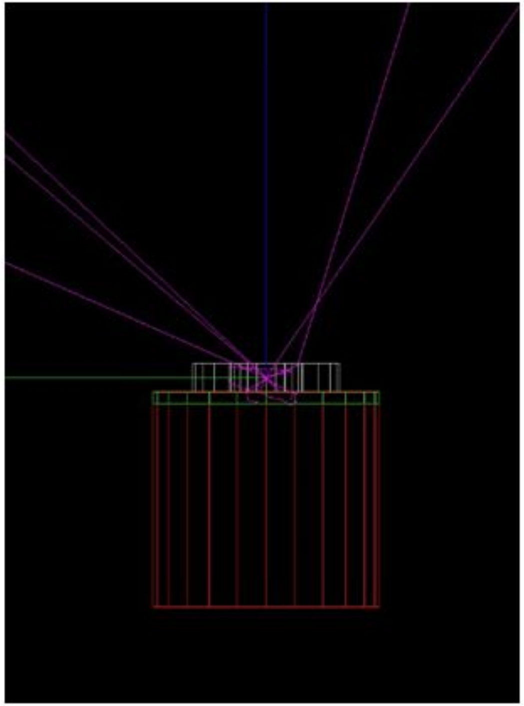
Isotope	Half Life (s)	Decay Const. (1/s)	Decay Mode	Reaction	Threshold (MeV)	CS (mb)	Source
^{26}Al	6.346	0.10923	EC, β-	$^{27}Al(n,2n)^{26}Al^*$	13.546	8.48 at 14.1 MeV	Target Chamber
^{15}C	2.449	0.28303	β-	$^{18}O(n,\alpha)^{15}C$ $^{14}C(n,\gamma)^{15}C$ $^{15}N(n,p)^{15}C$	5.29 0 9.59	7.6 at 14.5 MeV 1.5 at 14.7 MeV 1.6 at 14.8 MeV	Air, C in target room
^{16}N	7.130	0.09722	β-	$^{16}O(n,p)^{16}N$	10.25	42.0 at 14.1 MeV	Air

Experiment and Analysis: Simulating the Detectors

GEANT4 Simulations: Modeling particle interactions with the detectors

- Absolute Efficiency?
- How do background sources affect the 2-D histograms?





Experiment and Analysis: Simulating the Detectors

	Getter Det. Outside Det. Shot 96188	4π Det. Inside Det. Shot 96184	4π Det. Outside Det. Shot 96184	Getter Det. ^{27}Al foil Shot 96188	Getter Det. ^{27}Al bar Shot 96188
Calculated Product per shot	1.6×10^{9} ^{16}N	1.1×10^{7} ^{16}N	1.6×10^{9} ^{16}N	[calc] ^{26}Al	[calc] ^{26}Al
Predicted nuclei per million	155 ^{16}N	4.8×10^{5} ^{16}N	4.5×10^{3} ^{16}N	[calc] ^{26}Al	[calc] ^{26}Al
Predicted nuclei per shot	2.5×10^{5} ^{16}N	5.4×10^{6} ^{16}N	7.0×10^{6} ^{16}N	[calc] ^{26}Al	[calc] ^{26}Al
	(at t= 0.2 s)	(at t= 30 s)		(at t= 0.2 s)	
Detected decays expected in 1ms	23 ^{16}N	29 ^{16}N	37 ^{16}N	[calc] ^{26}Al	[calc] ^{26}Al
Detected decays measure in 1 ms	~18 ^{16}N	~120 ^{16}N	~120 ^{16}N	[calc] ^{26}Al	[calc] ^{26}Al

Summary

^{41}Ar Experiment

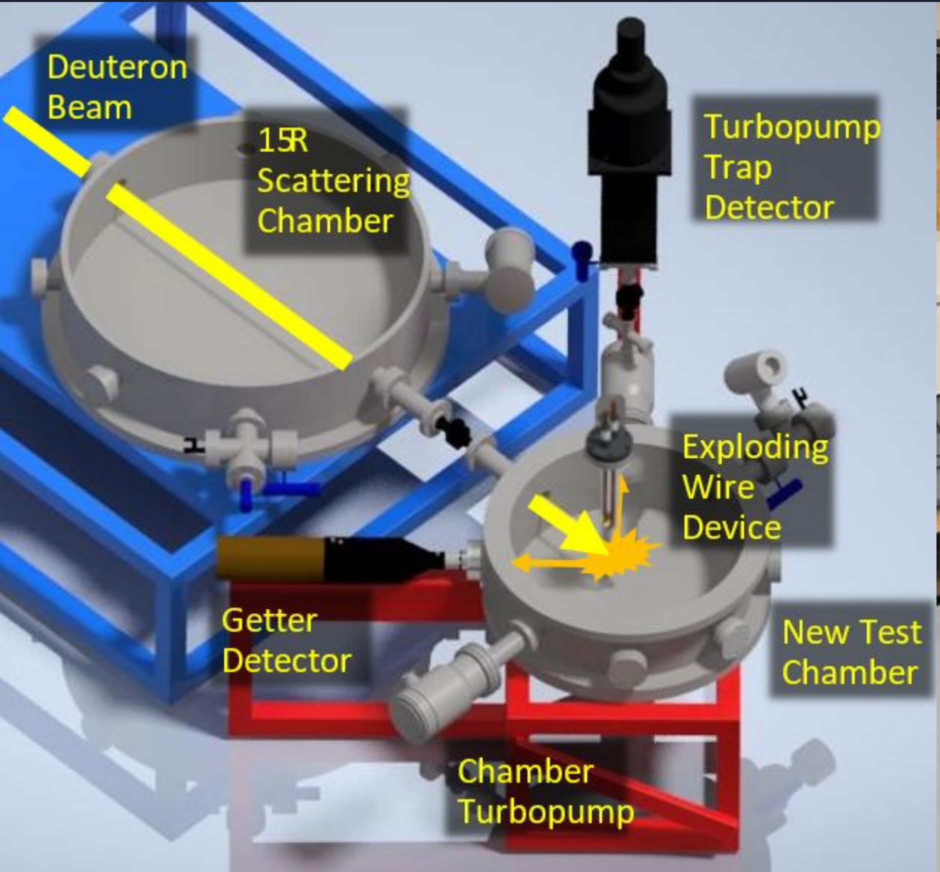
- Created a radioactive, inert gas
- Captured and contained the gas within the 4π Detector's inner volume
- Successfully identified and measure the decay of a radioactive inert gas

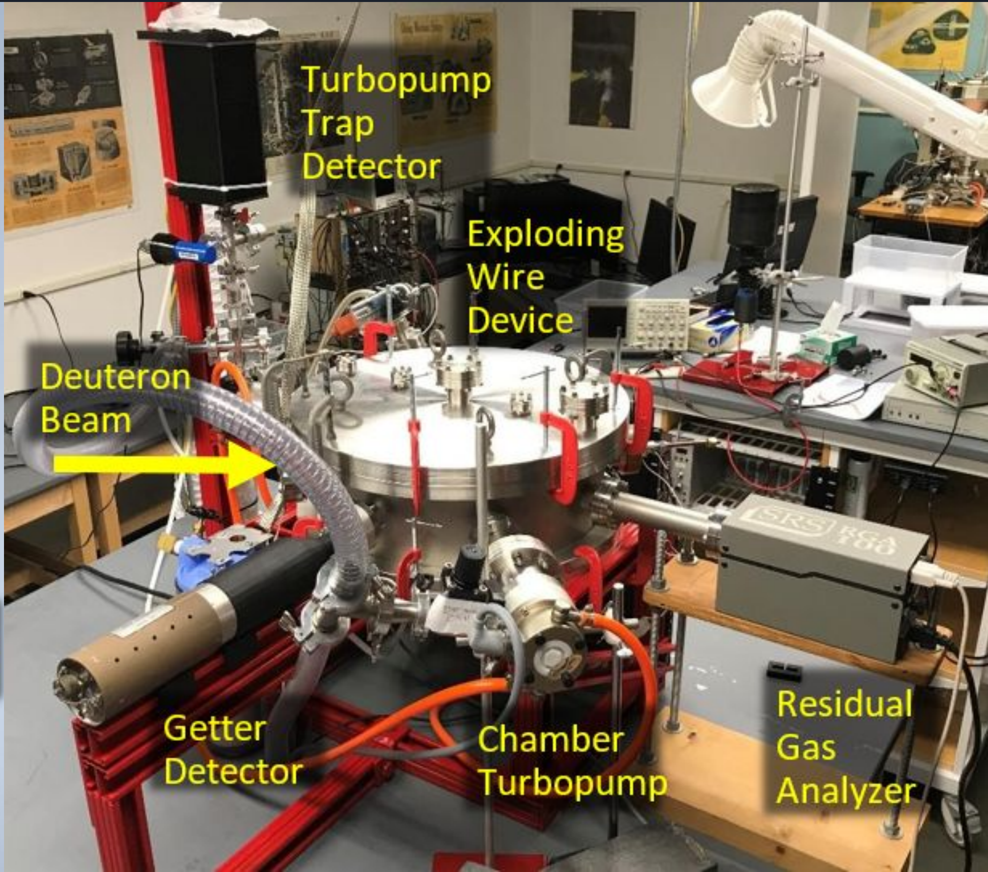
LLE Ride-Along

- Successfully tested relays and electronics behavior after an ICF implosion
- Initial estimate of background rate
- Simulated detector behavior

Future Work: Exploding Wire Experiment

What is the collection fraction of each collection method?





Future Work: Exploding Wire Experiment

What is the collection fraction of each collection method?

Reaction	Reaction Threshold (MeV)	Reactant Natural Abundance (%)	Approx. Cross-Section (barns)	Product Half-Life (s)	Product Beta End Point Energy (MeV)	Yield (Total Number of Product Nuclei)
Deuteron Reaction: Deuteron beam 10 nA, Deuterons/second = 6.25×10^{10}, 2 MeV						
$^{27}Al(d, p)^{28}Al$	0.0	100	1.5×10^{-1}	134.7	2.8	3.3×10^{7}
$^{65}Cu(d,p)^{66}Cu$	0.0	31	6.5×10^{-2}	307.2	2.6	5.2×10^{6}
Neutron Reaction: Deuteron beam 10 nA, Deuterons/second = 6.25×10^{10}, 2 MeV; Neutron Energy = 5 MeV, neutrons/second = 3.87×10^{6}						
$^{19}F(n, \alpha)^{16}N$	1.6	100	2.1×10^{-1}	7.1	4.2	1.6×10^{4}
$^{55}Mn(n, p)^{55}Cr$	1.9	100	2.0×10^{-2}	209.8	2.6	2.6×10^{5}
$^{27}Al(n, p)^{27}Mg$	1.9	100	2.0×10^{-3}	567.4	1.7	1.3×10^{4}

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