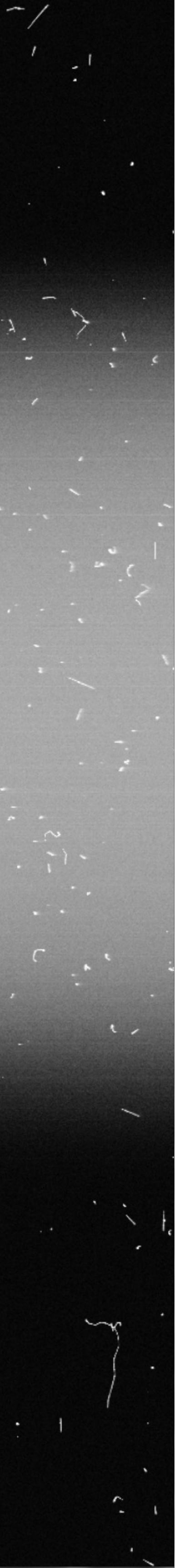


Measuring cosmogenic activation rates in active detector material

Richard Saldanha

18th March 2021

CPAD Instrumentation Frontier Workshop 2021

Virtual Event @ Stony Brook University

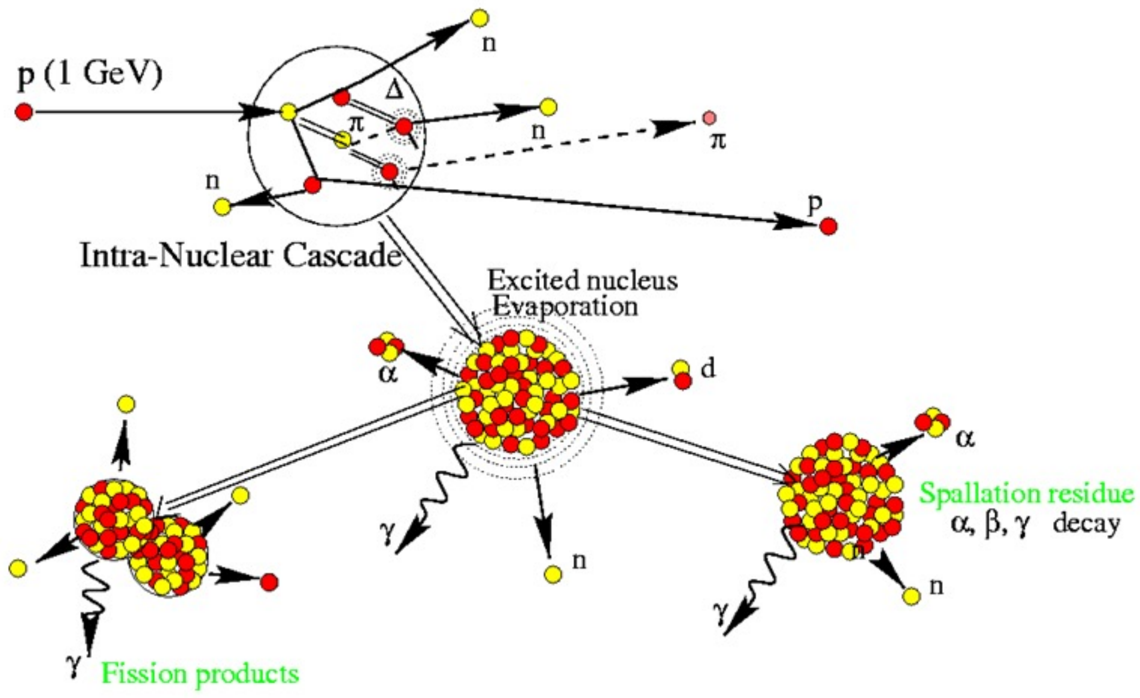
NSF/J. Yang

Cosmogenic Activation

- Radioactive isotopes produced by cosmogenic particle interactions in detector materials can be one of the leading sources of backgrounds in rare event searches

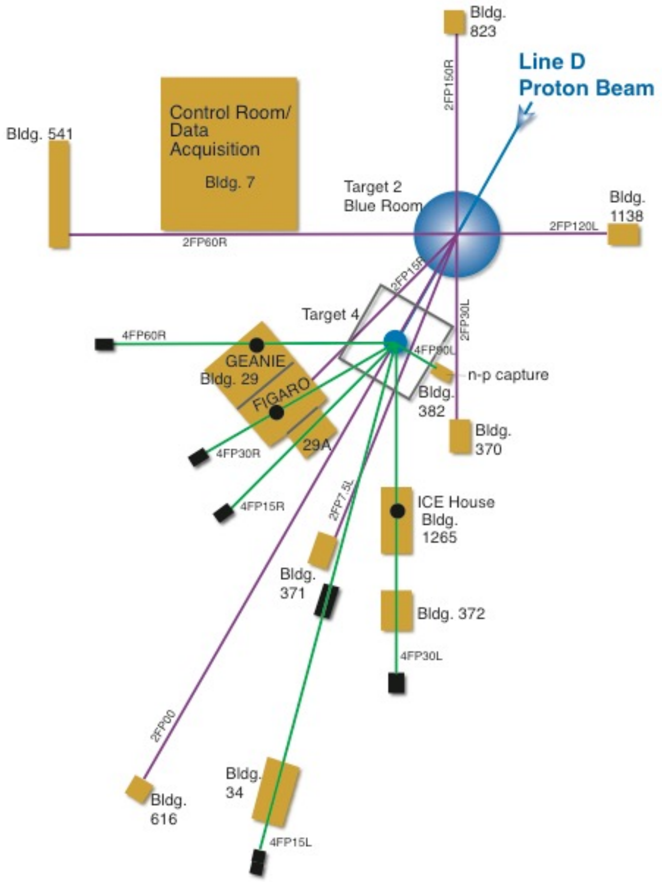
- Understanding the production rate of these isotopes is extremely important in order to evaluate the total surface residency time, transportation options, and storage requirements for low background detector components

- Small production rates and low energy decays of interest for next generation dark matter experiments (tritium, ^{39}Ar) make it difficult to measure sea-level activation without building a full-scale experiment

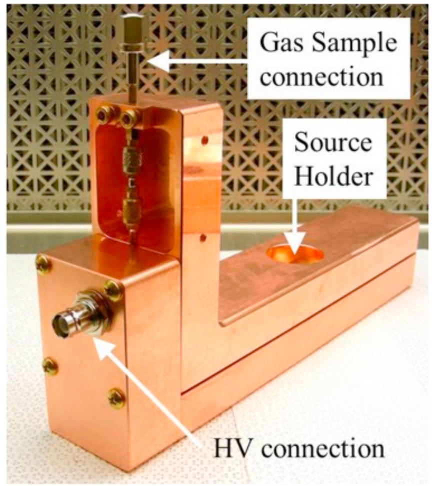


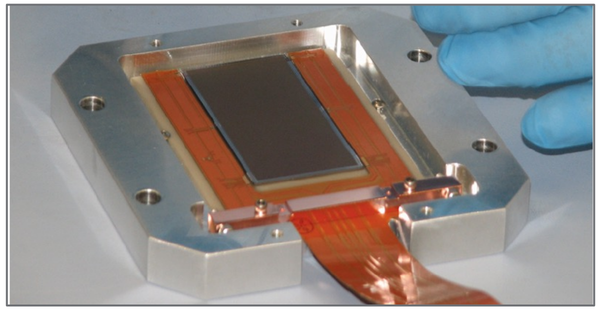
Measurement Technique

Use high intensity neutron beam to greatly increase production rate compared to sea-level cosmic rays

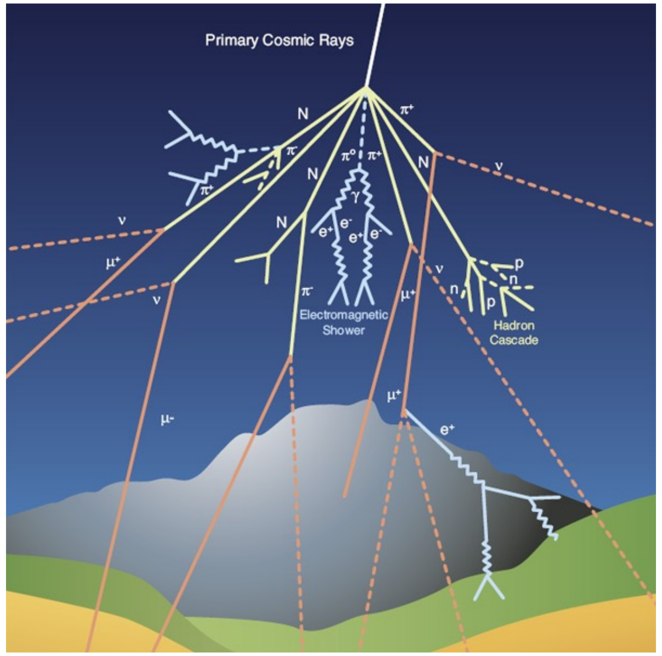


Irradiate active detector materials and use self-counting techniques to measure low-energy beta decays and x-rays



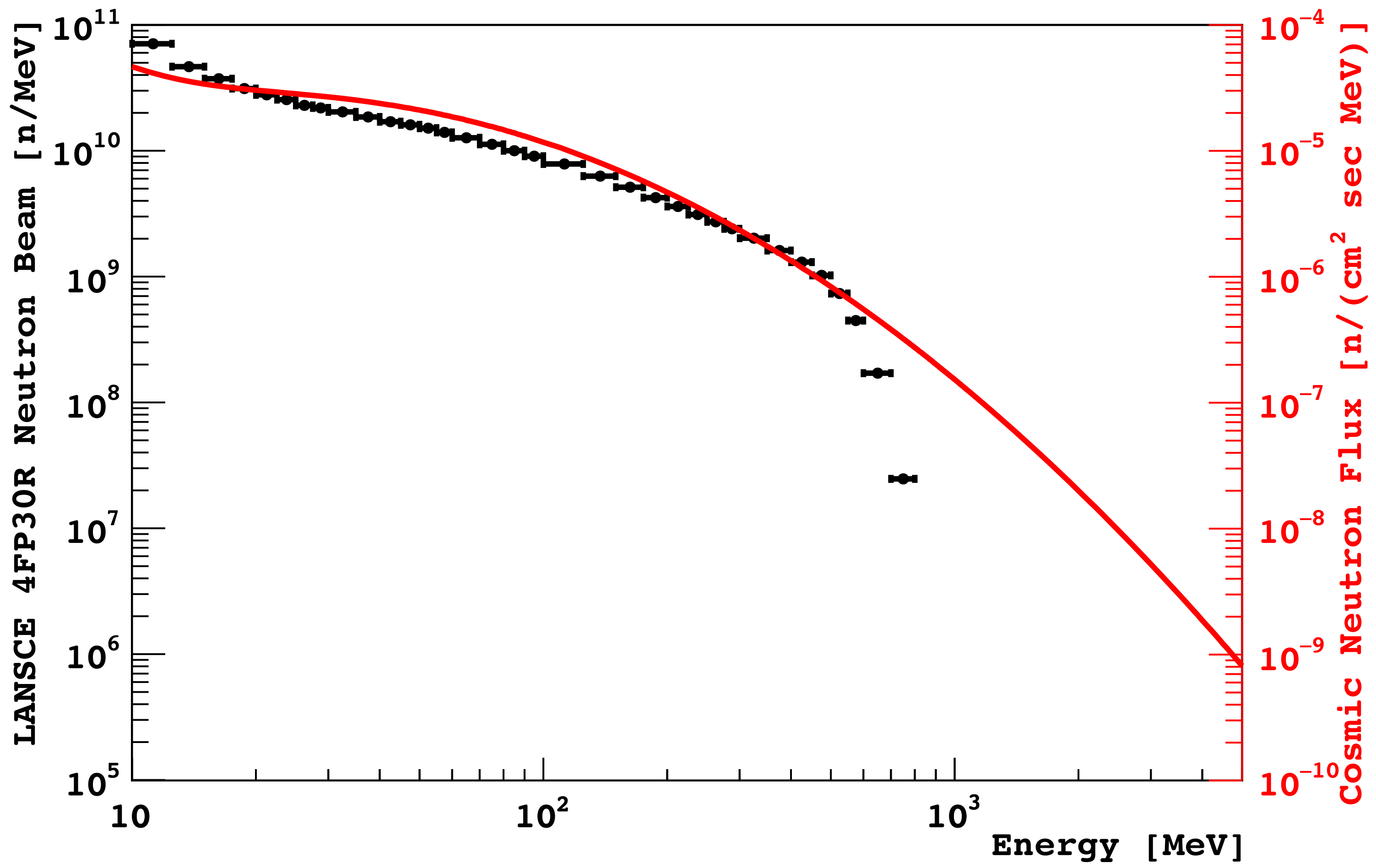


Extrapolate from measured activity to expected sea-level cosmogenic production rate



LANSCE ICE-HOUSE Neutron Beam

Los Alamos Neutron Science Center (LANSCE) Weapons Neutron Research (WNR) Facility has a neutron beam (4FP30R ICE-HOUSE II) that is very similar in spectral shape to the cosmic ray spectrum



The good agreement in spectral shape between 10–500 MeV allows for low-uncertainty extrapolations to cosmic ray activation rates

The neutron flux is roughly **$5x10^8$ times larger** than the sea-level cosmic neutron flux

1 second on beam
~ 16 years on the surface

Activation Measurements for Dark Matter Experiments

^{39}Ar, ^{37}Ar in Argon

Pacific Northwest National Laboratory · Los Alamos National Laboratory

Phys. Rev. C 100, 024608 (2019)
arXiv:1902.09072

^{3}H, ^{7}Be, ^{22}Na in Silicon

Pacific Northwest National Laboratory · Los Alamos National Laboratory · CENPA Center for Experimental Nuclear Physics and Astrophysics · KICP Kavli Institute for Cosmological Physics at The University of Chicago

Phys. Rev. D 102, 102006 (2020)
arXiv:2007.10584

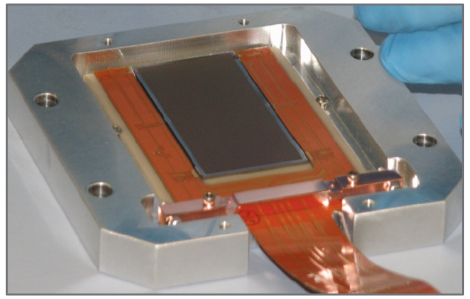
^{3}H, ^{109}Cd, ^{125}I in Sodium Iodide

Pacific Northwest National Laboratory · Los Alamos National Laboratory · Illinois University of Illinois at Urbana-Champaign · Yale · Australian National University

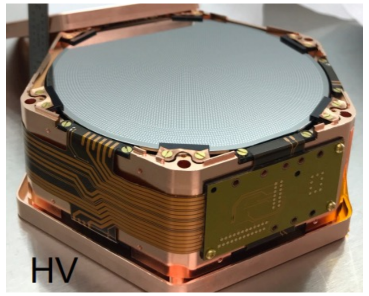
Beam Time Nov 2019
Analysis Underway

DarkSide 50

DEAP 3600



DAMIC



SuperCDMS

COSINE

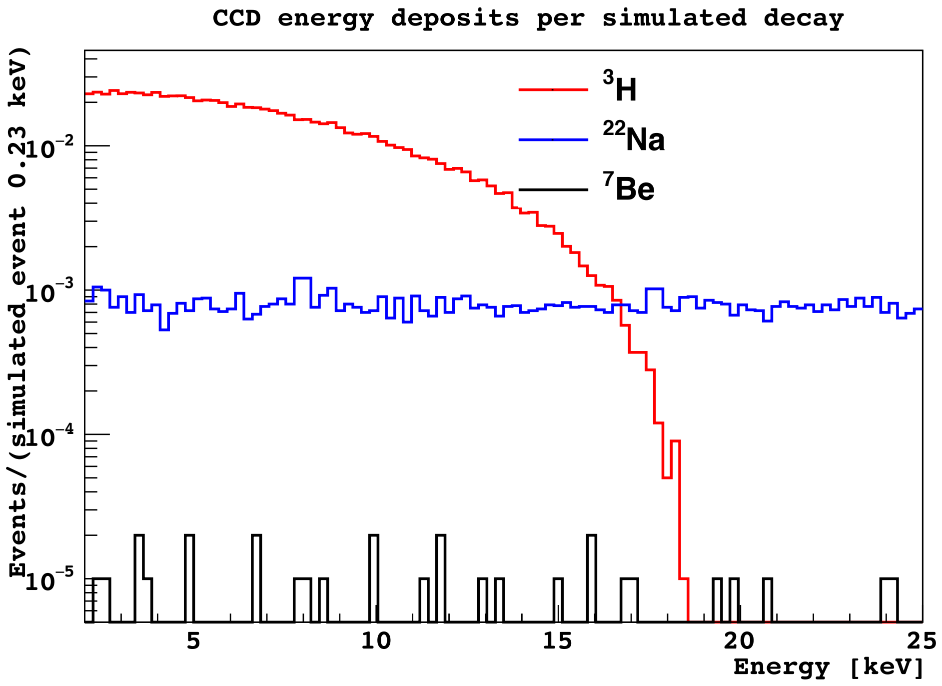
SABRE

Cosmogenic Activation of Silicon

- Searched through Table of Isotopes for all isotopes that are lighter than Si + n/p and have a half-life of more than 30 days (also checked for radioactive daughters)
- Isotopes with half-lives greater than 100 years will not build up enough activity during the typical above-ground exposure of silicon detectors (< 10 yrs) to be a significant source of background
- ^{3}H: Low-energy pure beta-emitter, most dangerous isotope for dark matter search
- ^{7}Be: Electron-capture + 480 keV gamma, very unlikely to deposit energy in CCD
- ^{22}Na: Positron emitter + 1274 keV gamma, low-level background from continuous positron spectrum

All Si activation products with half-life >30 days and any of their radioactive daughters

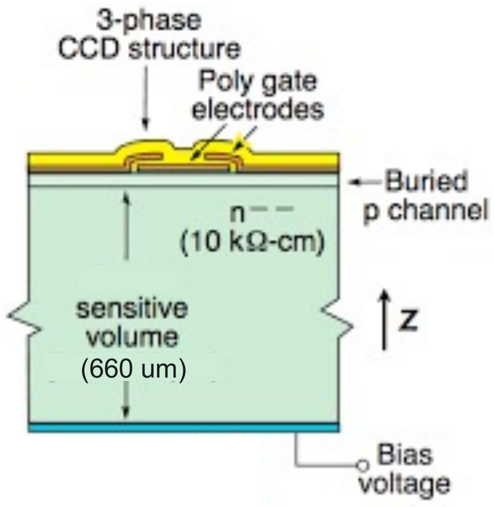
Isotope	Half-Life [yrs]	Decay Mode	Q-value [keV]
^{3}H	12.32 ± 0.02	β-	18.591 ± 0.003
^{7}Be	0.1457 ± 0.0020	EC	861.82 ± 0.02
^{10}Be	$(1.51 \pm 0.06) \times 10^{6}$	β-	556.0 ± 0.6
^{14}C	5700 ± 30	β-	156.475 ± 0.004
^{22}Na	2.6018 ± 0.0022	β+	2842.2 ± 0.2
^{26}Al	$(7.17 \pm 0.24) \times 10^{5}$	EC	4004.14 ± 6.00

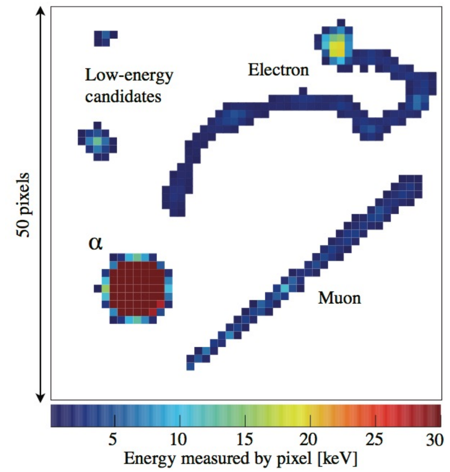


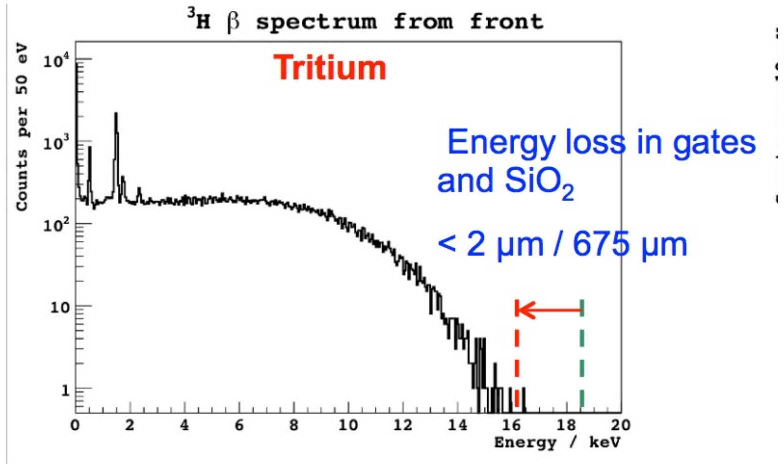
Beam Targets

CCDs have demonstrated energy thresholds, resolution, and linearity for tritium detection

- Use **silicon wafers** to measure the gamma-ray emissions from ^{22}Na and ^{7}Be and look for any other gamma-emitters
- Use **silicon CCDs** to measure the low-energy tritium beta decays and look for any other beta decays
- CCD and readout can undergo radiation damage in beam affecting dark current and charge transfer – trade off between activation and CCD performance
- Based on previous tests with SNAP CCDs* we aimed to keep maximum dose < 2×10^{8} MeV/g
- We used 3 CCDs on a 1” beam with staggered exposures to ensure we had at least one CCD that survived



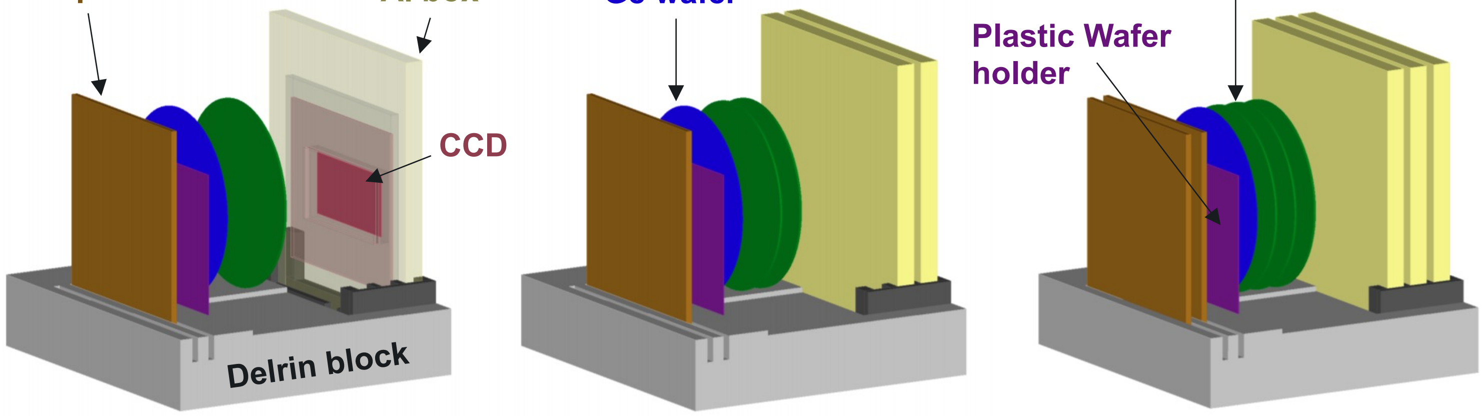




Beam Targets

Unsure about CCD performance vs. neutron damage

→3 CCDs exposed to beam for different durations



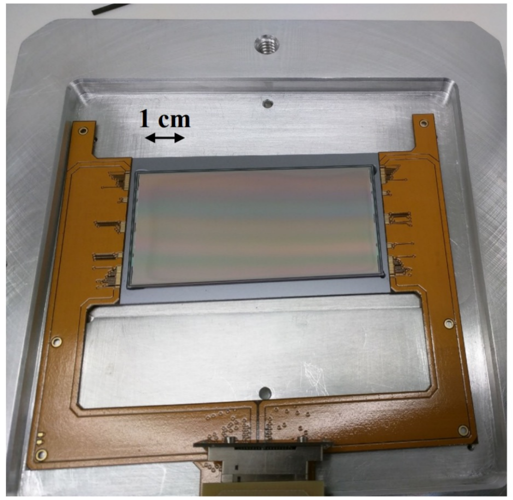
Long exposure samples

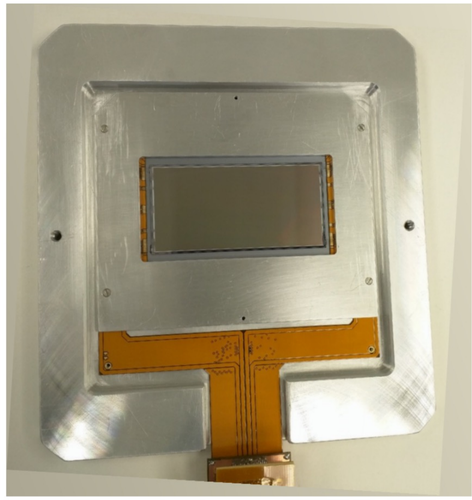
Long + medium exposure samples

Long + medium + short exposure samples

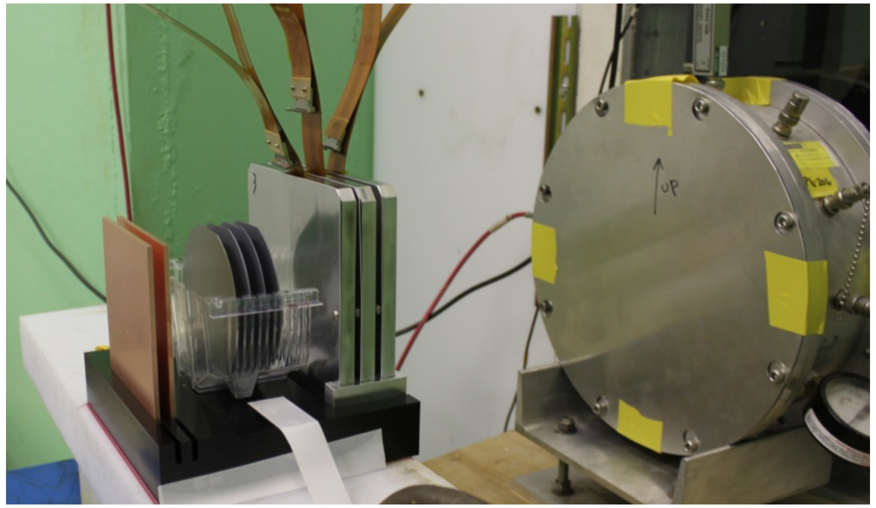
Target	Exposure Time [hrs]	Neutrons through target (> 10 MeV)
CCD 1	109.4	$(2.39 \pm 0.18) \times 10^{12}$
Wafer 1	109.4	$(2.64 \pm 0.20) \times 10^{12}$
CCD 2	62.7	$(1.42 \pm 0.11) \times 10^{12}$
Wafer 2	62.7	$(1.56 \pm 0.12) \times 10^{12}$
CCD 3	22.8	$(5.20 \pm 0.39) \times 10^{11}$
Wafer 3	22.8	$(5.72 \pm 0.43) \times 10^{11}$

DAMIC CCD in Protective Al Box





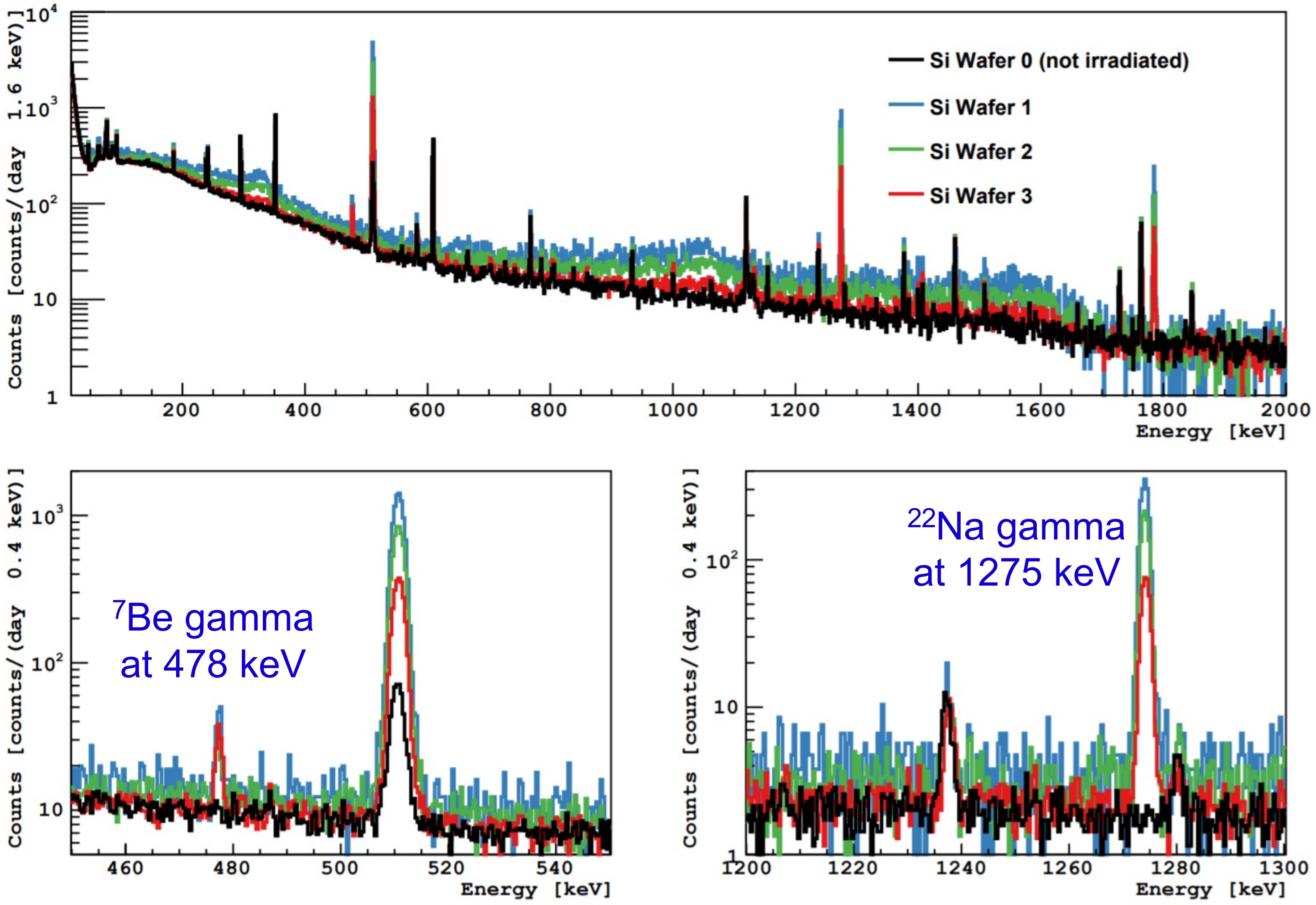
CCD kept in protective Al Box on beam line to reduce possibility of mechanical and ESD damage



Targets on beam line at LANSCE, LANL

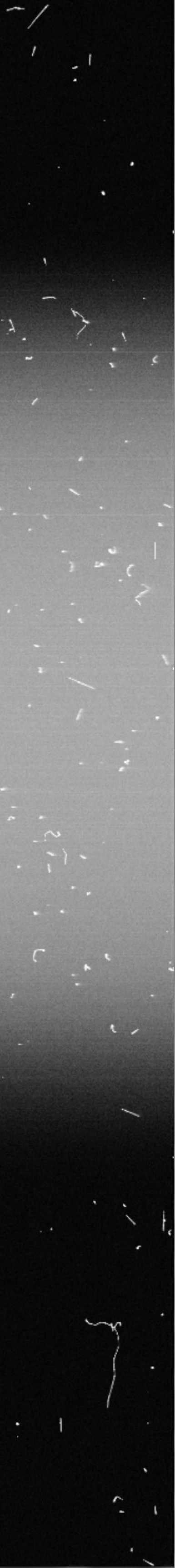
Silicon Wafer Counting

- Each CCD was paired with two Si wafers that were exposed for the same duration on the LANSCE beam
- Wafer pairs were gamma counted at PNNL on a HPGe detector in underground lab



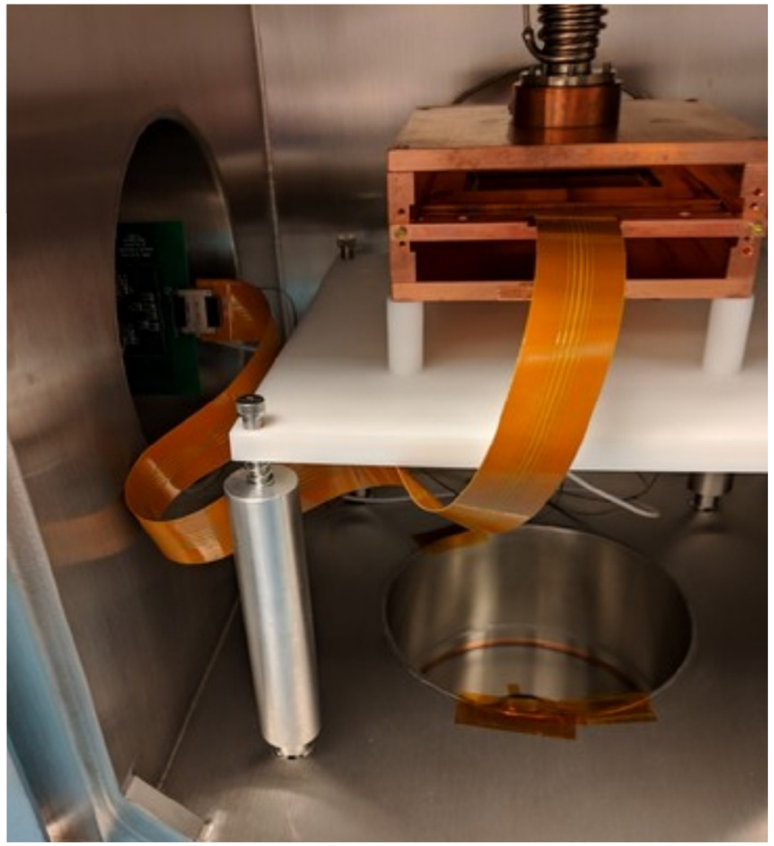
- ^{7}Be and ^{22}Na peaks visible above background
- No other peaks observed relative to unexposed Si control wafers (black spectrum)
- Lack of a peak at 1809 keV constrains ^{26}Al activation at the MDA level of HPGe detector
  - ~58x lower than ^{22}Na activation rate in wafer pair #1 (i.e., the longest-exposure wafers)

	Wafer 0	Wafer 3
Si areal density [atoms/cm^2]		
Beam to meas. time [days]	-	82.342
Ge counting time [days]	7.000	7.000
Measured ^{7}Be activity [mBq]	<40	149 ± 12
Decay-corrected ^{7}Be activity [mBq]	-	437 ± 34
Beam-avg. ^{7}Be cross section [cm^2]	-	$(1.01 \pm 0.12) \times 10^{-27}$
Measured ^{22}Na activity [mBq]	<5.1	139.5 ± 6.3
Decay-corrected ^{22}Na activity [mBq]	-	148.2 ± 6.6
Beam-avg. ^{22}Na cross section [cm^2]	-	$(6.15 \pm 0.58) \times 10^{-27}$

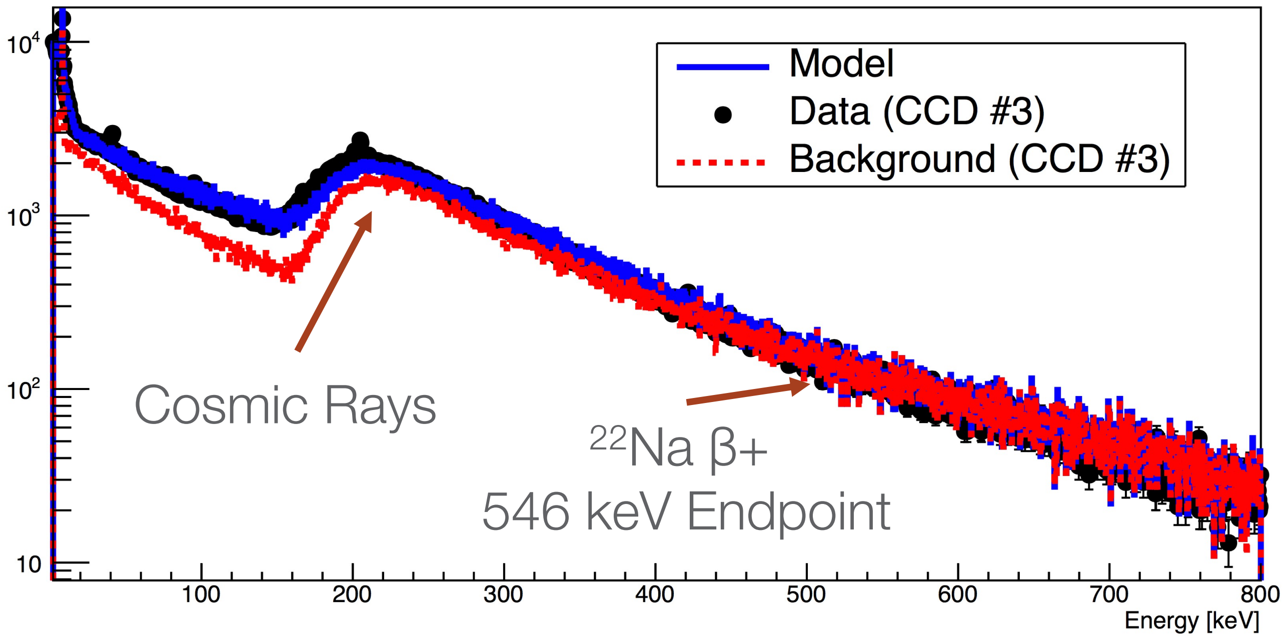


CCD Counting

- CCDs operated at University of Chicago surface lab
- Individually self-counted & compared to pre-exposure background levels
- All three CCDs show clear evidence of tritium betas and ^{22}Na positrons
- Increased CTI and dark rate required modifications to standard DAMIC analysis
- CCD3 (least irradiated CCD) was the most straightforward to analyze and is basis of the tritium measurement



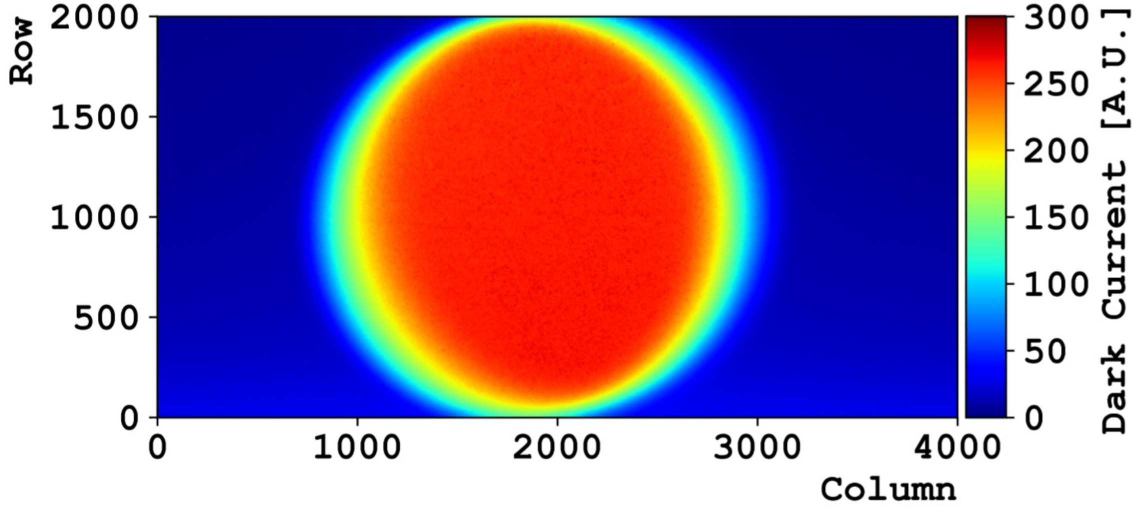
Full energy spectrum



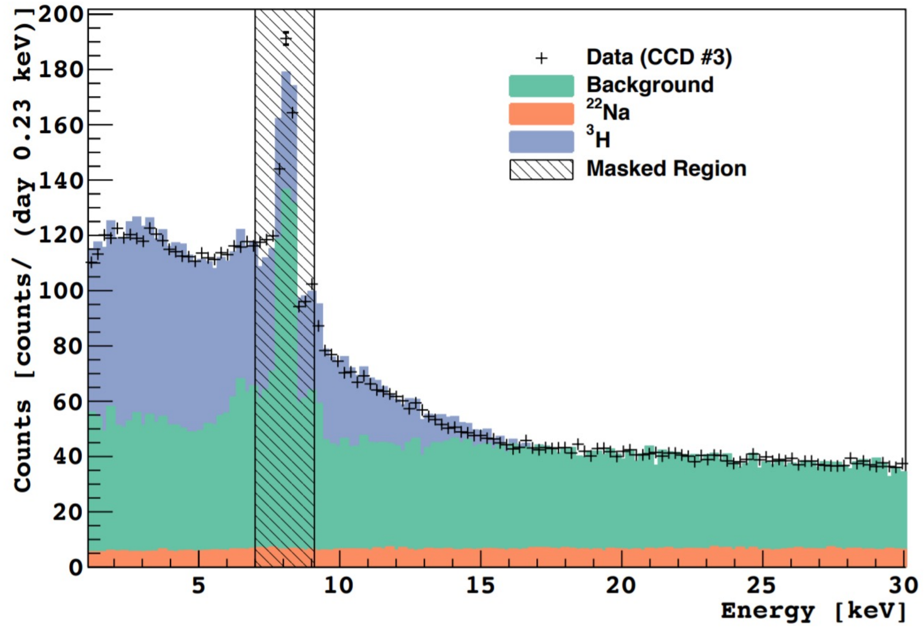
CCD Analysis

- Simulated "blank" images were created with the same noise and dark-current profile as post-irradiation data
- Ionization from Geant4-simulated decays added to images before applying full reconstruction code and analysis
- Operation, readout, analysis all follow standard DAMIC methods
- CTI modeled with constant Poissonian kernel representing charge loss for each vertical transfer (~ 9×10^{-4})
- Binned Poissonian likelihood fit of energy spectrum to determine contributions of ^{3}H and ^{22}Na

Short-exposure CCD (#3) dark current profile



Low-energy spectrum and fit



Best Fit Parameters:
Tritium: 45.7 +/- 0.5 (stat) +/- 1.5 (syst) mBq

^{22}Na: 126 +/- 5 (stat) +/- 26 (syst) mBq
(expectation from wafer: (88.5 +/- 5.3) mBq)

Cosmogenic Neutron Production Rates

What we are trying to calculate

$$P_C = \int \Phi_C(E) \cdot \sigma(E) \cdot n \cdot dE$$

P_C is the cosmogenic production rate

$\Phi_C(E)$ is the Cosmogenic neutron flux

$\sigma(E)$ is the production cross-section (UNKNOWN)

n is the number of silicon targets per unit mass

What we have measured

$$P_L = \int \Phi_L(E) \cdot \sigma(E) \cdot n \cdot dE$$

P_L is the LANSCE production rate

$\Phi_L(E)$ is the LANSCE neutron flux

IF the LANSCE neutron spectral shape was the same as the cosmogenic neutron spectral shape, then we wouldn't need to care about the cross-sections

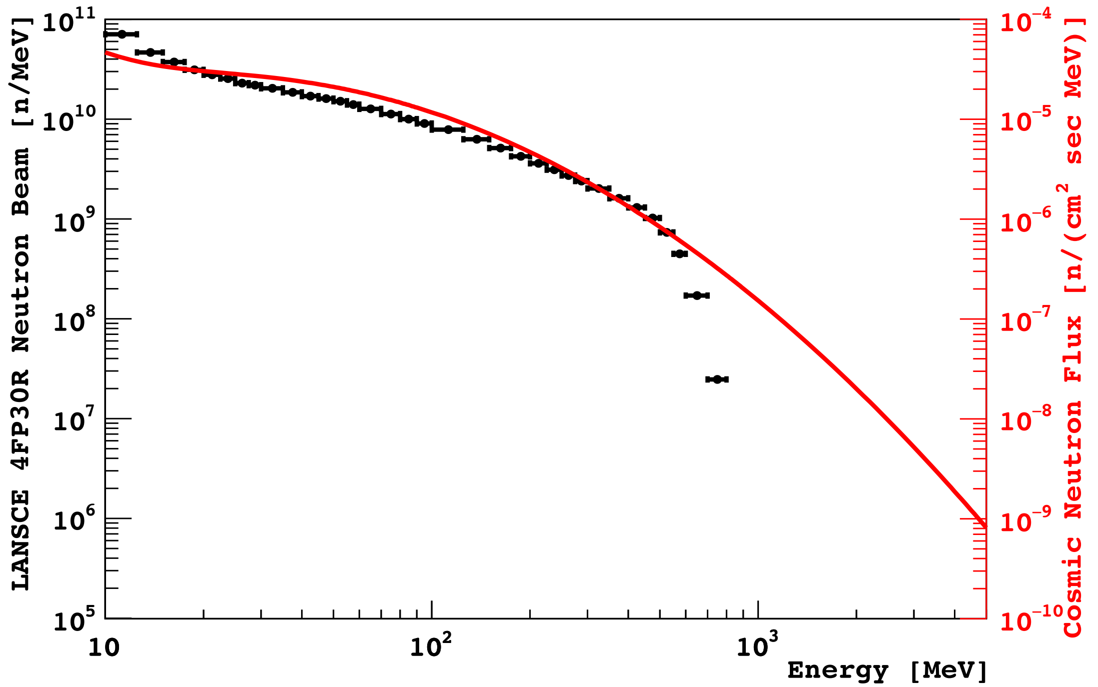
$$\text{If } \Phi_L = k \cdot \Phi_C$$

$$\text{Then } P_C = P_L / k$$

$$\text{Regardless of } \sigma(E)$$

But it is not at high energies, so

we need a cross-section model to extrapolate from P_L to P_C

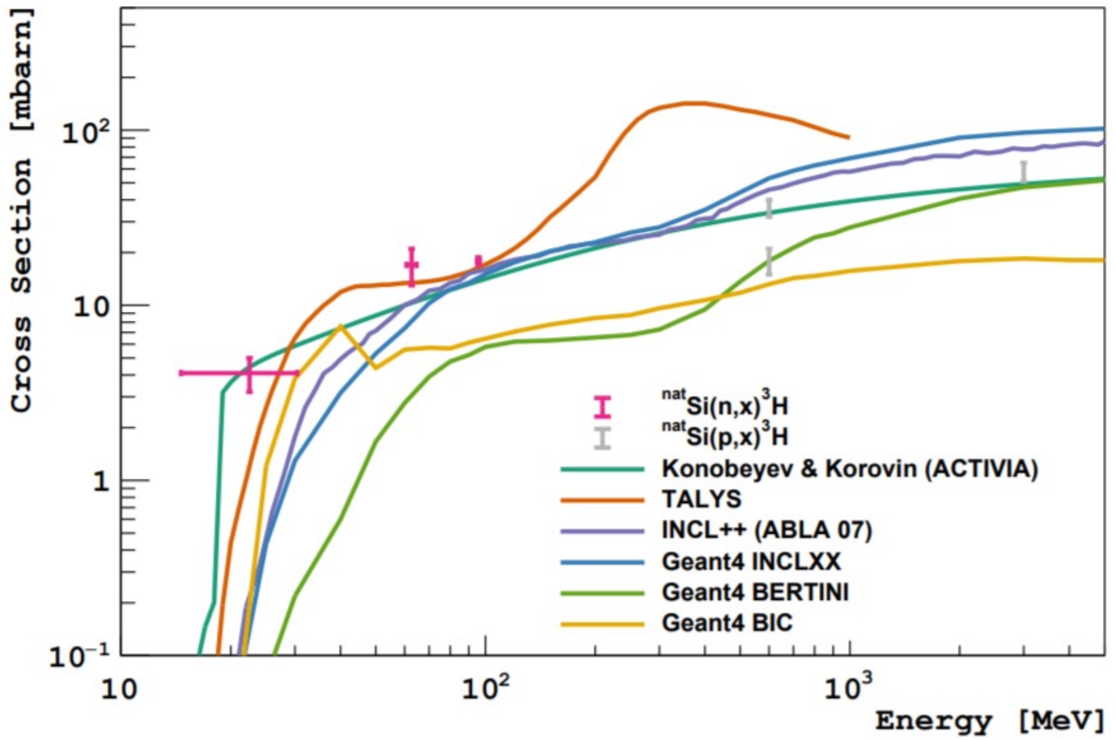


Cross-section Dependence on Neutron Energy

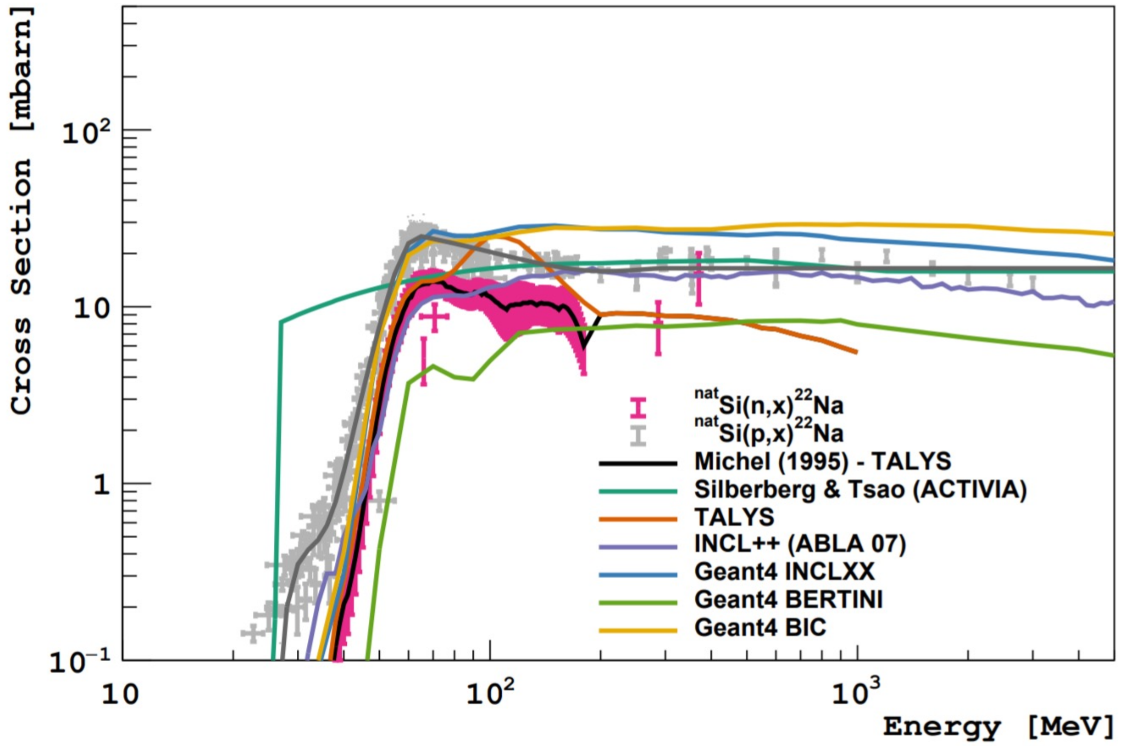
- Several models for the tritium production cross-section energy dependence
  Large difference between models … we don't know which one is correct
- Beam measurement integrates over entire spectrum:
  (i.e., no good way to unfold energy dependence)

$$P = \frac{n_a}{\tau} \int S(E) \cdot \sigma(E) \, dE$$

^{3}H models: energy dependence varies



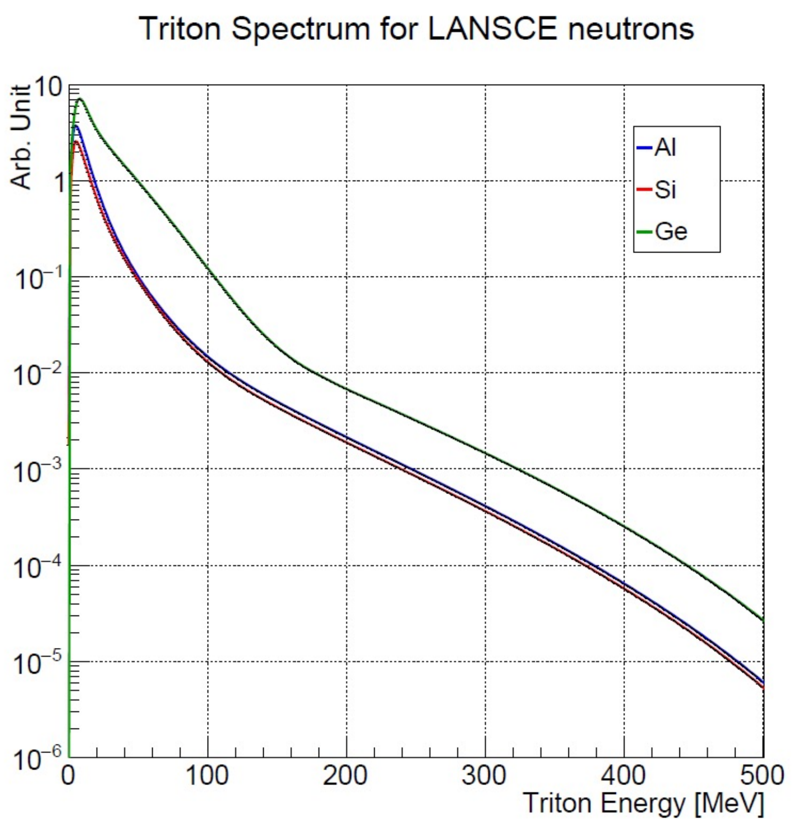
^{22}Na models: energy dependence very similar

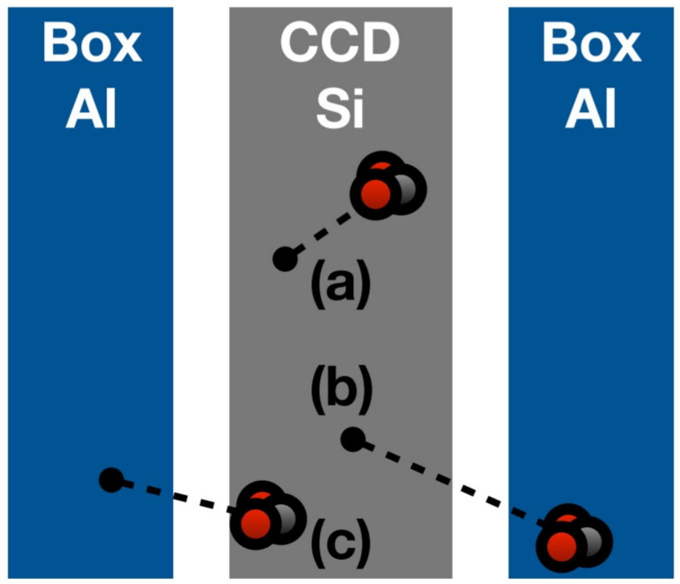


However we can use the LANSCE measurement to normalize each of the cross-section models so that they agree with the data

Triton Ejection and Implantation

- Tritons are produced with significant kinetic energy:
  - Fraction of triton produced in Si CCD are ejected
  - Fraction produced in Al boxes are implanted into CCDs
- Fraction ejected and implanted depend on initial kinetic and angular distributions as well as geometry of beam targets – needs dedicated Geant4 simulation to evaluate.





Geant4 INCLXX simulation of triton transfer

Implanted \ Produced	CCD1	CCD2	CCD3	Box1	Box2	Box3	Si1	Si2	Si3	Ge	World
World	20	12	4	91	50	19	42	21	6	41	1653
Ge	1	1	0	3	2	1	17	16	9	183	5
Si3	0	0	1	0	1	2	3	11	40	4	1
Si2	1	2	1	2	5	3	29	111	2	5	2
Si1	4	4	2	14	14	9	187	5	0	4	7
Box3	2	4	8	6	22	151	1	0	0	0	1
Box2	11	22	0	61	414	3	2	0		0	3
Box1	36	1	0	693	9	0	2			0	21
CCD3	0	1	21	1	4	10	0				0
CCD2	3	59	0	9	29	0	0				0
CCD1	98	0		47	1		0				1

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Analysis Approach

Start with multiple cross-section models

Predict triton activity ejected from CCD & triton activity implanted into CCD for each model

Calculate ratio of measured-to-predicted residual activity in CCD

Model	Pred. LANSCE ^{3}H prod. act. P_{CCD3} [mBq]	Ejected Activity E_{CCD3} [mBq]	Implanted Activity I_{CCD3} [mBq]	Pred. LANSCE ^{3}H res. act. R_{CCD3} [mBq]	Meas./Pred. ^{3}H res. act.
K&K (ACTIVIA)	40.8 ± 4.2			41.5 ± 5.4	1.10 ± 0.15
TALYS	116 ± 16	46.70 ± 0.12	53.8 ± 2.1	123 ± 17	0.370 ± 0.052
INCL++(ABLA07)	41.8 ± 4.5			42.5 ± 5.7	1.07 ± 0.15
GEANT4 BERTINI	13.0 ± 1.4	3.354 ± 0.072	3.699 ± 0.045	13.3 ± 1.5	3.43 ± 0.40
GEANT4 BIC	17.8 ± 1.7	4.995 ± 0.084	6.421 ± 0.059	19.2 ± 1.9	2.38 ± 0.25
GEANT4 INCLXX	42.3 ± 4.8	20.65 ± 0.11	16.94 ± 0.10	38.5 ± 4.4	1.19 ± 0.14

Predict total triton activity produced for each model

Predict residual triton activity in CCD for each model

For models without ejection/implantation information, use average of other models

Convert to Cosmogenic Production Rate

$$P_{Ci} = \left(\frac{P_L}{\int \Phi_L(E) \cdot \sigma_i^N(E) \cdot n \cdot dE} \right) \int \Phi_C(E) \cdot \sigma_i^N(E) \cdot n \cdot dE$$

LANSCE-measured to predicted production ratio (from previous slide)

Predicted cosmogenic production rate (uses cosmic-ray neutron spectrum instead)

This ratio normalizes each model so that it agrees with our measurement

Model	Meas./Pred. ^{3}H res. act.	Pred. Cosm. ^{3}H prod. rate [atoms/(kg d)]	Scaled Cosm. ^{3}H prod. rate [atoms/(kg d)]
K&K (ACTIVIA)	1.10 ± 0.15	98 ± 12	108 ± 20
TALYS	0.370 ± 0.052	259 ± 33	96 ± 18
INCL++(ABLA07)	1.07 ± 0.15	106 ± 13	114 ± 21
G4 BERTINI	3.43 ± 0.40	36.1 ± 4.5	124 ± 21
G4 BIC	2.38 ± 0.25	42.8 ± 5.4	102 ± 17
G4 INCLXX	1.19 ± 0.14	110 ± 14	130 ± 23

This spread is assigned as a systematic uncertainty (±10.7%)

Final Neutron-induced Cosmogenic Activations

Tritium: **112** **$\pm 14_{exp}$** **$\pm 12_{cs}$** **$\pm 14_{nf}$** atoms per kg Si per day sea-level exposure

^{7}Be: **8.1** **$\pm 1.3_{exp}$** **$\pm 1.1_{cs}$** **$\pm 1.0_{nf}$** atoms per kg Si per day sea-level exposure

^{22}Na: **43.0** **$\pm 4.6_{exp}$** **$\pm 0.4_{cs}$** **$\pm 5.4_{nf}$** atoms per kg Si per day sea-level exposure

Experimental uncertainties
(e.g., beam flux, count statistics, fits)

Neutron flux uncertainty
(i.e. cosmic flux)

Cross-section energy dependence uncertainty
(i.e., spread among different cs models)

Overall Cosmogenic Production Rates

Source	^{3}H production rate [atoms/(kg day)]	^{7}Be production rate [atoms/(kg day)]	^{22}Na production rate [atoms/(kg day)]
Neutrons	112 ± 24	8.1 ± 1.9	43.0 ± 7.1
Protons	10.0 ± 4.5	1.14 ± 0.14	3.96 ± 0.89
Gamma Rays	0.73 ± 0.51	0.118 ± 0.083	2.2 ± 1.5
Muon Capture	1.57 ± 0.92	0.09 ± 0.09	0.48 ± 0.11
Total	124 ± 24	9.4 ± 2.0	49.6 ± 7.3

Sea-level ^{3}H production rate of 124 atoms/kg/day corresponds to a background rate of ~ 0.002 dru/day in the 0-5 keV energy range.

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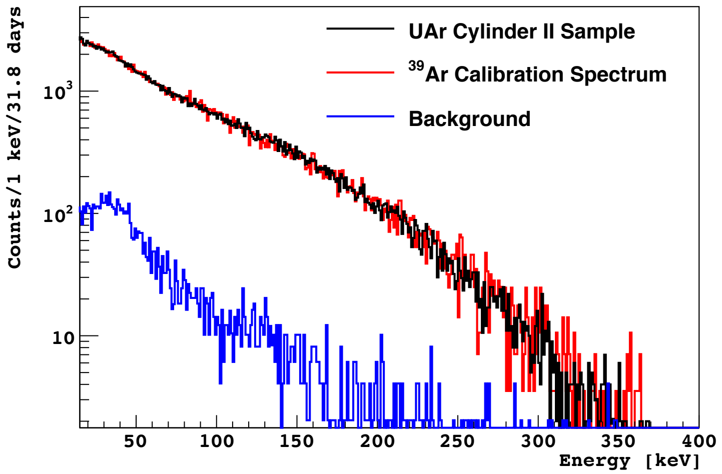
Summary

- Activation rates of critical long-lived cosmogenic isotopes are not well-known due to low production rates and low energy of decays
- We have used a method of irradiating active detector material in a high energy neutron beam and self-counting the activation products to estimate the production rates
- By irradiating silicon CCDs and wafers, we have made the first measurement of the cosmogenic production rate of ^{3}H, ^{7}Be, and ^{22}Na in silicon (Phys. Rev. D 102, 102006 (2020))

Argon

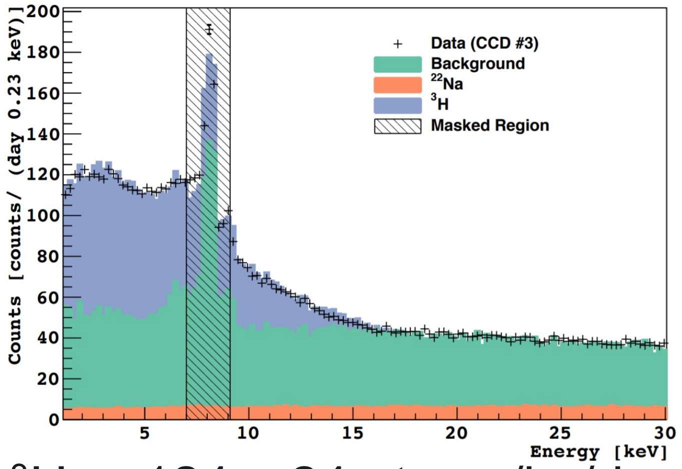


^{39}Ar: 1048 ± 133 atoms/kg/day

^{37}Ar: 92 ± 13 atoms/kg(AAr)/day

56.7 ± 7.5 atoms/kg(UAr)/day

Silicon

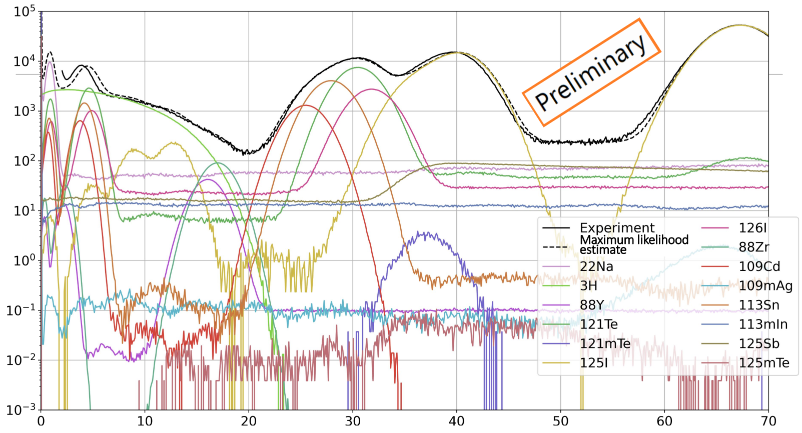


^{3}H: 124 ± 24 atoms/kg/day

^{7}Be: 9.4 ± 2.0 atoms/kg/day

^{22}Na: 49.6 ± 7.3 atoms/kg/day

Sodium Iodide



Analysis in Progress

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Thank You

PHYSICAL REVIEW D **102,** 102006 (2020)

Cosmogenic activation of silicon

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