Development of a High-Energy Two-Component Gamma Calibration Source

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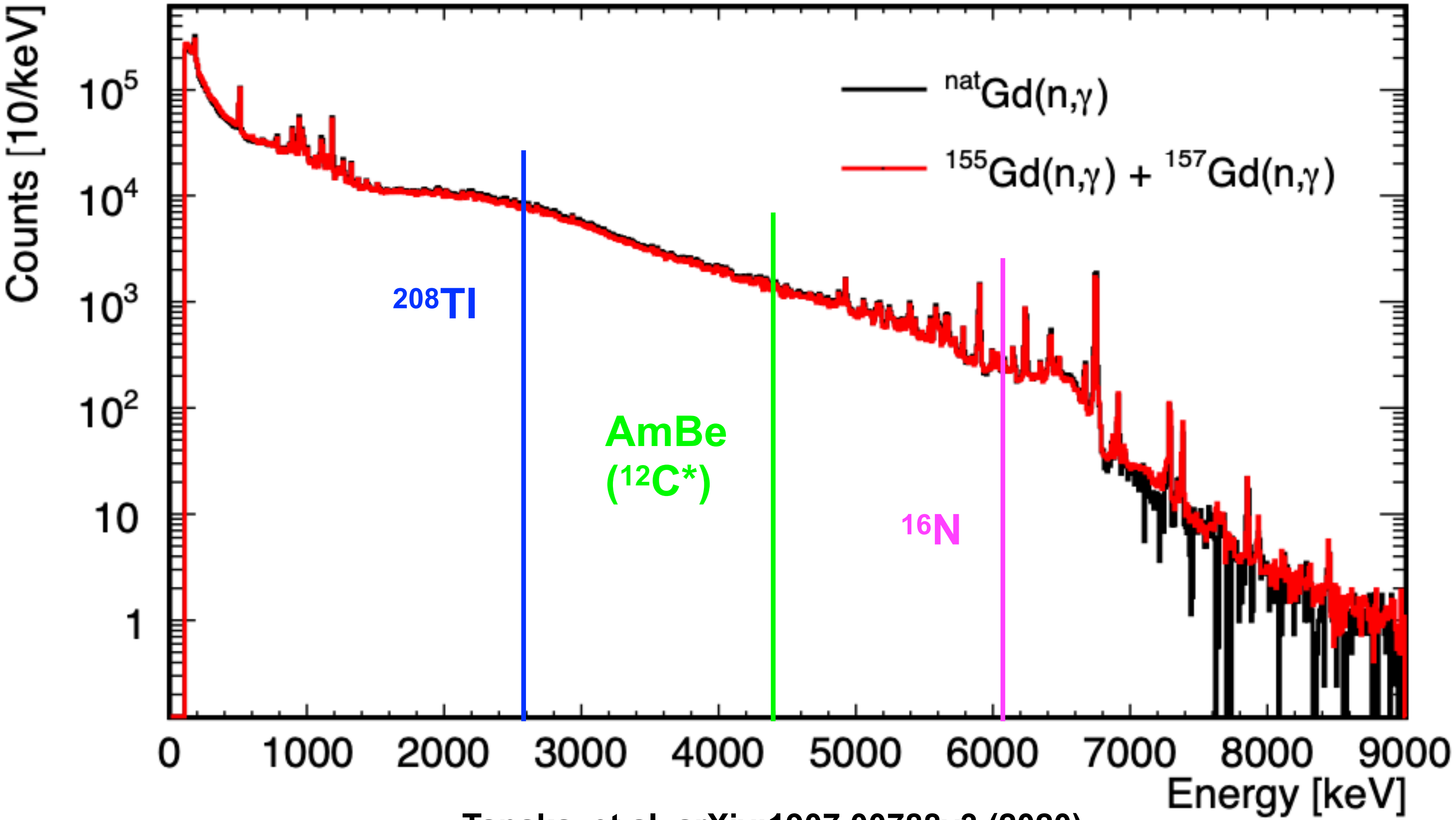
Correlated-particle sources for calibrating (large) antineutrino detectors

- **High-energy gamma rays → calibration of IBD positron response**
- **Neutrons → direct calibration of neutron capture response**
- **Correlated-particle sources → timing information improves event reconstruction**

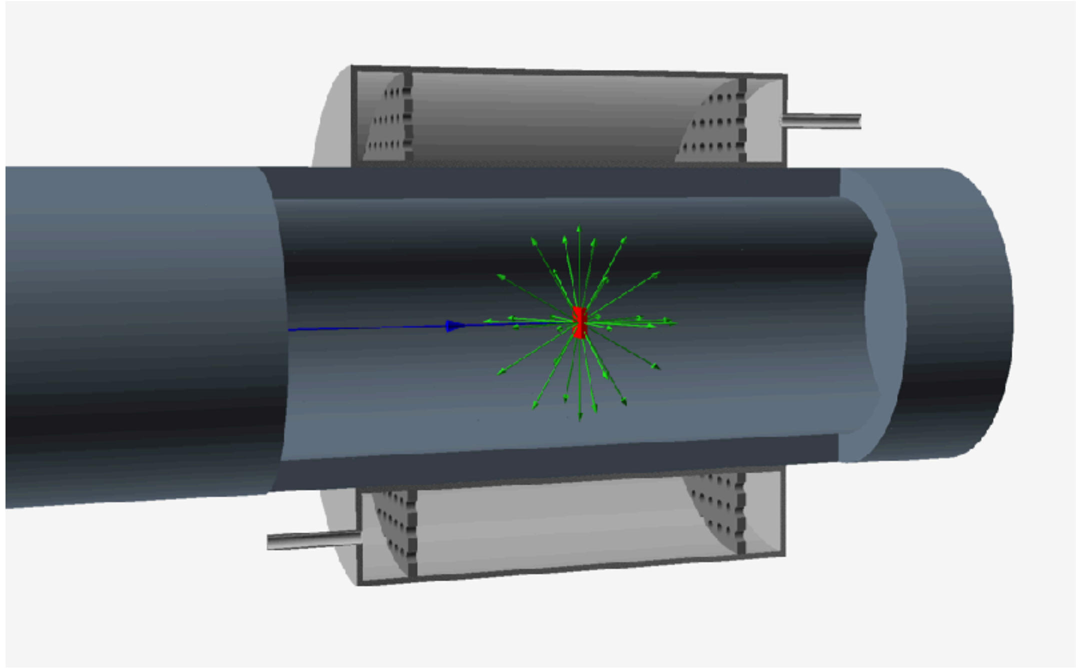
Gamma Ray Energy Spectrum from Thermal Neutron Capture on Gd



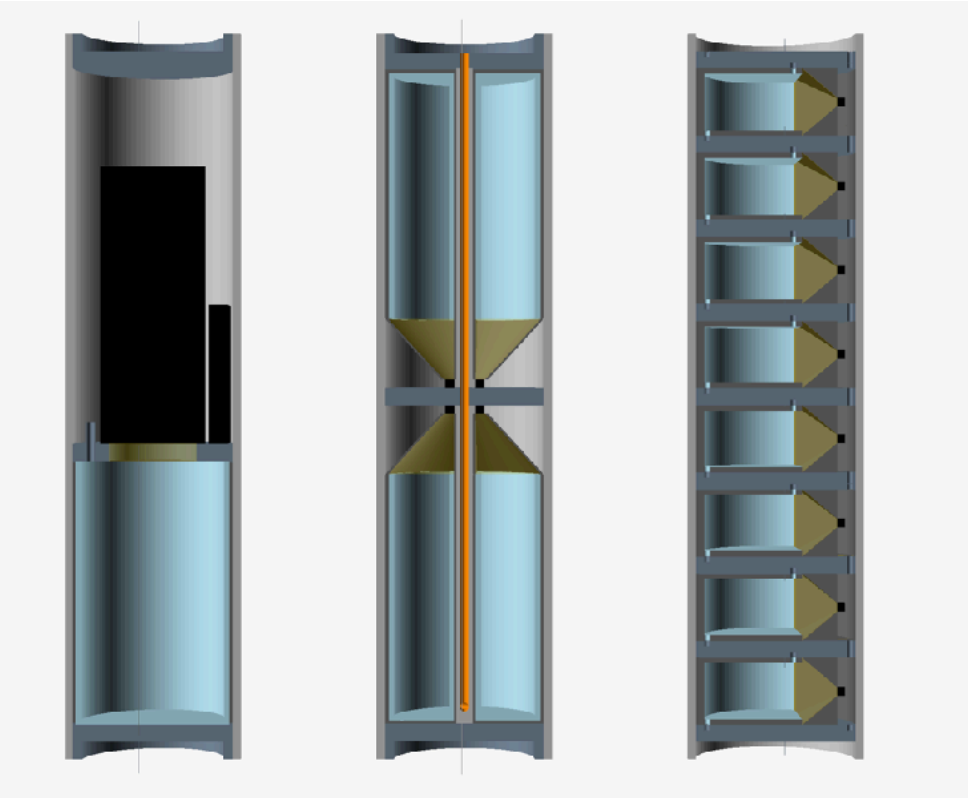
Tanaka, et al. arXiv:1907.00788v3 (2020)

^{16}N can be produced by neutron irradiation of CO_2 gas and is transferred to a decay chamber inside the detector volume

Target Chamber Design



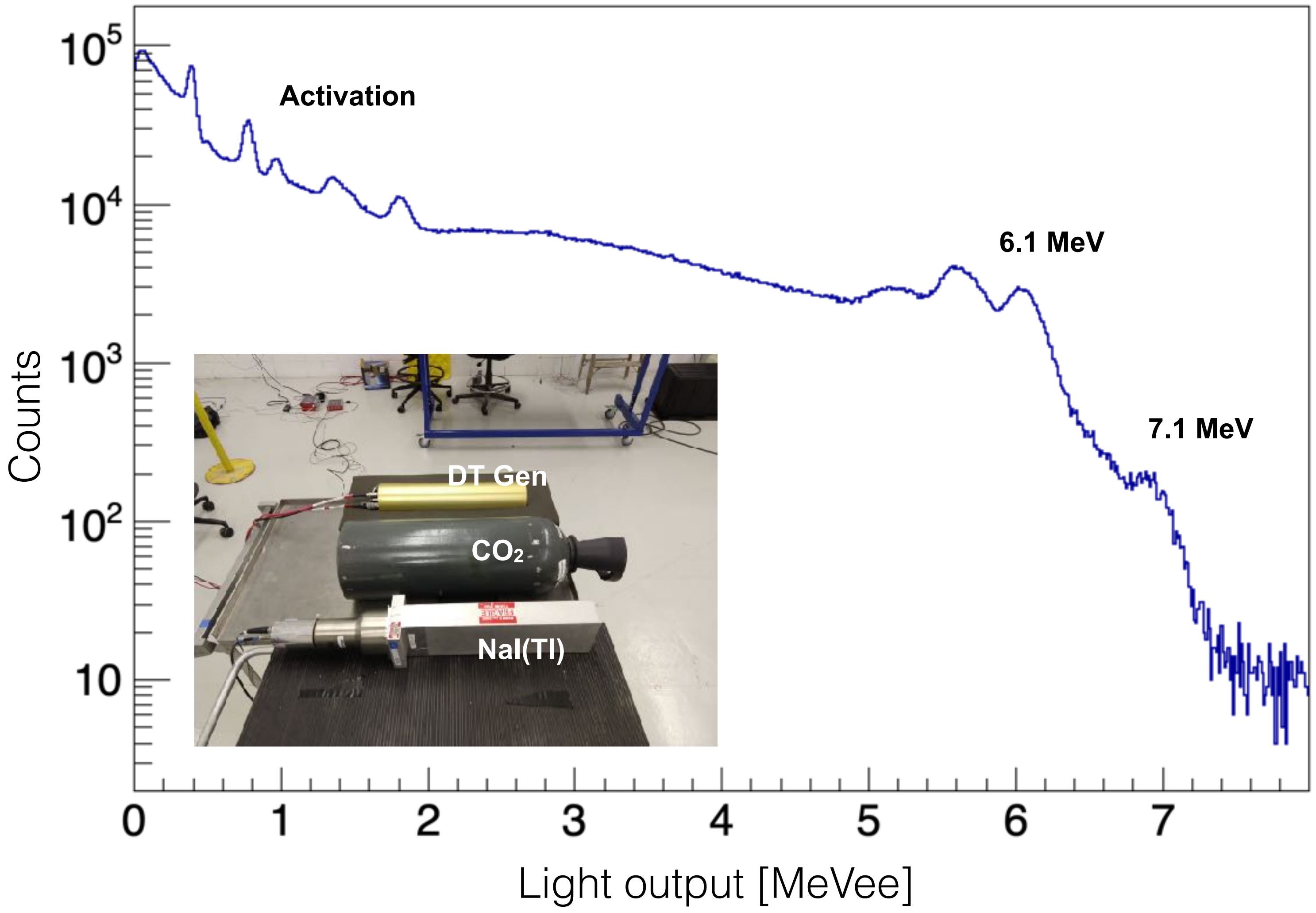
Decay Chamber Design



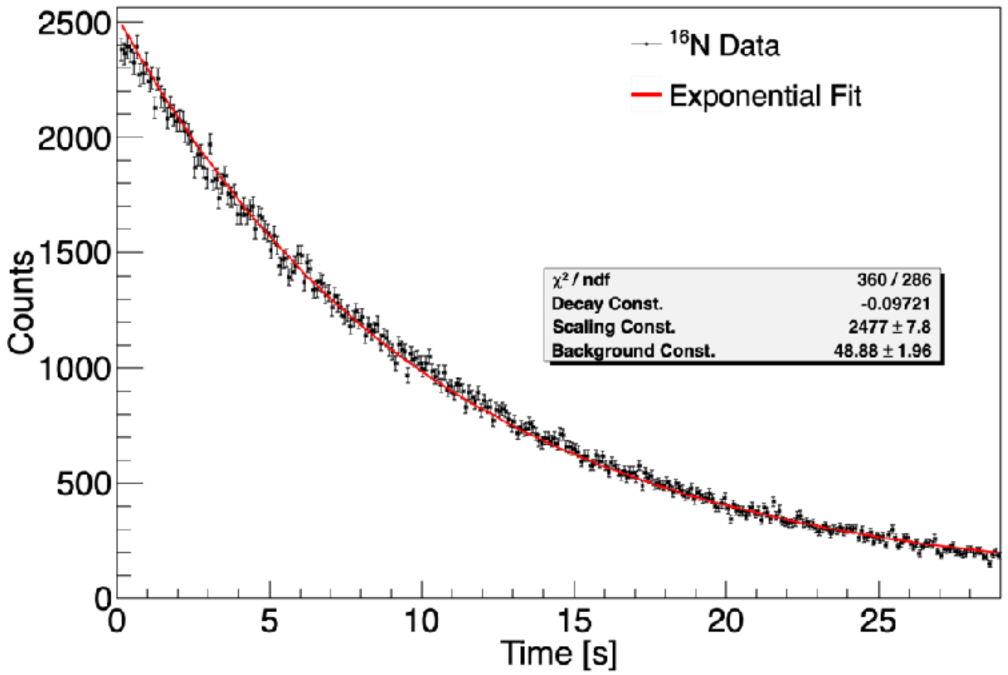
- A design for source and delivery system has been investigated in the earlier stages of AIT-NEO.
- ^{16}N is produced via $^{16}O(n,p)^{16}N$ reactions in CO_2 irradiated by a DT neutron generator.
- The decay chamber is lined with plastic scintillator to detect beta particles emitted during ^{16}N decay and provide a time-tag for the gamma-rays.
- ^{16}N has a short half-life (7.1 s), so the source must be continually replenished and cycled through the decay chamber.

We conducted modeling and production tests for $^{16}O(n,p)^{16}N$

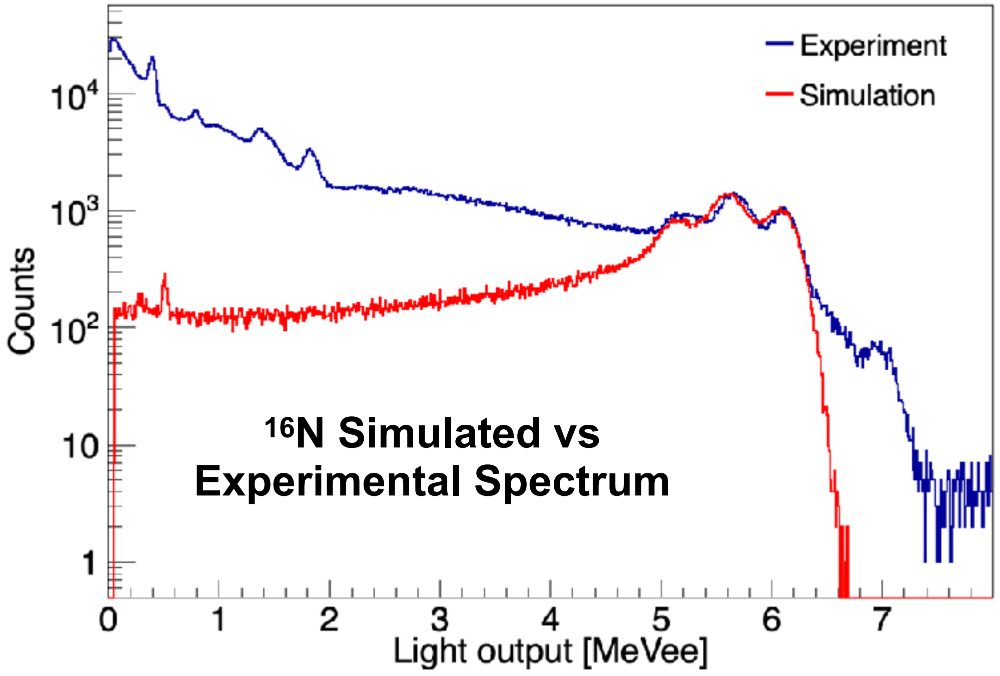
Light Output Spectrum for CO_2 Irradiated by DT Generator



Decay Time Profile for ^{16}N

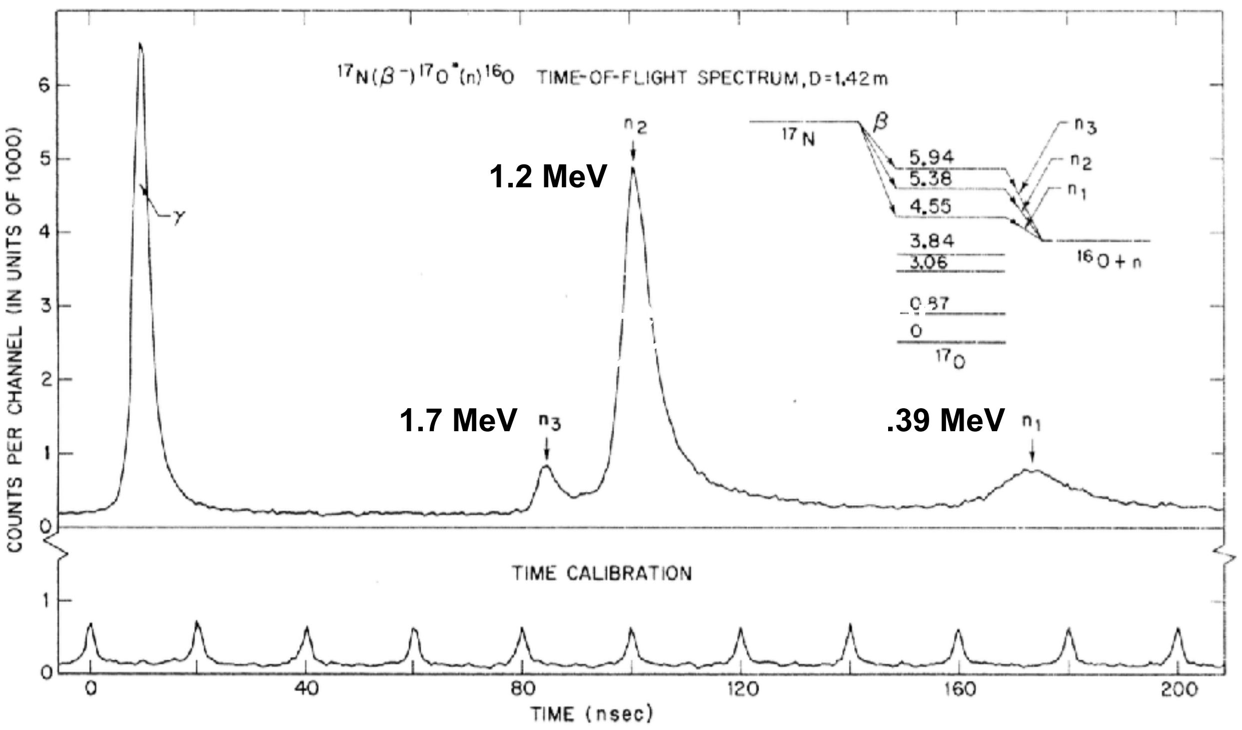


χ^2 / ndf	360 / 286
Decay Const.	-0.09721
Scaling Const.	2477 ± 7.8
Background Const.	48.88 ± 1.96

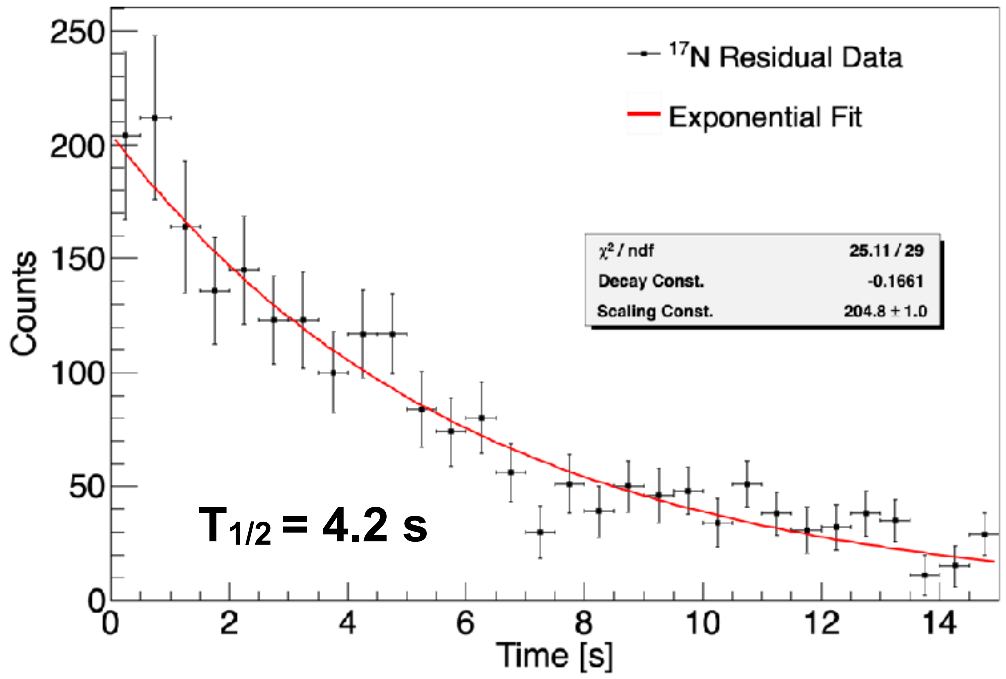


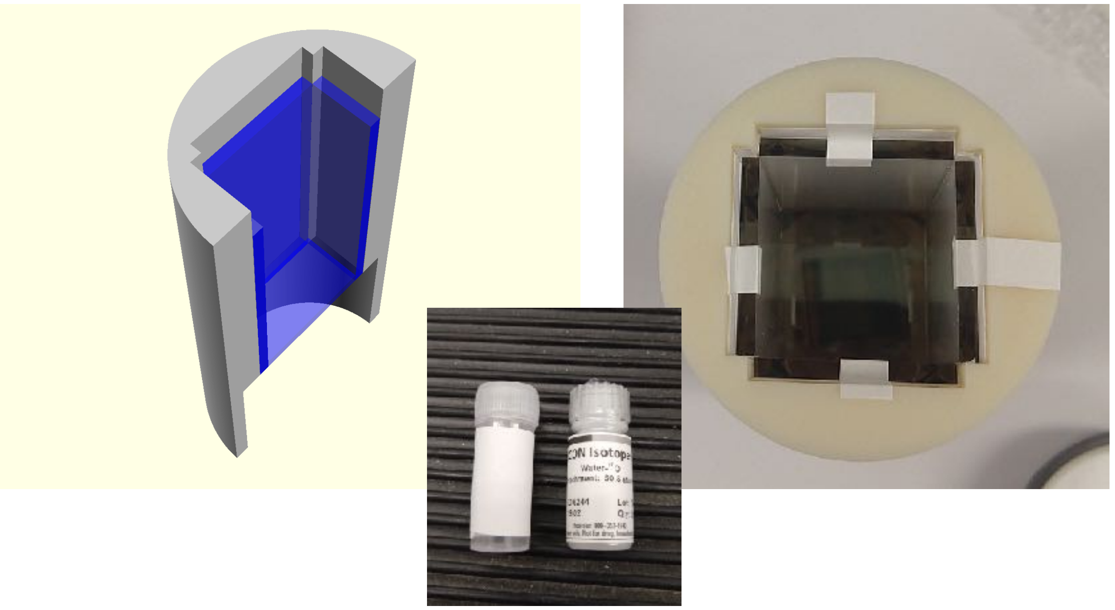
^{16}N Simulated vs Experimental Spectrum

CO$_2$ system can be adapted to produce delayed neutrons

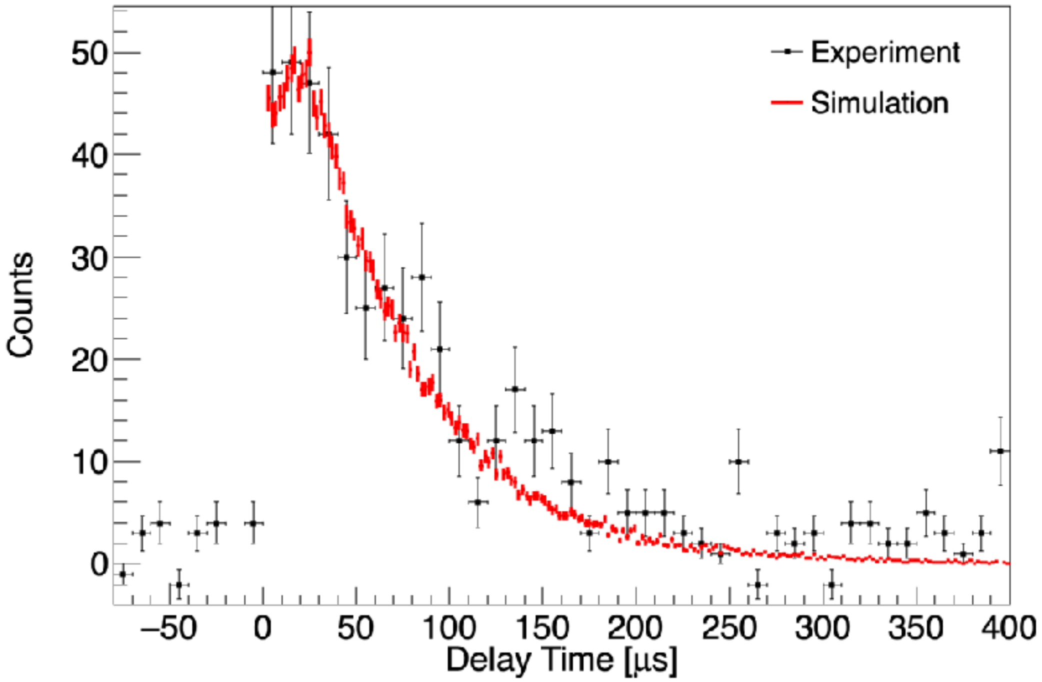


^{17}N Delayed Neutron Time Profile





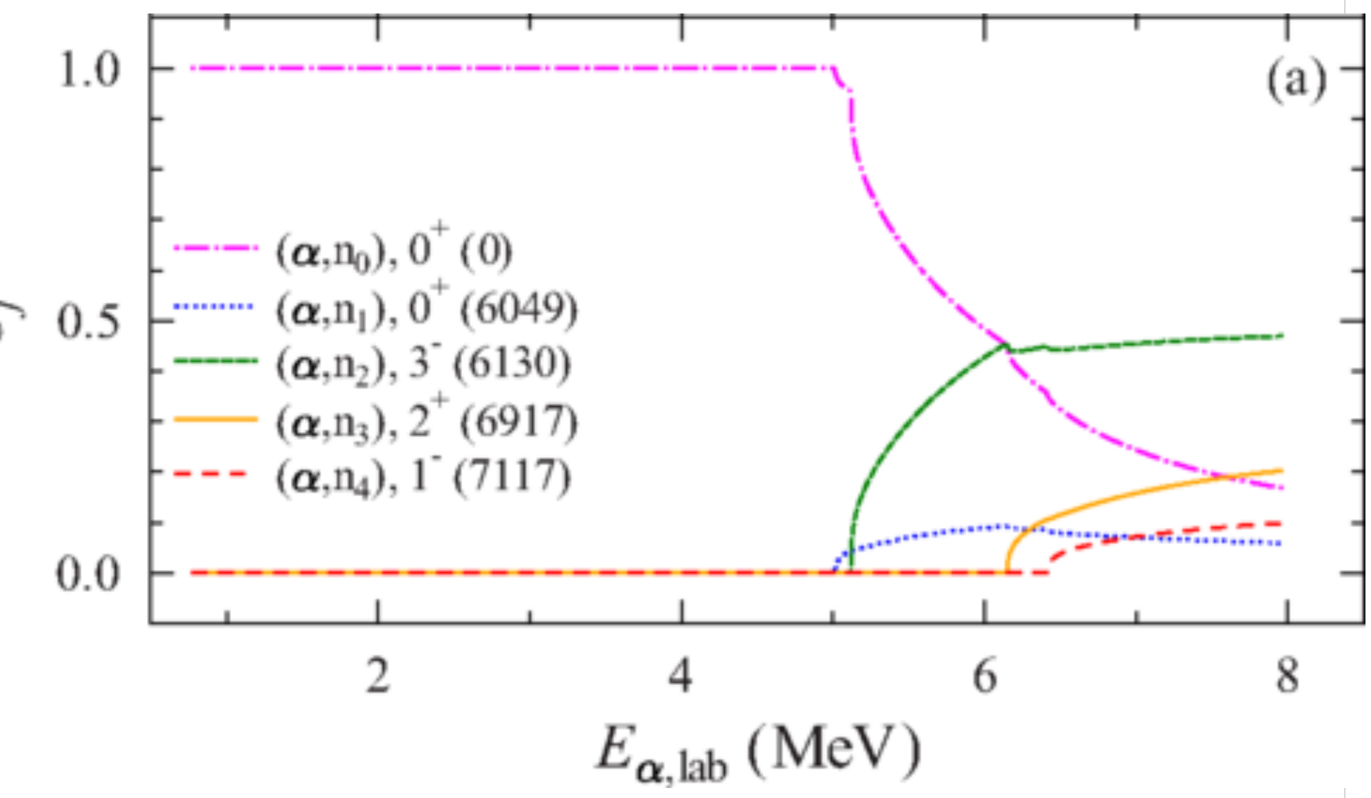
^{17}N Beta-Neutron Coincidence Time Distribution



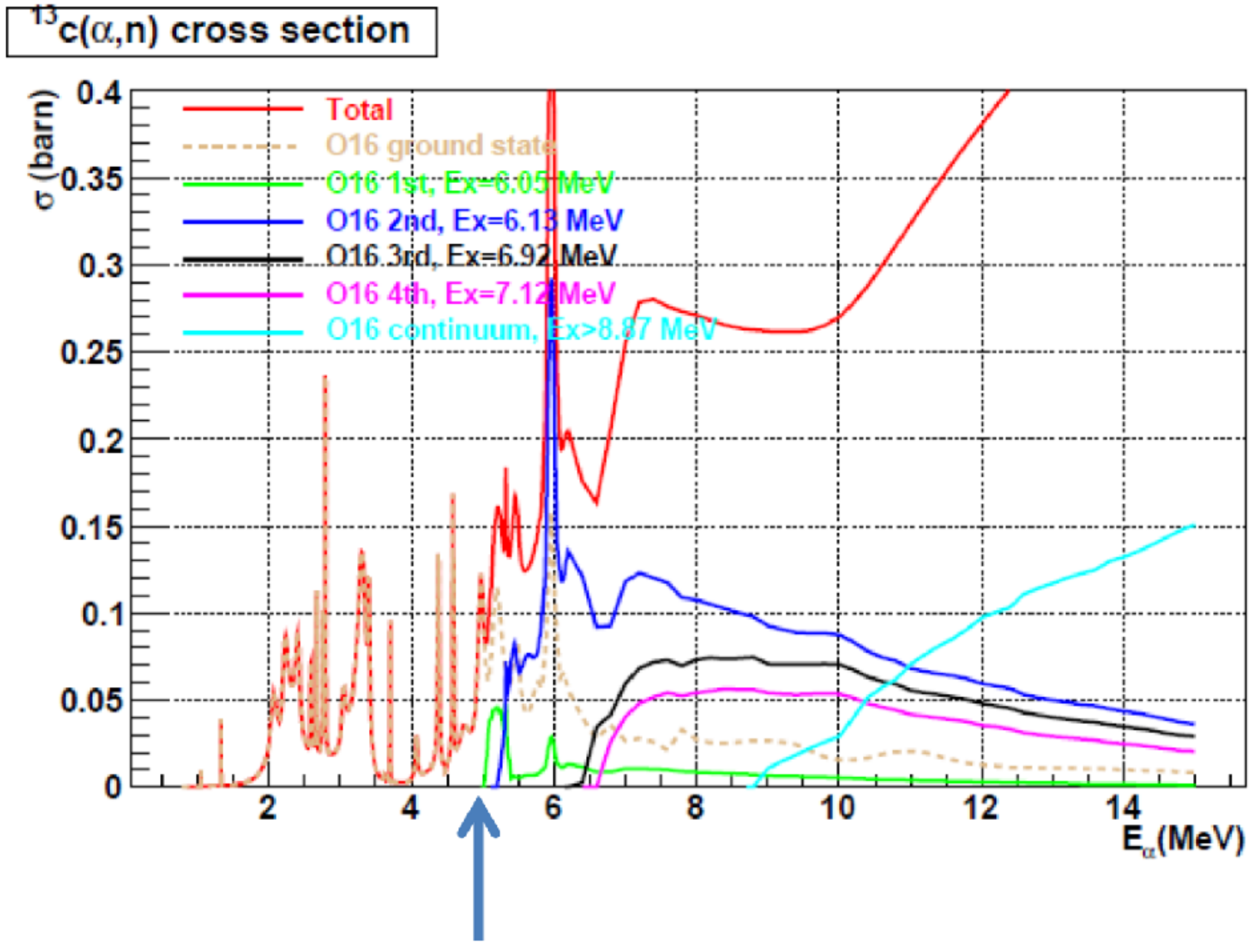
K. Ogren, A. Kavner, S. Dazeley, and I. Jovanovic, NIM A 1033, 166654 (2022).

$^{13}C(\alpha,n)^{16}O$ could provide an alternative source of 6.1-MeV gamma rays correlated with neutrons

$^{13}C(\alpha,n)^{16}O$ branching ratios



P. Mohr. 10.1103/PhysRevC.97.064613



^{16}O excited state threshold

Cross-section for $^{13}C(\alpha,n)^{16}O$ is about 170 mb at 5.5 MeV (JANIS).

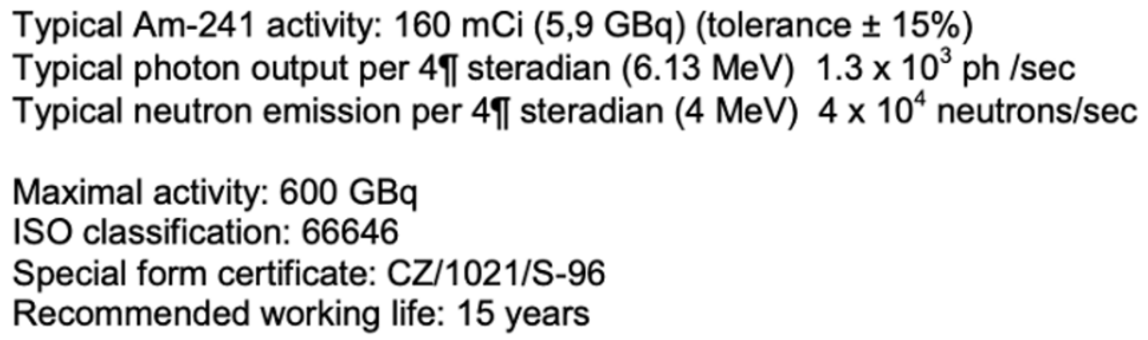
Branching ratio to 6.1-MeV ^{16}O excited state is about ~30% for alpha energy of ~5.5 MeV.

Eckert and Ziegler commercial radioisotope source

This special source is prepared from a homogenous mixture of the ^{241}Am and ^{13}C powder which is compacted and double encapsulated in stainless steel. The capsules are sealed by tungsten inert gas welding.

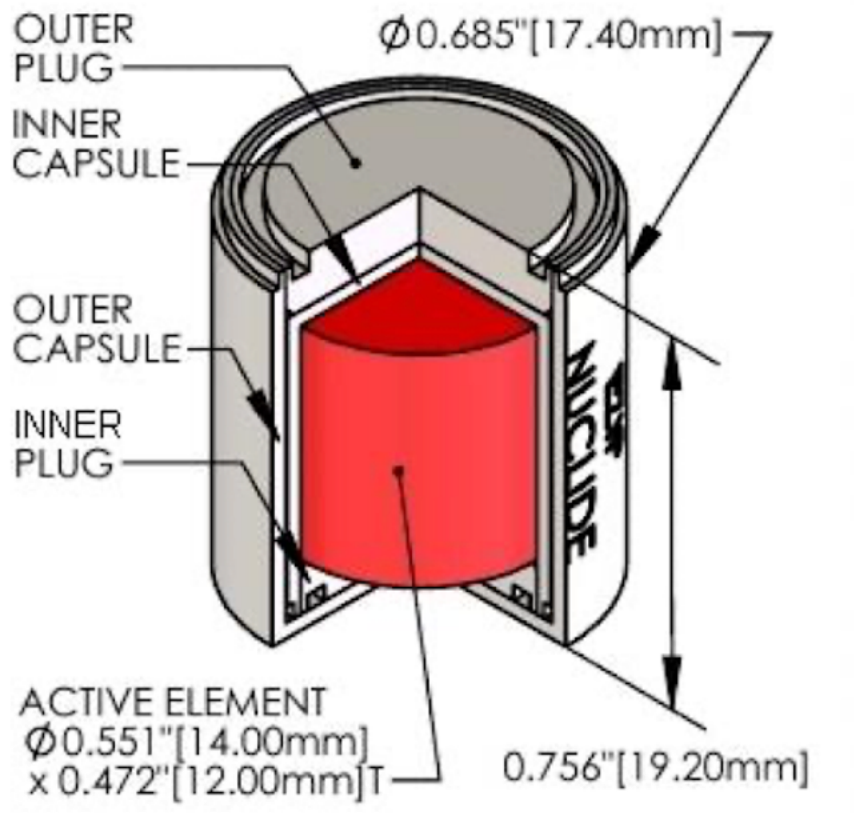
Gamma/neutron ratio: ~3%

$70k



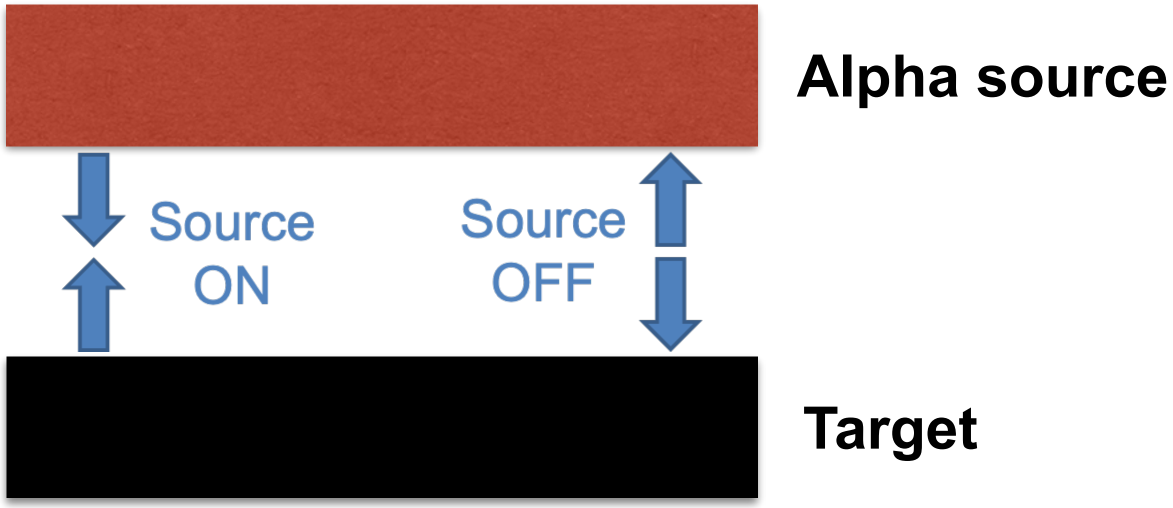
Typical Am-241 activity: 160 mCi (5,9 GBq) (tolerance ± 15%)
Typical photon output per 4¶ steradian (6.13 MeV) 1.3 x 10^3 ph /sec
Typical neutron emission per 4¶ steradian (4 MeV) 4 x 10^4 neutrons/sec

Maximal activity: 600 GBq
ISO classification: 66646
Special form certificate: CZ/1021/S-96
Recommended working life: 15 years



Eckert & Ziegler

Alternative: an "actuated" radioisotope calibration source



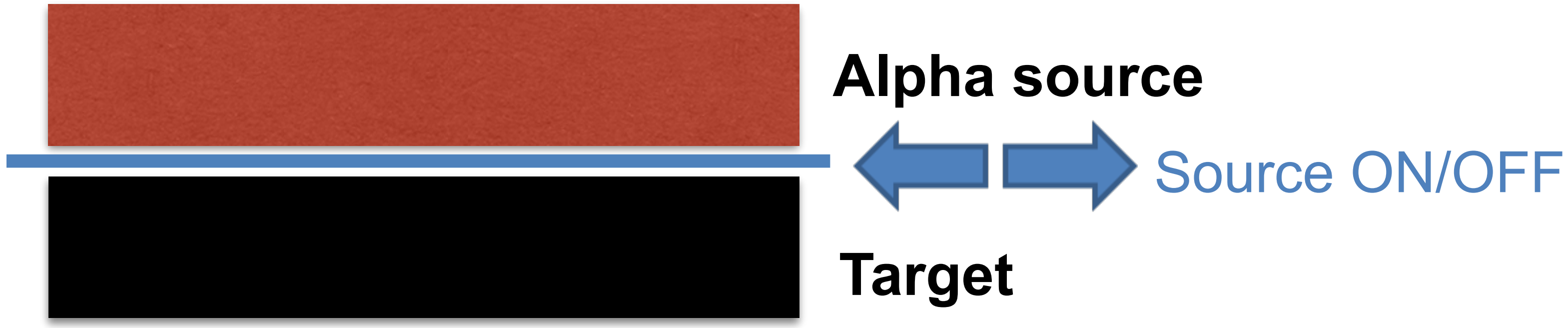
Alpha source

Source ON

Source OFF

Target

- Control over gamma/neutron ratio by source design (alpha stopping)
- Permanent placement in the detector?
- No bulky shielding required for storage as in the case of ^{252}Cf or AmBe
- Tagging in main detector volume or in dedicated detector



Alpha source

Source ON/OFF

Target

Daya Bay ^{241}Am^{13}C neutron source

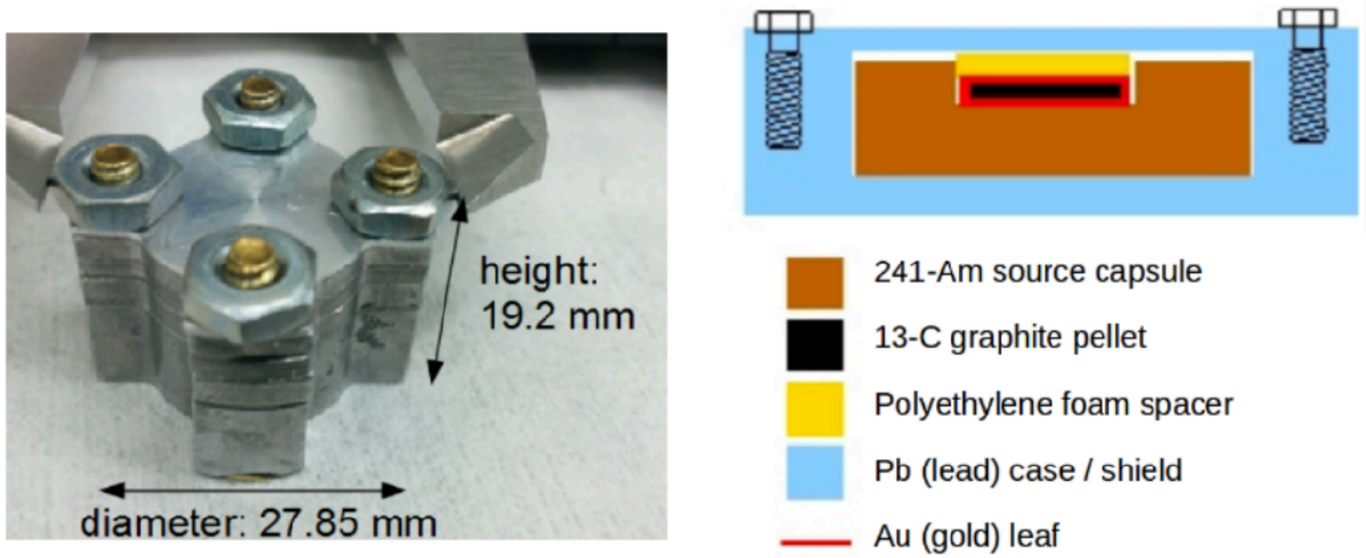


Figure 6.4: *Left*: Fully assembled source capsule. *Right:* Schematic of the AmC source components, viewed from the side.

E. Ludert. Detailed characterization of nuclear recoil pulse shape discrimination in the DarkSide-50 direct dark matter experiment. University of Hawaii. 2017.

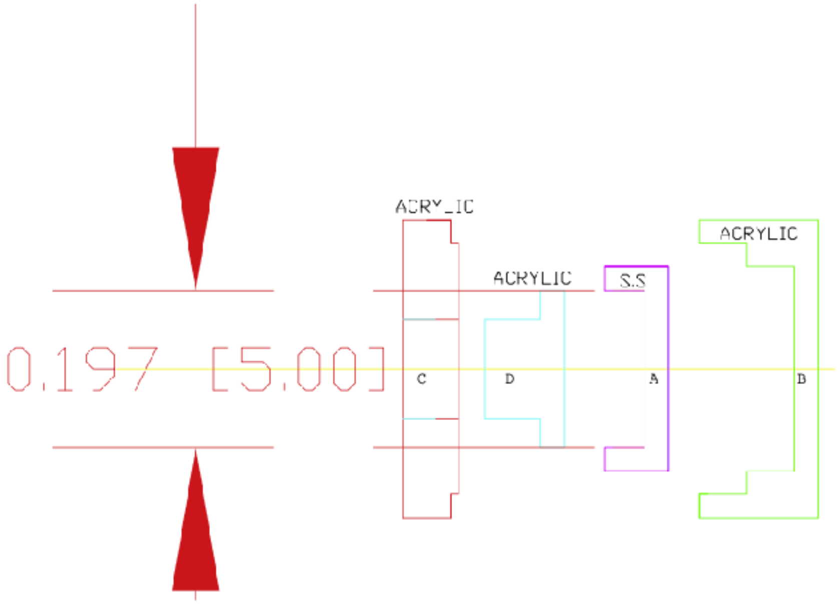
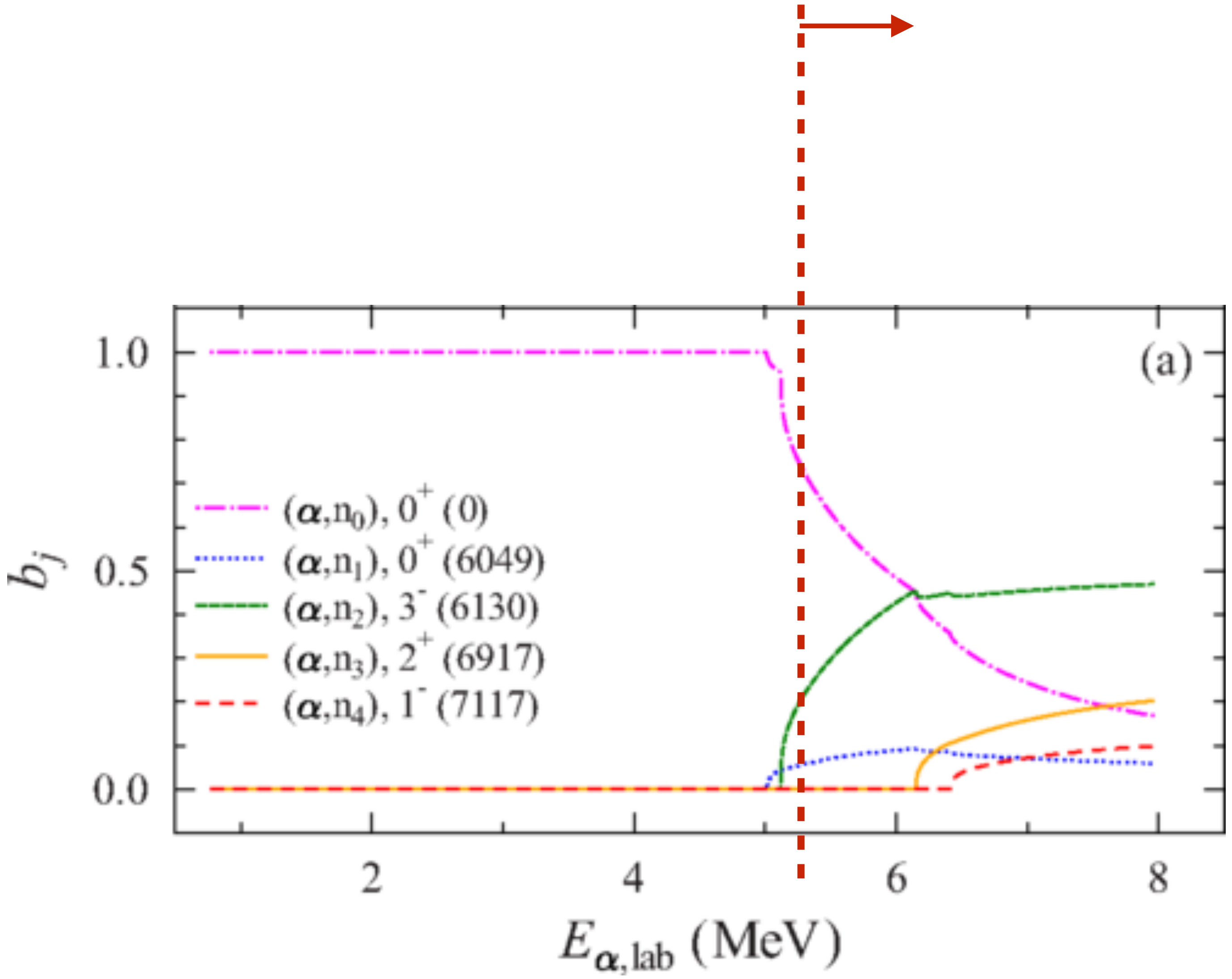


Fig. 3. Mechanical drawing of the ^{241}Am–^{13}C source assembly. See text for more details.

- **Previous ^{241}Am^{13}C source designs have used a gold foil between the Am and C to reduce alpha energy and avoid gamma ray emission**
- **In the Daya Bay design (right), the ^{241}Am, foil, and ^{13}C are sandwiched tightly and pressed into a stainless steel cup by an acrylic plunger**
- **We have been attempting to do the opposite: avoid reducing the alpha energy and thus maximize the chance for 6.1-MeV gamma emission**

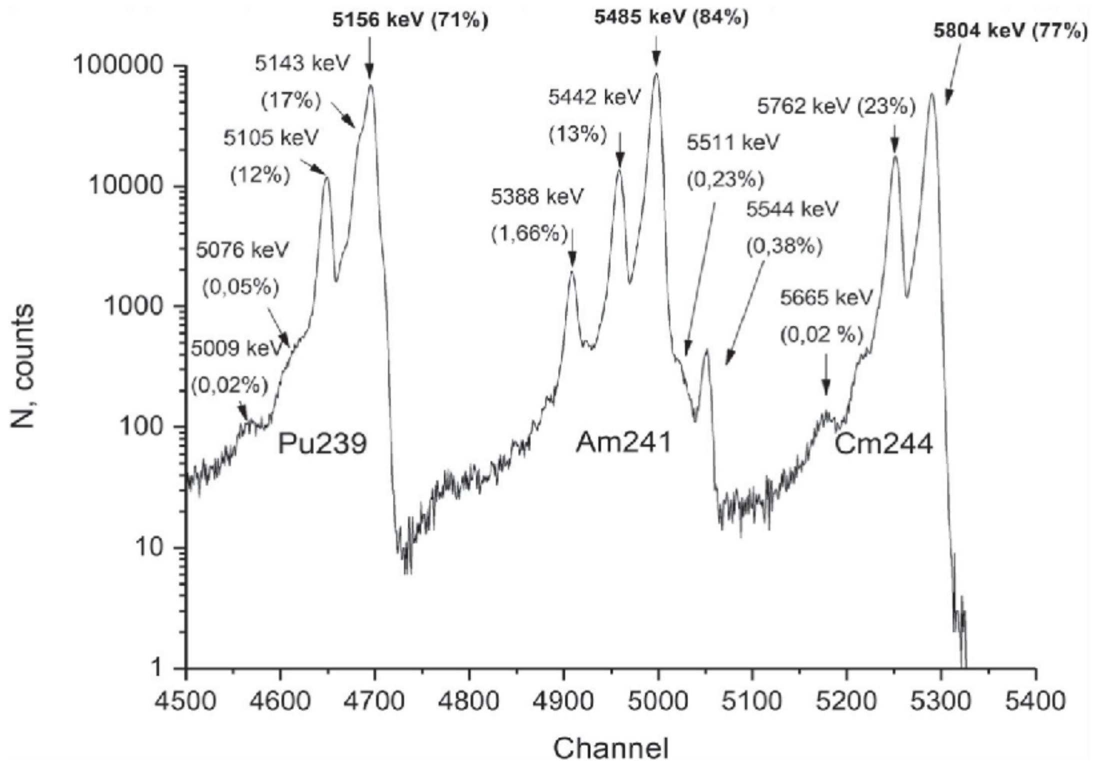
Candidate alpha sources

Design source such that $E_\alpha \gtrsim 5$ MeV in ^{13}C



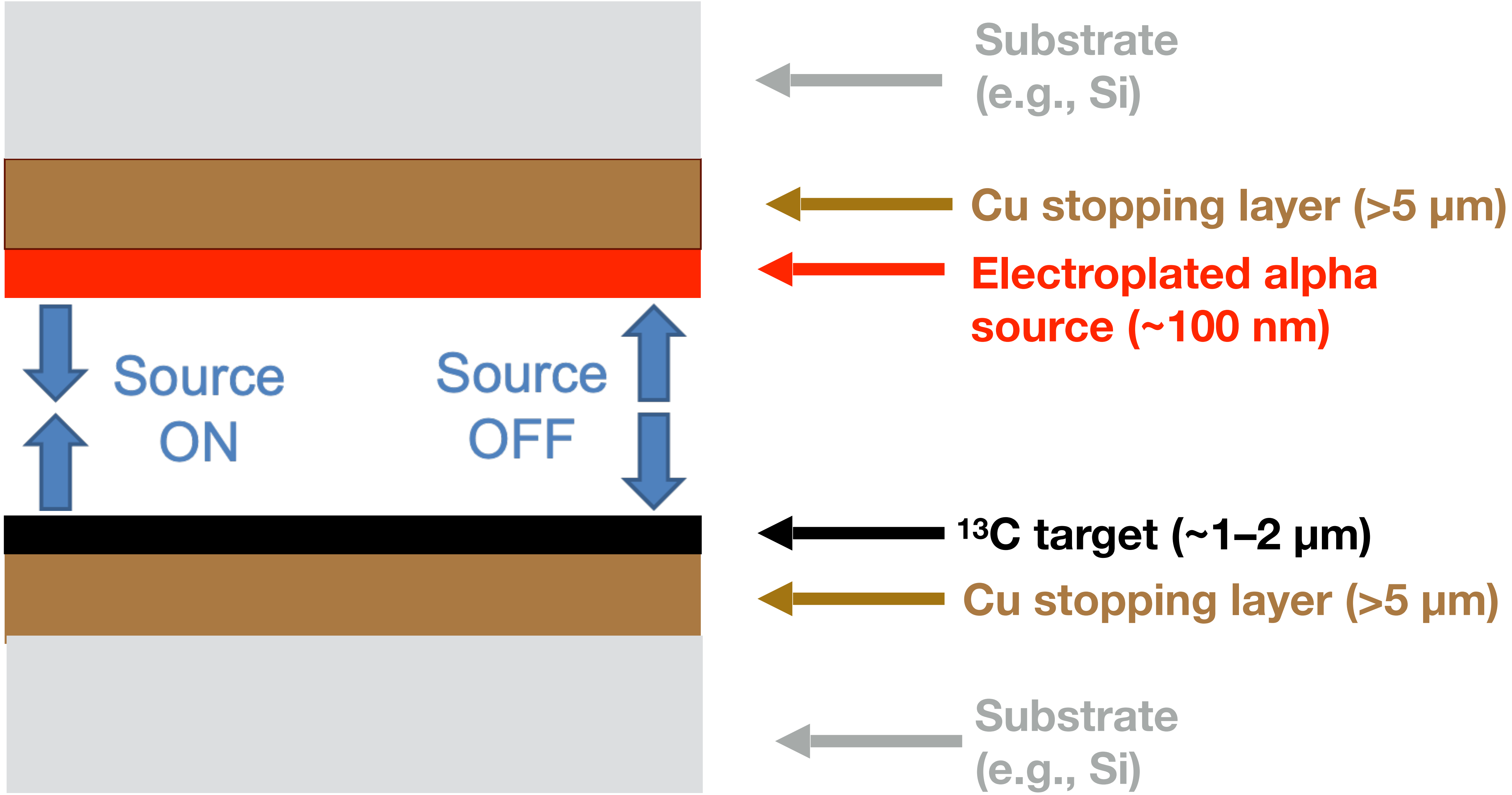
Alpha energy

^{244}Cm (5.8 MeV)
^{238}Pu (5.6 MeV)
^{241}Am (5.5 MeV)
^{210}Po (5.41 MeV)
^{239}Pu (5.2 MeV)



We have to consider not only the alpha energy requirement but also the specific activity and regulatory controls.

Conceptual source design



Substrate (e.g., Si)

Cu stopping layer (>5 μm)

Electroplated alpha source (~100 nm)

^{13}C target (~1–2 μm)

Cu stopping layer (>5 μm)

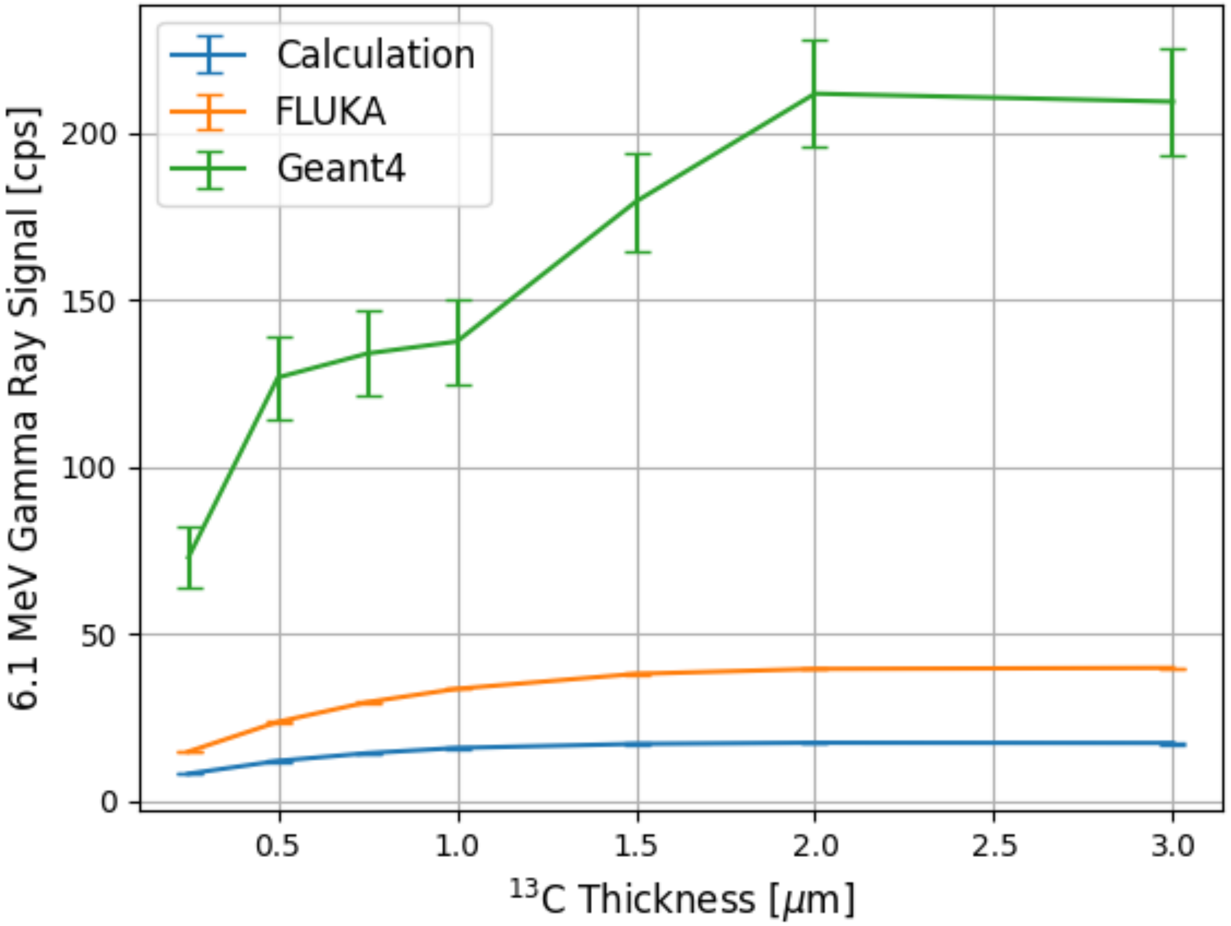
Substrate (e.g., Si)

Copper selected to minimize (α,n) – no neutron production below ~8 MeV

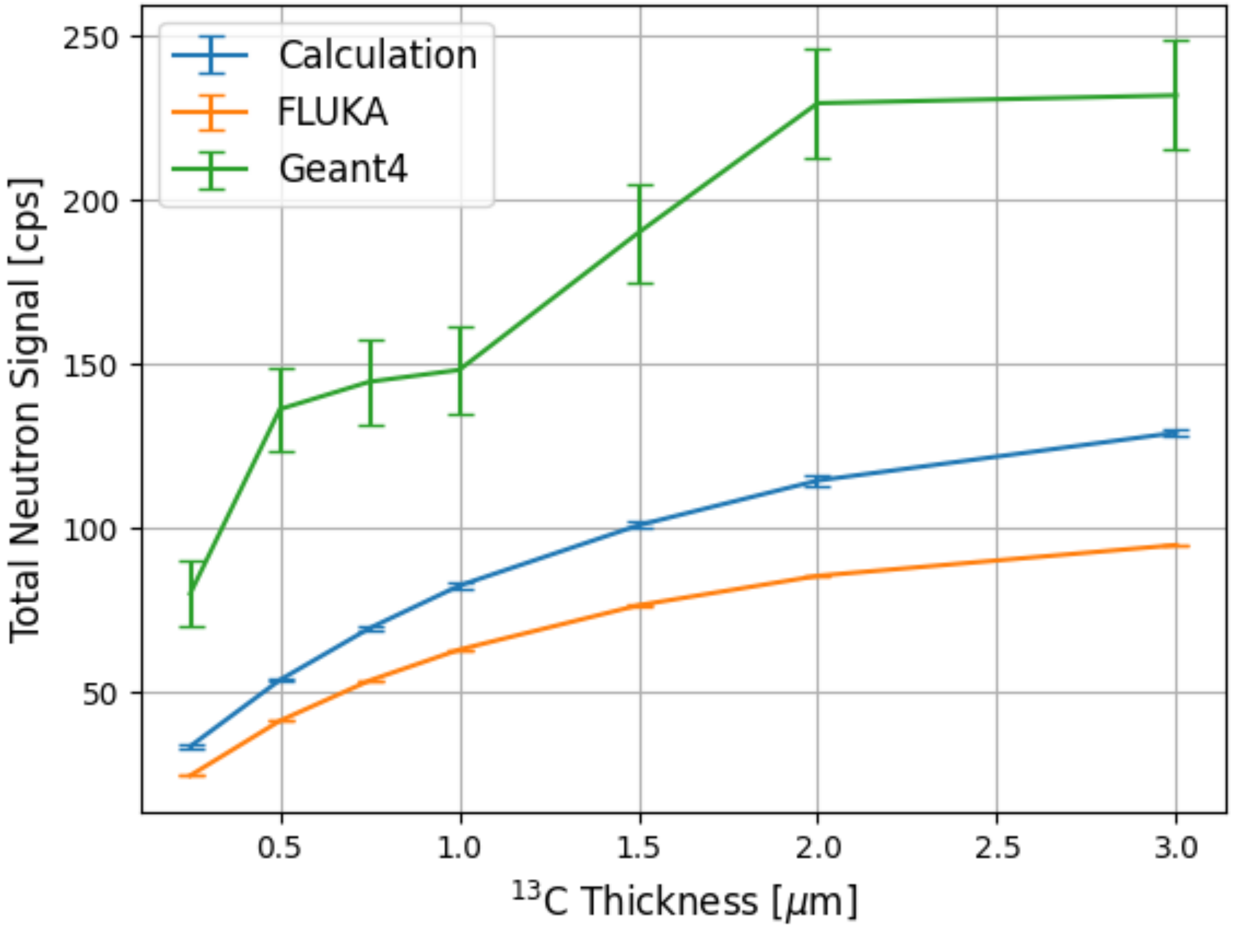
Simulations of neutron and gamma-ray production in ^{241}Am^{13}C

- **Geant4**
- **FLUKA**
- **Semi-analytical calculation based on linear interpolation of measured stopping power, cross-section, and branching ratio**

6.1-MeV gamma-ray yield

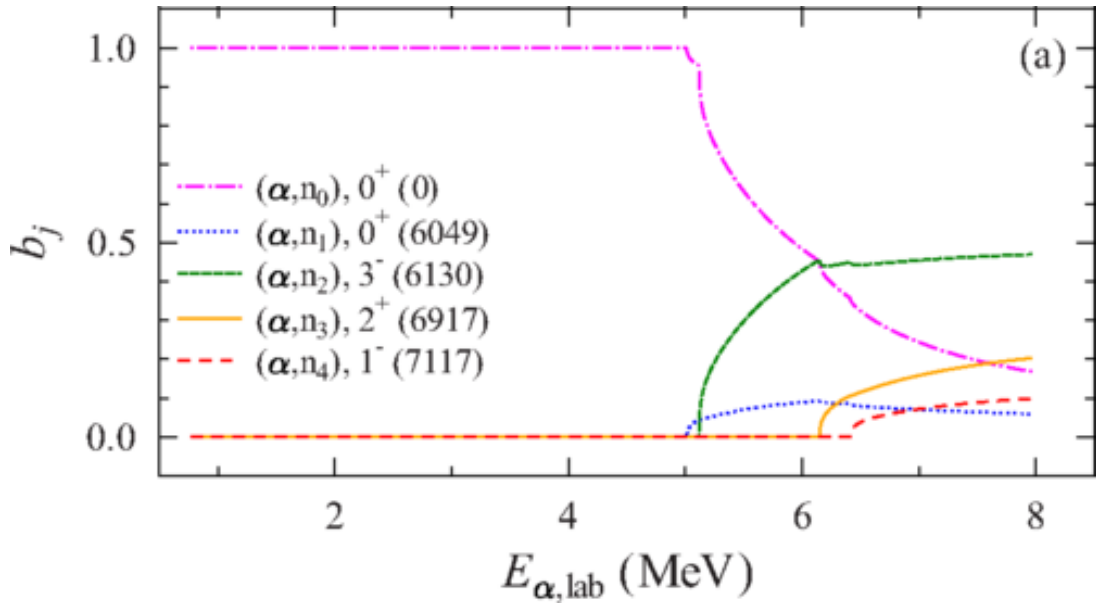


Total neutron yield

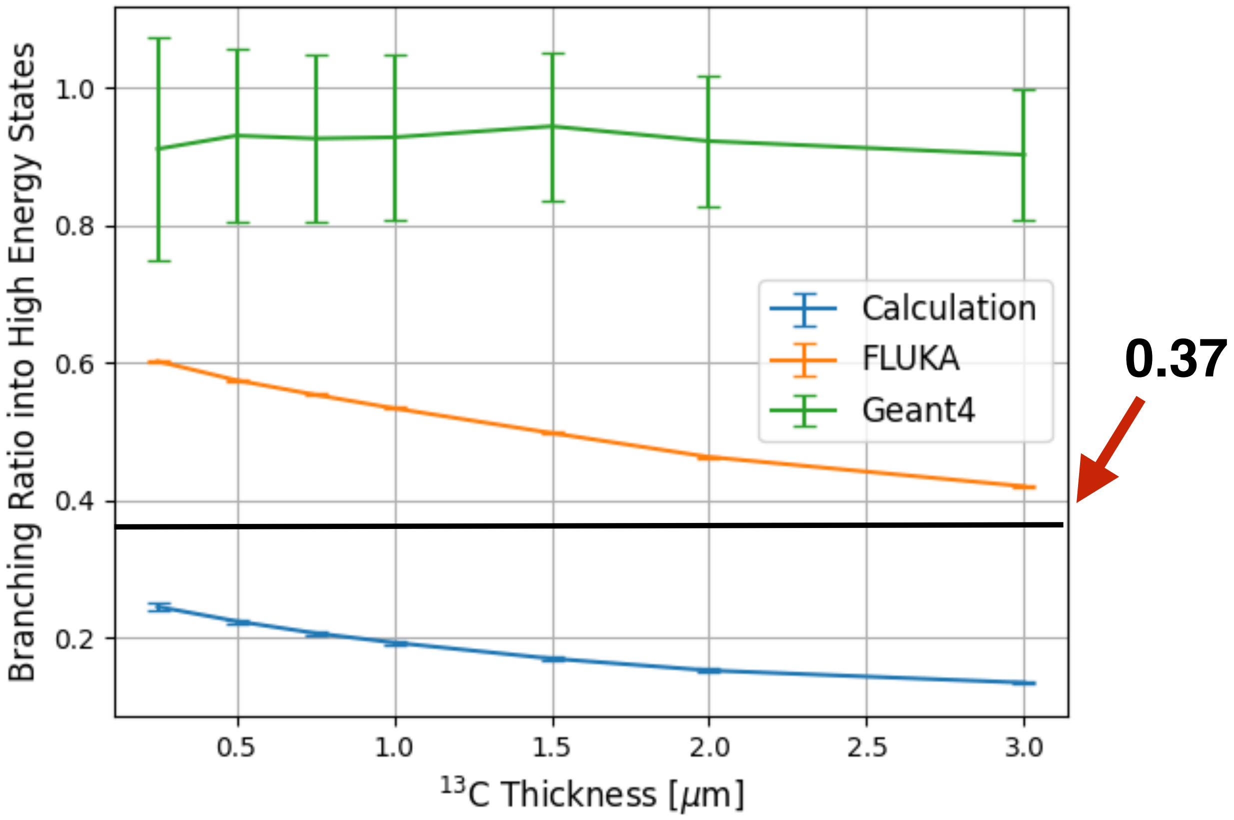


Branching ratio data seem to be the source of discrepancy

P. Mohr. 10.1103/PhysRevC.97.064613



Reported branching ratio at 5.5 MeV: 0.37

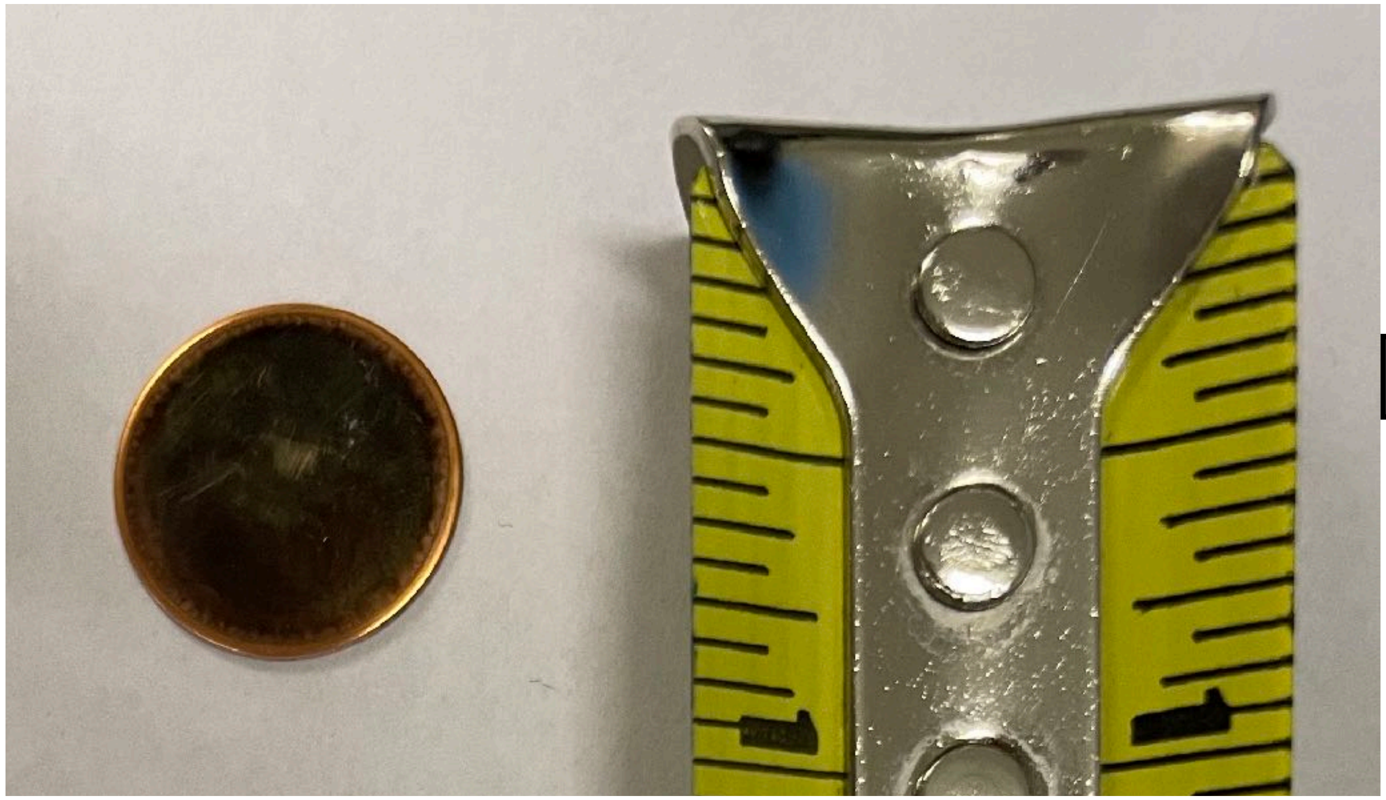


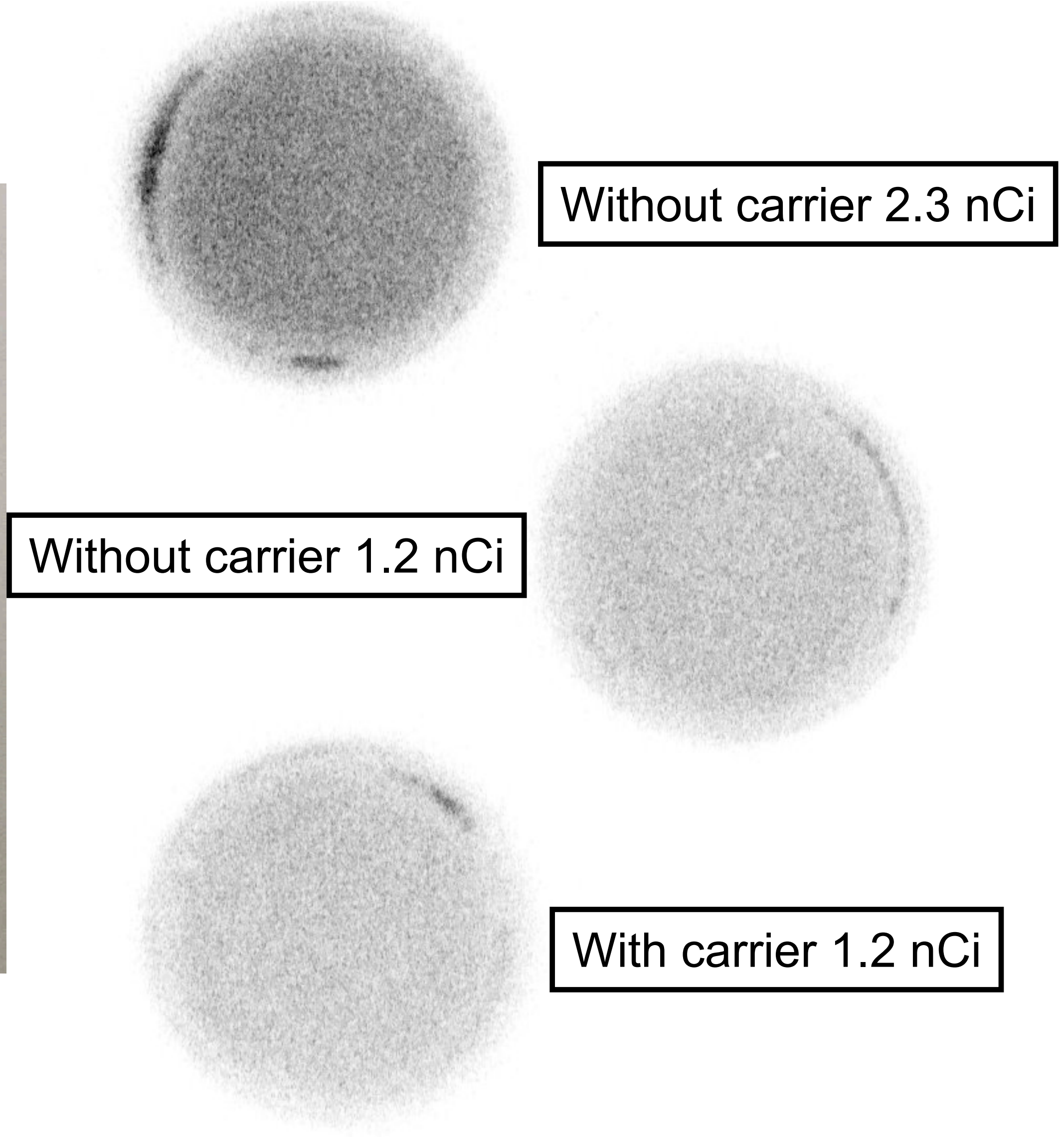
Preliminary source parameters

- 1 cm radius disk
- 1 mCi ^{241}Am disk of 0.1 μm thickness
- ^{13}C of 1–2 μm thickness
- Gamma-to-neutron ratio: ~25% – one order of magnitude increase over homogeneous source, but there is large uncertainty in simulations
- Expected 6.1-MeV gamma rate (using our conservative semi-analytical estimate): 10–100 s^{-1}

^{241}Am deposited planchet

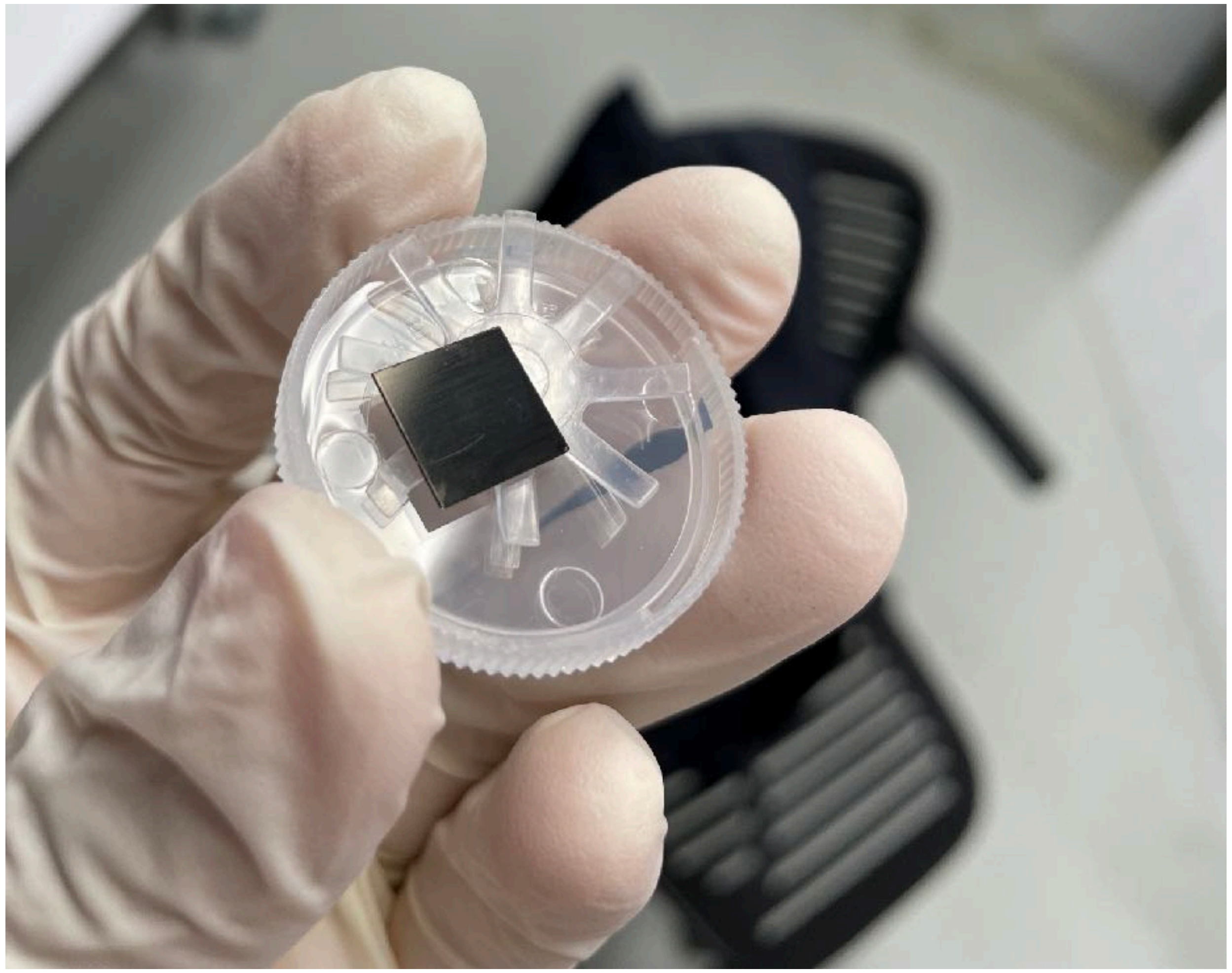
^{241}Am deposited planchet fabricated at the University of Cincinnati



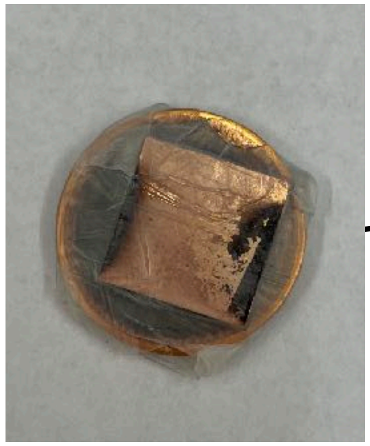


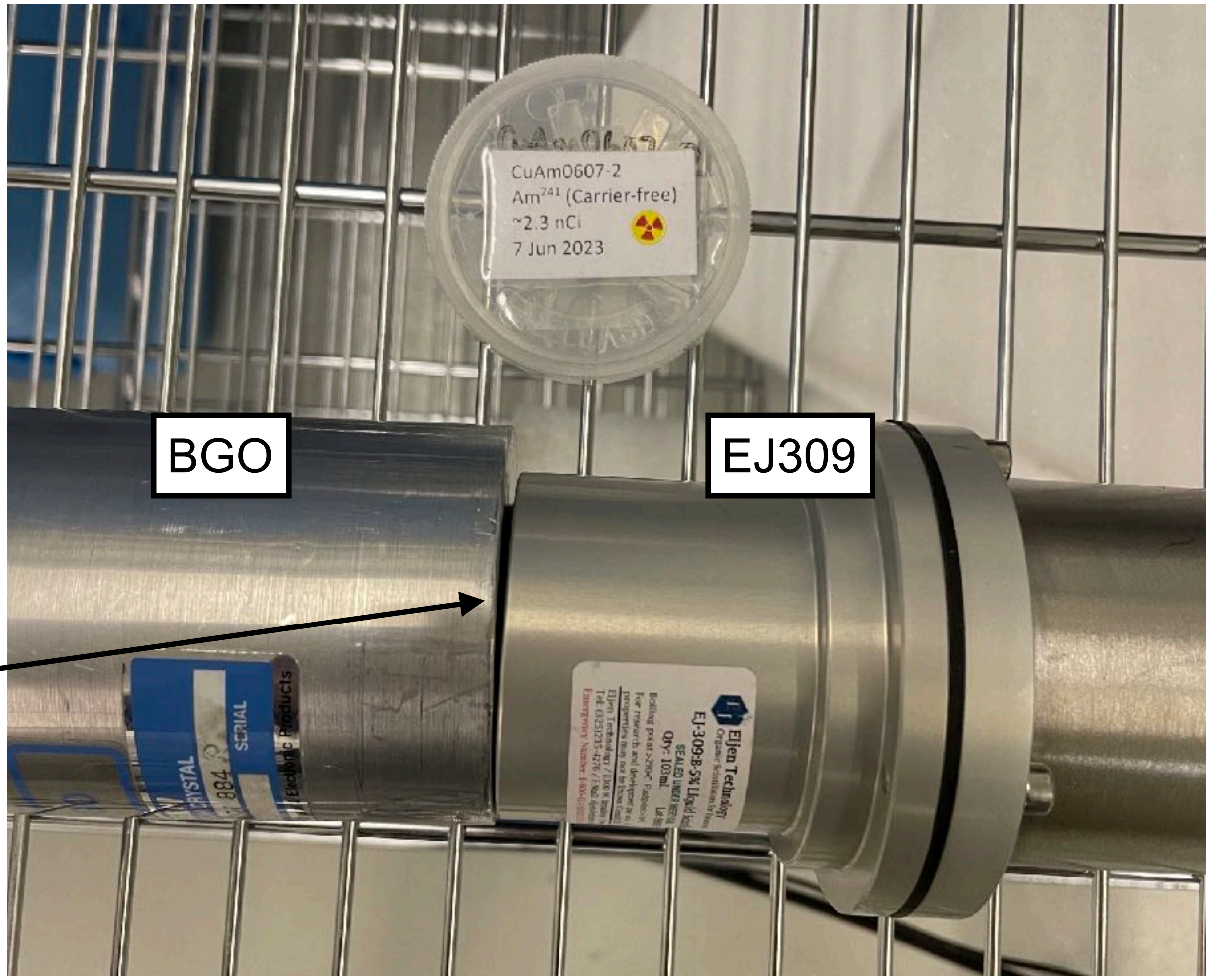
^{241}Am deposited planchet measured with an imaging plate

^{241}Am-^{13}C preliminary characterization

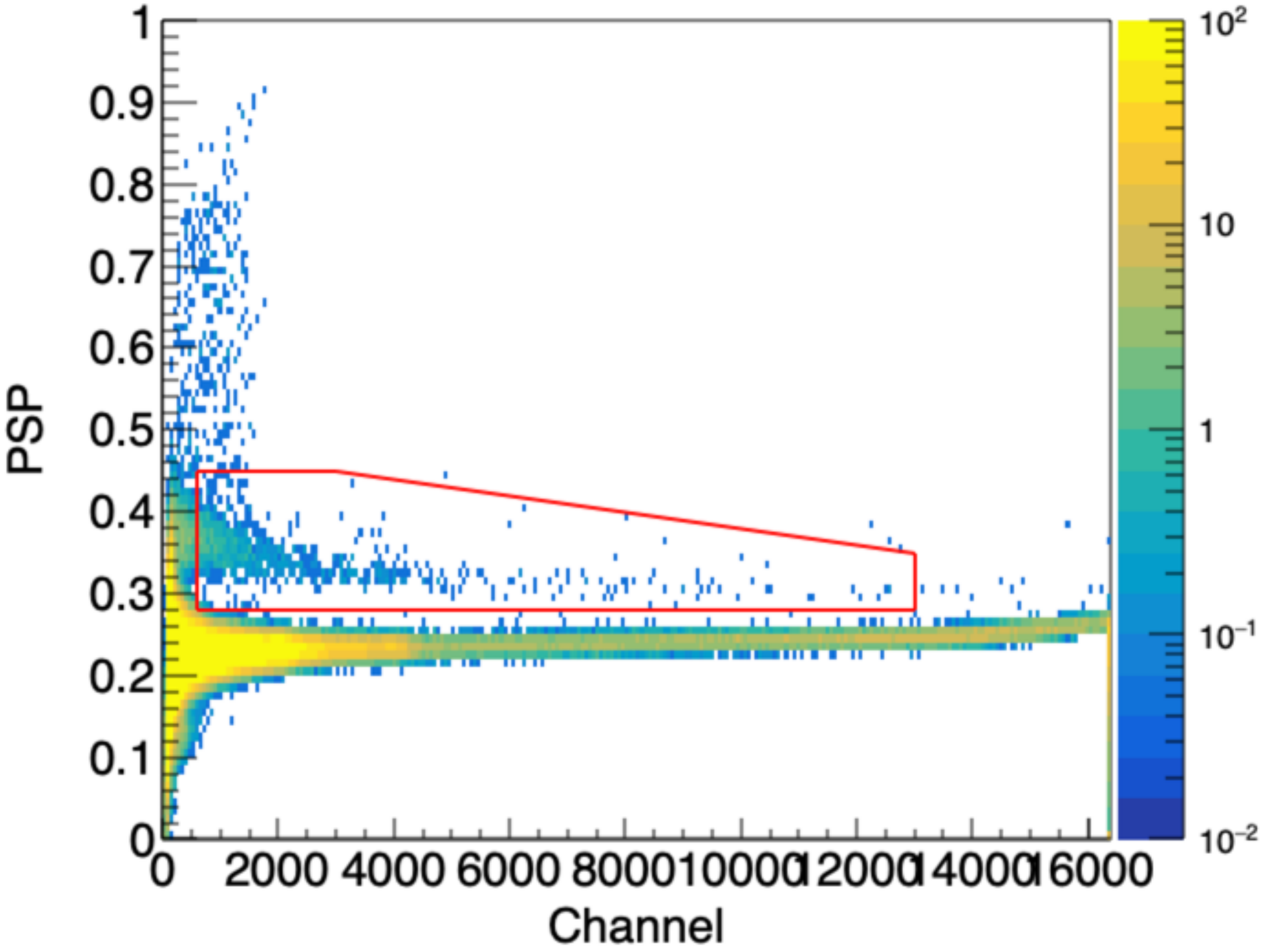


^{13}C deposited sample (~1.5 µm)





^{241}Am-^{13}C preliminary characterization



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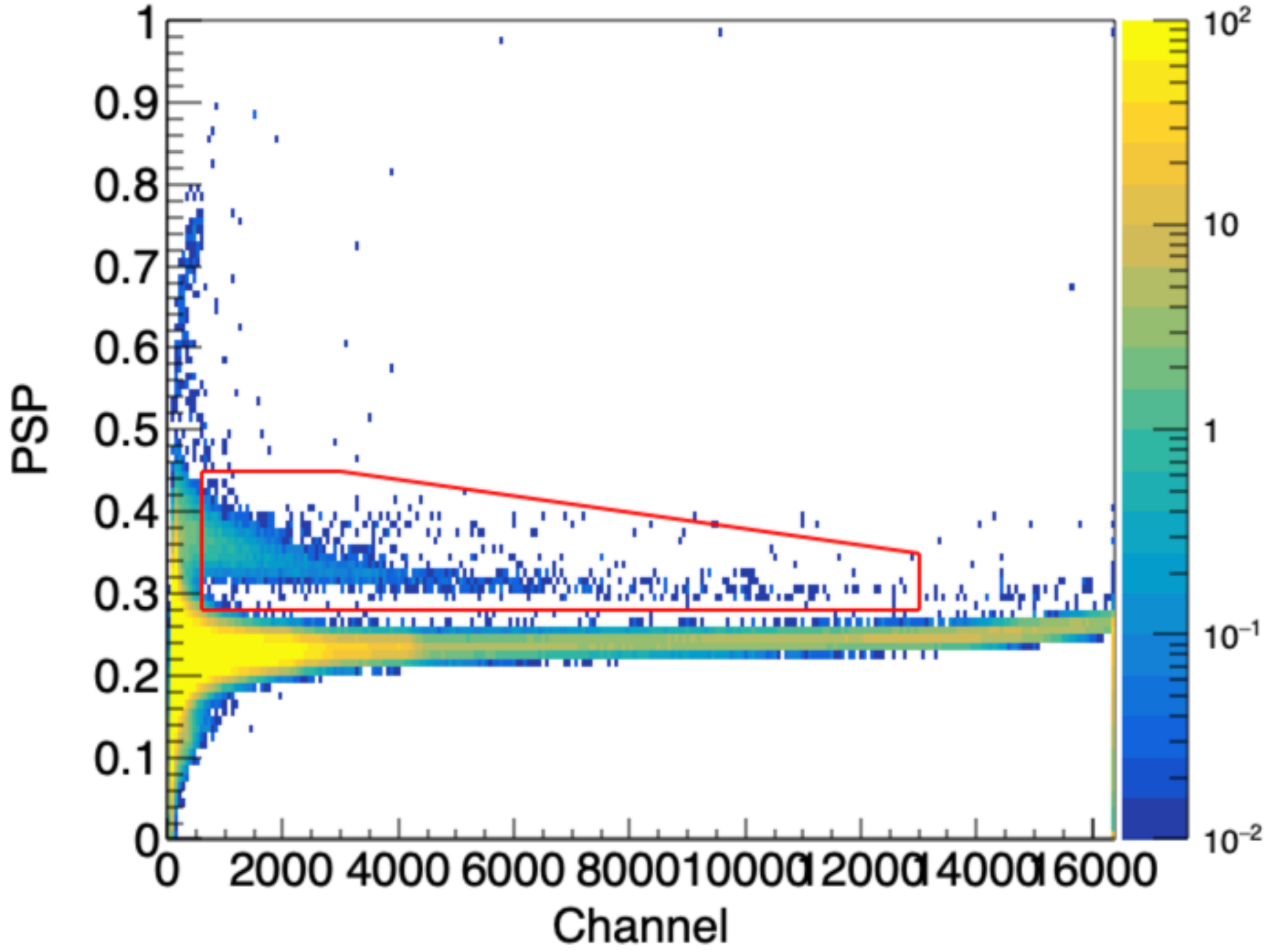

^{241}Am (0.9 µCi)+^{13}C

Summary

- ^{241}Am^{13}C may serve as an alternative to ^{16}N as a source of 6.1-MeV gamma rays with coincident neutrons
- Does not require an expensive DT generator facility
- Solid-state calibration source that can be rapidly turned on/off by mechanical actuation → permanent deployment?
- Control gamma/neutron ratio by source design
- Some uncertainties in simulations → address in experiment
- Mechanical actuation could be extended to more standard sources such as AmBe

Backup

Source tagging

Option 1: Tag using neutron capture in the large detector
– simple but it is a looser coincidence tag

Option 2: Dedicated neutron tagging detector at the source
– more complex and requires PSD at low energies to distinguish neutrons
– may also use capture-gated detector

also need a thin layer to stop low-energy gammas from ^{241}Am