Project 5: Production and Use of ^{18}F for Neutrino Detector Calibration

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Particles and Cosmology
17th Baksan School on Astroparticle Physics
2025

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1 Task description

Certain n-activated radionuclides are valuable for calibrating neutrino detectors. One such isotope is fluorine-18 (^{18}F), a e^+ emitter widely used in medical imaging and neutrino physics. In this project, we will design a method to produce ^{18}F using a compact n generator, analyze its decay signature, and study its application in calibrating a large liquid scintillator detector (LSD), like JUNO [1].

2 Design of the Activation Setup

Firstly, we need to figure out how to obtain a sample with ^{18}F from polytetrafluoroethylene (PTFE). PTFE is a synthetic fluoropolymer widely recognized for its exceptional chemical resistance, thermal stability, and low friction properties. Commercially known as Teflon, PTFE is a white, waxy solid at room temperature. PTFE consists of a carbon backbone fully substituted with fluorine atoms, giving it the formula $(C_2F_4)_n$. Therefore, PTFE is chemically pure and contains a high proportion of fluorine atoms, ensuring minimal contamination. In addition, PTFE is quite cheap and widely available and can be processed into various forms to suit experimental needs.

According to the task requirements, the production of ^{18}F for neutrino detector calibration will involve the irradiation of PTFE samples using a neutron generator. Neutron generators are compact devices that produce neutrons through nuclear fusion reactions, primarily using deuterium (D) and tritium (T). We discussed two possible options.

1. Deuterium-Deuterium (D-D) generator:
   $^2\mathrm{H} + {}^2\mathrm{H} \rightarrow {}^3\mathrm{He} + n$, where $E_n \approx 2.5$ MeV

2. Deuterium-Tritium (D-T) generator:
   $^2\mathrm{H} + {}^3\mathrm{H} \rightarrow {}^4\mathrm{He} + n$, where $E_n \approx 14$ MeV

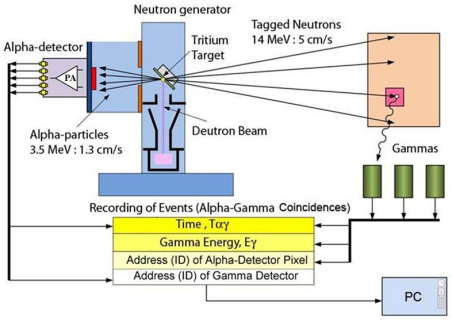


Figure 1: Schematic diagram of the tagged neutron generator setup, illustrating the production of 14 MeV neutrons via the $^3\mathrm{H}(d,n)^4\mathrm{He}$ reaction.

PTFE irradiation with fast neutrons is described by the nuclear reaction

$$^{19}\mathrm{F}(n,2n)^{18}\mathrm{F}, \tag{1}$$

which energy threshold is 10.4 MeV. Based on this fact, we can use only the D-T generator. The TANGRA facility at JINR [2] provides an example of such a generator. The core of TANGRA is a portable D-T neutron generator with a flux of up to 10^8 n/s. A schematic of this generator is shown in Fig.1. It is worth noting that the neutron flux used in the following calculations is 10^6 $n/s/cm^2$, as specified in the task conditions.

The cross-section of reaction (1) depends on the neutron energy, as shown in Fig.2. According to this plot, if our hypothetical D-T generator produces neutrons with energy about 14 MeV, the reaction cross-section $\sigma \approx 0.05 \pm 0.01$ b.

The activity of the irradiated sample increases during irradiation and approaches a saturation value when the production and decay rates become equal. It can be described by formula:

$$A(t) = \lambda N(t) = \phi\sigma N_0(1 - e^{-\lambda t}), \tag{2}$$

includes dependencies on the neutron flux ϕ, the cross section of the reaction σ, the number of target nuclei N_0, the decay constant λ, and the irradiation time t. The flux and the cross section have been defined above. The decay constant depends inversely on the half-life of an isotope:

$$\lambda = \frac{ln(2)}{T^{1/2}}, \tag{3}$$

for ^{18}F $T^{1/2} \approx 110$ min. To determine the irradiation time, we have considered two options for the target mass, which are 5 g and 10 g of PTFE. As shown in Fig.3, the time required to produce 100 Bq of ^{18}F is approximately 3 minutes for a 5 g PTFE sample. This result is consistent with the estimate from [4],

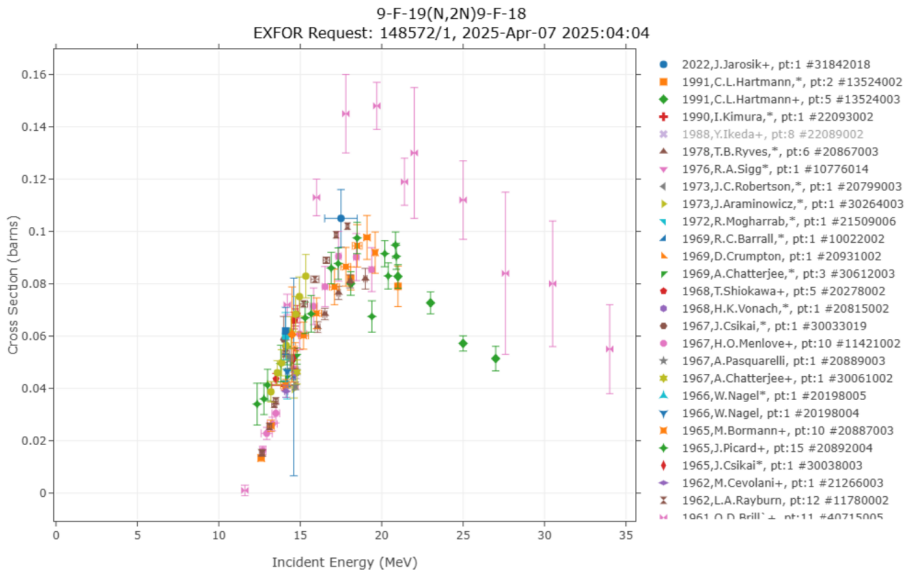


Figure 2: Experimental cross-section data for the $^{19}\mathrm{F}(n, 2n)^{18}\mathrm{F}$ reaction as a function of incident neutron energy, compiled from the Experimental nuclear reaction data (EXFOR) database [3].

which reports a production time of less than 10 minutes for a cylindrical PTFE sample of comparable mass. The increase in irradiation time accounts for two key factors:

- Self-shielding effects within the PTFE sample, which reduce neutron flux penetration.
- The delay between the end of irradiation and the start of calibration, ensuring sufficient $^{18}\mathrm{F}$ accumulation for reliable measurements.

3 Decay Properties

$^{18}\mathrm{F}$ is a key positron-emitting radioisotope. Positron emission accounts for 96.7% of decays, producing a positron and a neutrino while transforming into stable $^{18}\mathrm{O}$. The emitted positrons have a maximum energy of 635 keV and a continuous spectrum with a peak between 200 and 300 keV. In 3.3% of decays, electron capture occurs, directly yielding $^{18}\mathrm{O}$ without positron emission.

The endpoint of positron ionization is annihilation, producing two γ with energy 511 keV. Therefore, $^{18}\mathrm{F}$ is a source of γ with energy that mimics the prompt signal of inverse β-decay (IBD) events. Furthermore, short half-life allows repeating calibration without long-term contamination. As shown in section 2,

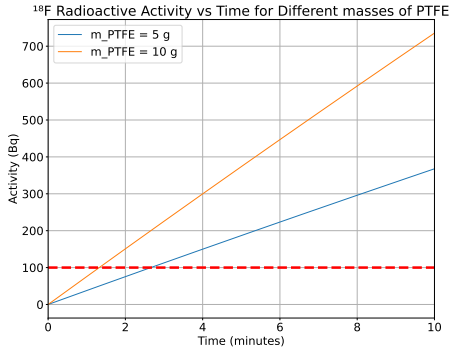


Figure 3: Radioactive activity of ^{18}F as a function of irradiation time for PTFE samples with masses of 5 g and 10 g. The red dashed line indicates the required activity of 100 Bq.

radioactive sample with ^{18}F can be easily generated before each deployment at the large LSD site along expected operational life of the experiment.

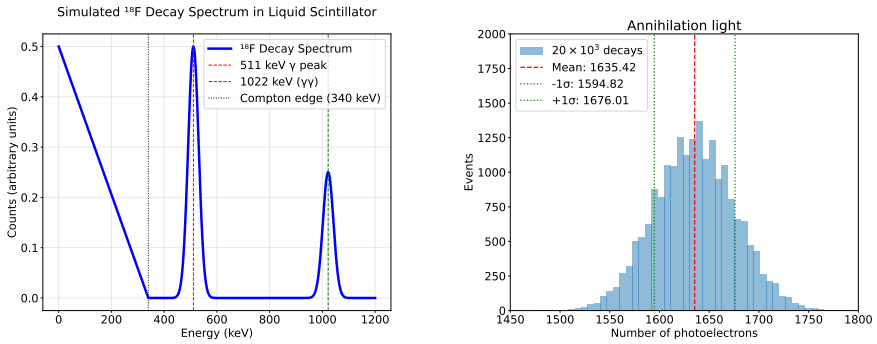
4 Detector Response Modeling

Assuming the irradiated PTFE is sealed in a stainless-steel capsule and placed in the center of a large LSD. Firstly, it prevents contamination to LSD. Secondly, the capsule shields positrons, so positron annihilation occurs only in the PTFE sample or in the capsule. Consequently, scintillation light is produced by γ-pairs. As shown in Fig. 4a, the detector response forms from:

- Compton Continuum (0 - 340 keV): Partial energy deposition from scattered gammas, with a sharp edge at 340 keV (Compton edge).
- A gaussian-like peak at 511 keV when the gamma deposits all its energy, assuming a signal from a γ-pair is read out as two single events.
- A gaussian-like peak at 1 MeV when the γ-pair deposits all its energy.

If the stainless-steel capsule is sufficiently thick, it will fully contain the positrons, preventing them from reaching the detector and inducing quenching effects. Under these conditions, the proposed calibration method remains reliable, as the positron kinetic energy does not contribute to the measured light yield. Without taking into account the detection efficiency and other effects, the number of photoelectrons (PE) collected from positron annihilation can be calculated by knowing the photon yield. The project condition suggests 1600 PE per MeV. Working only with energy integrated from whole detector, the 2γ-peak around 1 MeV can be described by Poission distribution (see Fig.4b):

$$P(\mu, n) = \frac{\mu^n}{n!} e^{-\mu}, \tag{4}$$



(a) (b)

Figure 4: (a) Simulated ^{18}F decay spectrum, assuming 50% of the detection efficiency. (b) Poission distribution of the number of PE detected for positron annihilation from 20,000 ^{18}F decays.

where mean value $\mu = 2 \cdot 511[\text{keV}] \cdot 1600[\text{PE/1 MeV}]$, and n is the number of ^{18}F decays.

5 Calibration precision

We can estimate the energy resolution and calibration precision of our method using Poisson distribution variables. An uncertainty in the peak position is equal to $\sqrt{\mu/n}$, while an uncertainty in the distribution width is $\sqrt{2\mu^2/n}$. Suppose that for both the energy peak reconstruction and the width, the ideal precision is 1% uncertainty. Fig.5 shows the number of decays, which is enough to achieve this uncertainty. Namely, it is more than 6 events for the peak position, and more than 20,000 events for the peak width.

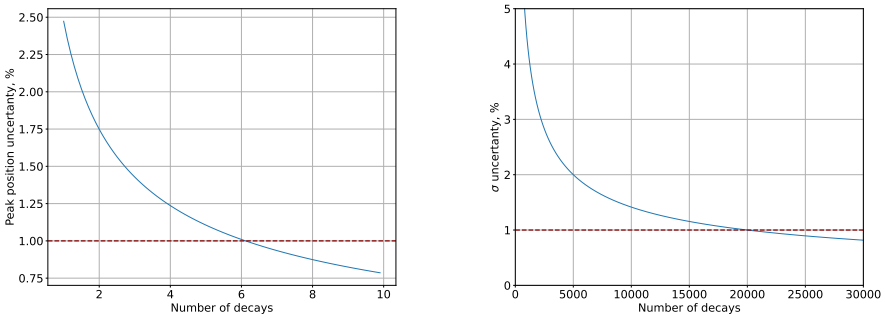
Estimates of the time the irradiated sample will be in the LSD are shown in Fig.6. As the initial activity of ^{18}F, $A_0 = 100$ Bq, decreases by law:

$$A(t) = A_0 e^{-\lambda t}, \tag{5}$$

with t being the post-irradiation time, the average number of decays becomes greater than 20,000 in 4 minutes.

6 Conclusion

^{18}F provides a viable source of positrons for calibrating large liquid scintillator detectors. Using a stainless-steel capsule ensures that only γ from positron annihilation deposit energy and mimic the prompt signal of IBD. Irradiating 5 g of PTFE with fast neutrons for approximately 5 minutes produces sufficient ^{18}F, and a 4-minute exposure within the detector achieves a calibration precision



(a) (b)

Figure 5: Uncertainty in the peak position (a) and width (b) as a function of the number of decays. The red dashed line indicates desired 1% uncertainty.

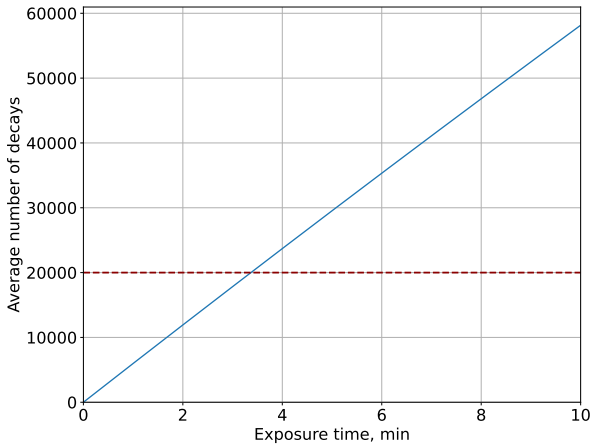


Figure 6: The average number of ^{18}F decays as a function of time. The red dashed line indicates the desired number for precise calibration.

with less than 1% uncertainty in both the peak position and width. All of our calculations can be found at [5].

We acknowledge D. Dolzhikov, D. Ilyushkin, I. Perevalova, N. Anfimov for insightful discussions and support throughout this project.

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