Neutron Detector Options for Future μCF Experiments

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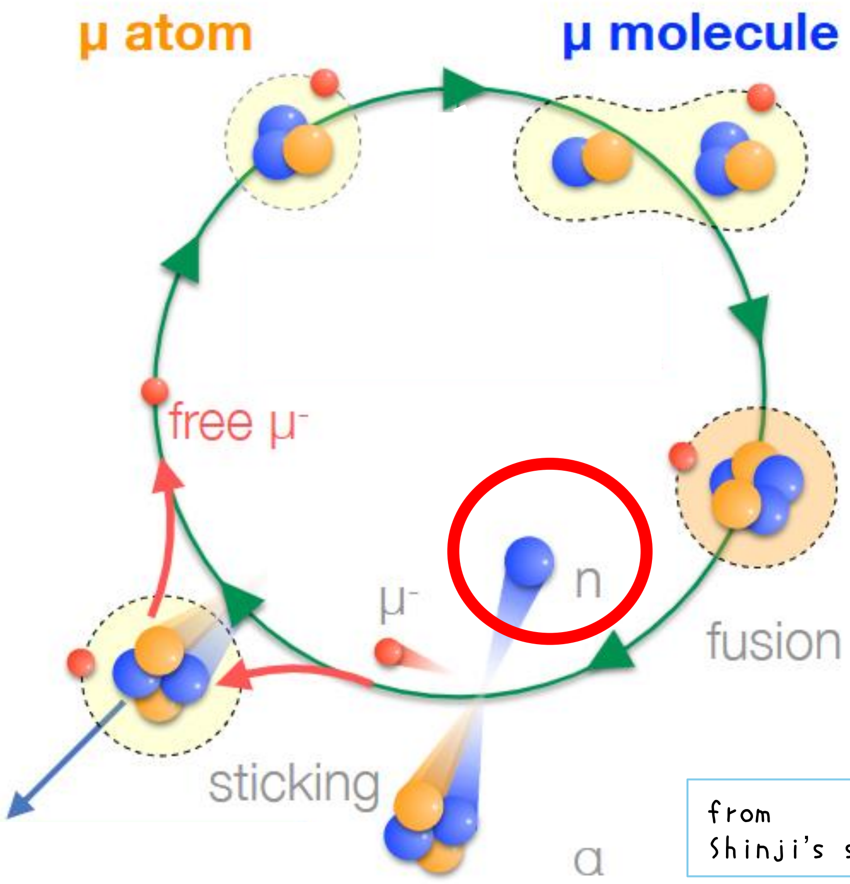
Neutron measurement for μCF

- $dt\mu \rightarrow \alpha + n + \mu + 17.6\ \mathrm{MeV}$
- Neutron measurements provide
  - fusion yield
  - cycling rate
  - background evaluation
  - etc…

Better neutron measurements
-> Better understanding of μCF



from
Shinji's slide

Requirements

- Future experiments aim at precision measurements of μCF processes.
- Detector should operate reliably under many experimental conditions.
  - dtμ, ddμ, ttμ, and so on.
- Reliable background evaluation is also important.
- Rather than simply counting neutrons, more detailed measurements would be desirable, ideally on an event-by-event basis.

-> Required detector performance

- High efficiency
- Good timing
- n/γ separation
- High rate capability
- Energy information

⇒ To meet these requirements, several detector options are being investigated.

Detector options

Candidate	Key strength	Challenges
Liquid scintillator	Mature, n/γ separation, good timing resolution	toxicity and flammability PSD & pileup rejection with AI?
Inorganic scintillator	Easy to handle, good energy resolution for γ	n/γ separation more studies
Organic glass scintillator (OGS)	Good n/γ separation, good timing resolution and efficiency, easy to handle	more studies
Deuterated scintillator	Energy information, good n/γ separation	more studies
(UV-curable scintillator)	Easy to handle, design flexibility	n/γ separation more studies

PSD: Pulse Shape Discrimination

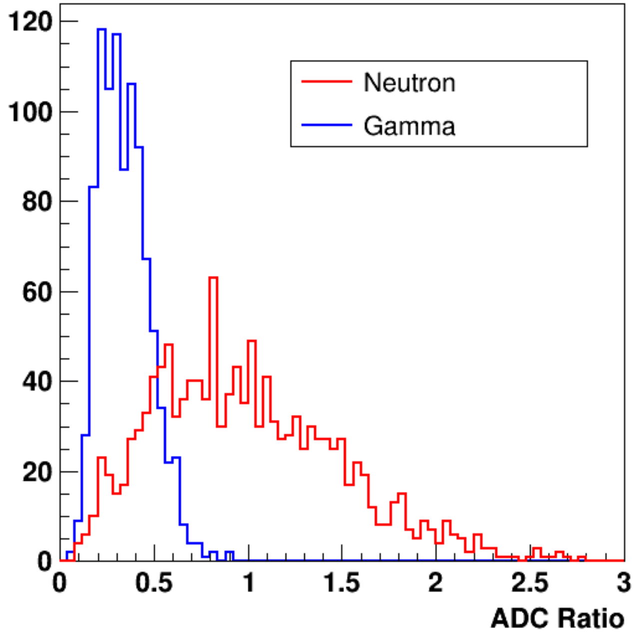
Liquid scintillator

- Commonly used for neutron detection.
- Difference in response between n and γ is used for n/γ separation.
- NE213 is widely used.
  - Recently, low-toxicity liquid scintillators, such as EJ-309, have been developed.
- We have borrowed one detector and are currently testing it. -> next talk

Inorganic scintillator

- Recently, several studies have been reported.
  - Eu:LiI-CaI2-based scintillator (Eu:LiCaI)
  - CsI(Tl)
- n/γ separations are still not good.
- They are still in development phase.

arXiv:2209.13189



10.1093/ptep/pty040

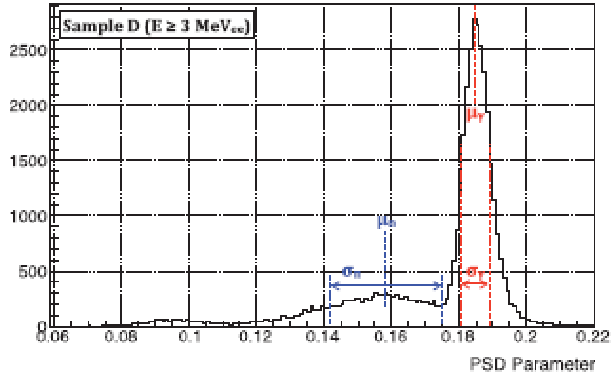


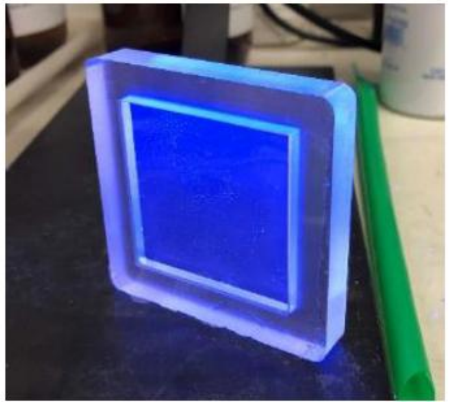
Fig. 7. Sample D's PSD parameter distribution for events with visible energy larger than 3 MeV$_{ee}$. The position of the neutron and gamma-ray peaks are identified by the μ_γ and μ_n labels. Their FWHM values are similarly identified with the σ labels.

10.1021/jacs.7b03989
10.1016/j.nima.2021.165676
10.1088/1748-0221/20/05/P05037
10.1016/j.nima.2023.168309
10.1007/978-3-030-73488-6_8

Organic glass scintillator

- Some R&Ds are ongoing.
- Good light yield, timing resolution, and efficiency have been reported.
- n/γ separation is not bad.

Fig. 8.11 Photograph under UV illumination of a 2.5" × 2.5" × 0.2" OGS scintillator fabricated by net-shape melt-casting in a silicone mold.



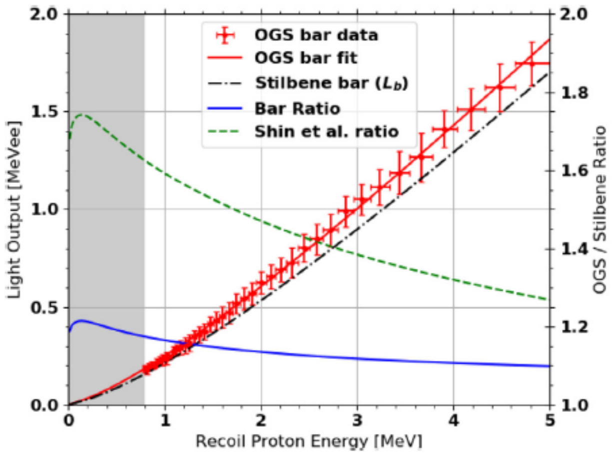


Fig. 13. Light output in an OGS bar and stilbene bar as a function of proton recoil energy (left axis). Horizontal error bars represent bin width and vertical error bars represent the width of the Gaussian fit to the derivative of the light output edge. The black dashed line is the measured light output curve for a stilbene bar along the L_b crystal direction, from Ref. [15]. Also plotted is the light output ratio of OGS to stilbene (right axis). The blue curve is the ratio of the red line to the black dashed line. The dashed green curve is the ratio between measured light outputs of ∅5.08 cm× 5.08 cm OGS and stilbene scintillators from Ref. [20]. The region below the recoil proton energy threshold (0.8 MeV) is grayed out.

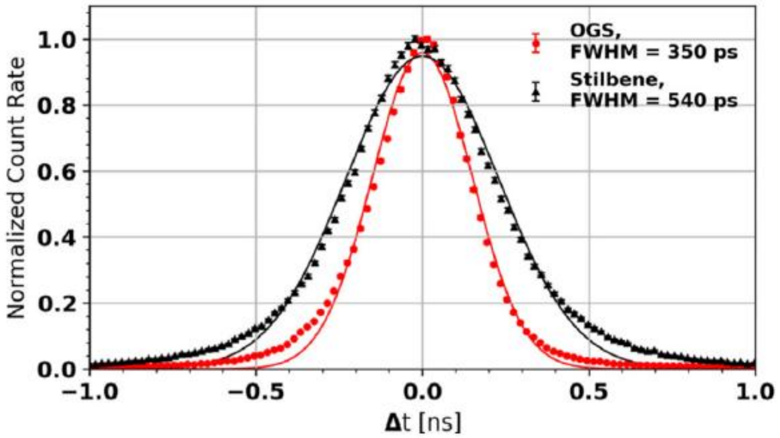


Fig. 7. Distribution of time differences between coincident detection events from a ^{22}Na source in 6 mm by 6 mm by 50 mm OGS and stilbene bars coupled to SiPMs (reproduced from (Giha et al., 2021)).

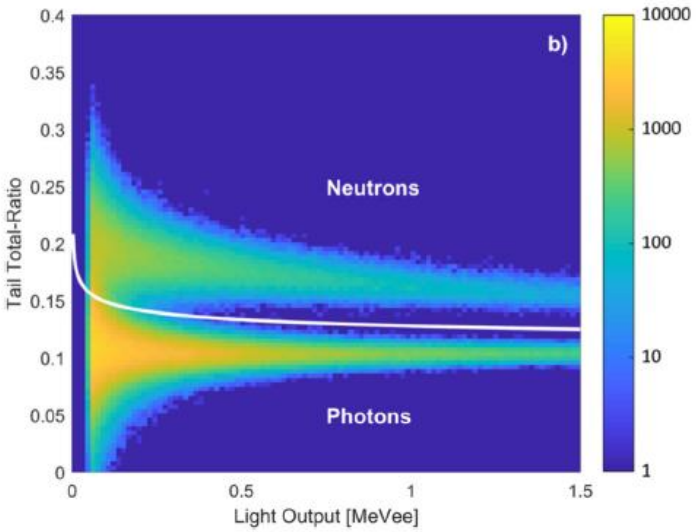


Fig. 10. Tail-to-total ratio for 1 million events for both stilbene (top) and OGS (bottom) detectors Figure taken from (Shin et al., 2019).

Deuterated scintillator

- There has recently been increasing interest in this technology.
- Good n/γ separation is reported.
  - it is stilbene based.
- Energy information can be extracted with unfolding method.

10.1016/j.nima.2017.08.034

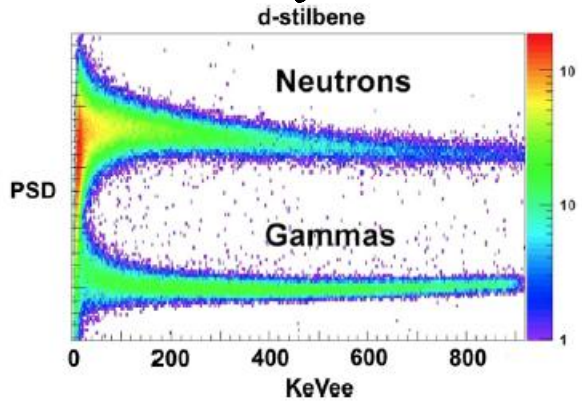


Fig. 17. PSD for a small crystal (a few cm^3) of d-stilbene [25] measured with a ^{252}CF fission neutron source. The bottom scale is electron-equivalent energy.

10.1016/j.nima.2020.164824

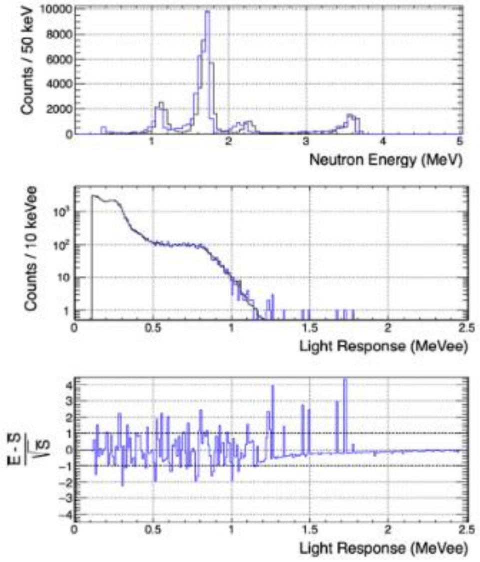
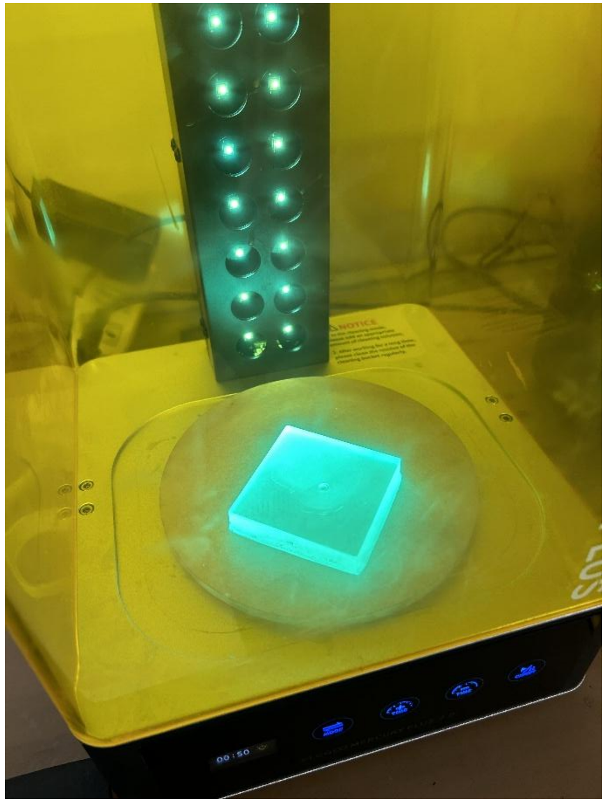


Fig. 4. Unfolded neutron energy spectrum (blue) compared to the same spectrum produced through neutron ToF (black) (top). The light response spectrum (blue) used in the unfolding compared to a estimate spectrum generated by feeding the unfolded spectrum into the forward problem (black) (center). The difference between input spectrum and estimate spectrum over the square root of counts in the input spectrum (bottom). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(UV-curable scintillator)

- R&D on UV-curable 3D printed scintillator is also ongoing (as a side project).
- In recent years, the development of neutron-sensitive UV-curable scintillators has begun in several research groups worldwide.
- Discussions are also underway among scintillator developers in the Japanese high-energy physics community.



Summary

- Neutron measurement is important for μCF experiment.
- Investigation of candidate neutron detector options has started.
  - Liquid scintillator
  - Inorganic scintillator
  - OGS
  - Deuterated scintillator
  - (UV-curable scintillator)
- Further investigation and development, together with preliminary tests using actual detectors, will continue.