Neutron shielding simulation for background reduction in Migdal search

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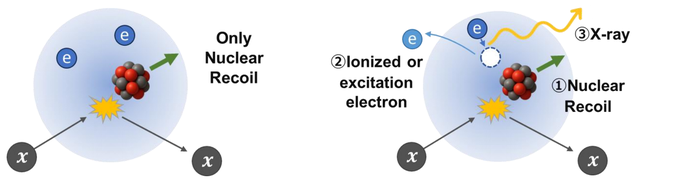
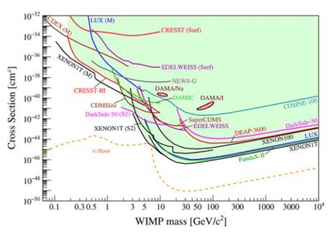
Although the existence of dark matter has been revealed from astronomical observations, it has not yet been directly detected. Recently, direct dark matter search experiments aim to extend the search region to sub-GeV mass ranges based on theories including dark sector models. The Migdal effect, predicted by quantum mechanical calculations, may enhance sensitivity to low-mass dark matter by adding electron recoil energy. The Migdal effect associated with nuclear recoil remains unobserved, experimental confirmation is required. In this study, the neutron shields for background reduction for Migdal search were studied using Geant4 simulation.

The Migdal effect

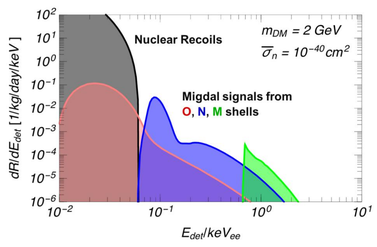
Electron ionization and excitation occur with Nuclear Recoils (NRs) at very low probability.



The Migdal signals contain Electron Recoils (ERs) energy → **the effective detection energy increases, enhancing sensitivity to low-mass Dark Matter.**



Rep. Prog. Phys. **85** (2022).



JHEP 03 (2018) 194.

The Migdal events with NR unobserved

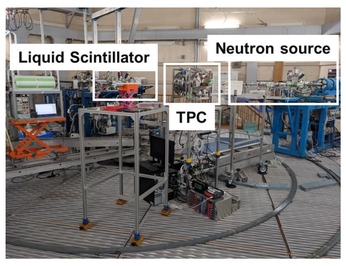
Low-pressure CF4 gas
Astroparticle Physics 151, 102853 (2023).

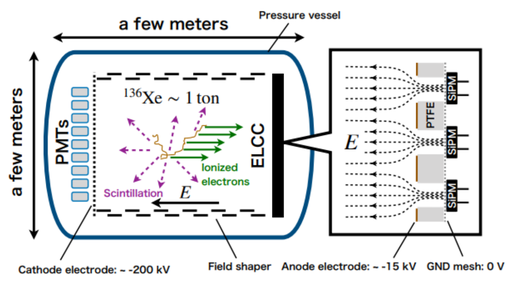
Liquid xenon
PHYSICAL REVIEW D 109, L051101 (2024).

MIRACLUE experiment

The signal from Migdal event is detected using a **high-pressure xenon gas TPC (Time Projection Chamber).**

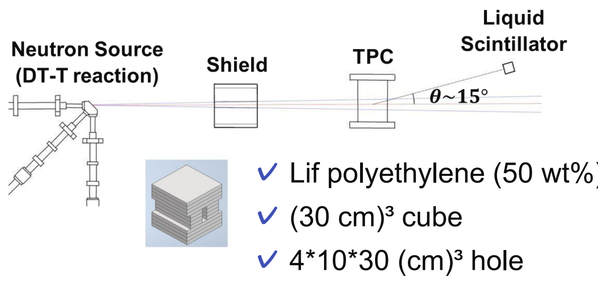
High energy resolution, Event topology





- ✓ 14.8 MeV neutrons are irradiated onto the TPC.
- ✓ Ionization electrons drift along *E* and are detected at ELCC.
- ✓ Neutrons scattered at 15° were detected by a liquid scintillator.

The 2024 beam test Seisiro Y., Master's thesis, Tohoku Univ., 2024.



- ✓ Lif polyethylene (50 wt%)
- ✓ (30 cm)³ cube
- ✓ 4*10*30 (cm)³ hole

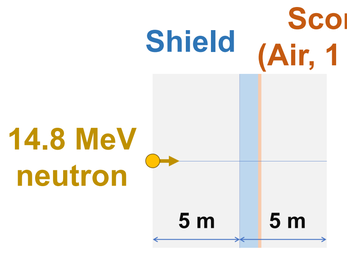
In this setup, **10^5 background events** occurred relative to the expected Migdal branching ratio.

↓

Need to reduce

Geant4 shield simulation

To investigate the optimal shielding for **reducing background-causing neutrons**, we performed simulations using Geant4.



World: (10 m)³ vacuum

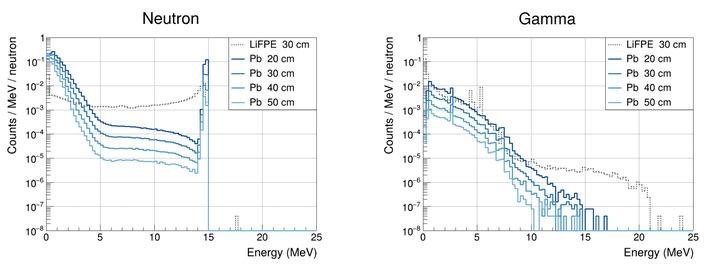
Model: QBBC

Simulated materials	g / cm³	information
Pb	7.874	-
Fe	11.35	-
Polyethylene (PE)	0.94	-
LiF-Polyethylene (LiFPE)	1.39	LiF 50 wt%
B-Polyethylene (BPE)	1.06	B_2O_3 20 wt%
Borated Water (BWATER)	1.05	$B(OH)_3$ 0.05 g/cm³
Boron-loaded rubber (BLR)	1.4	Silicone rubber with 50 wt% B_4C

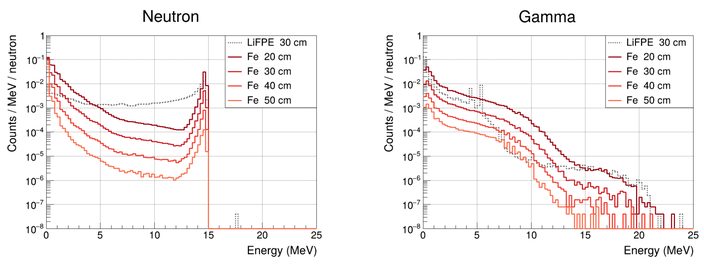
Results

1. Evaluation of degrader

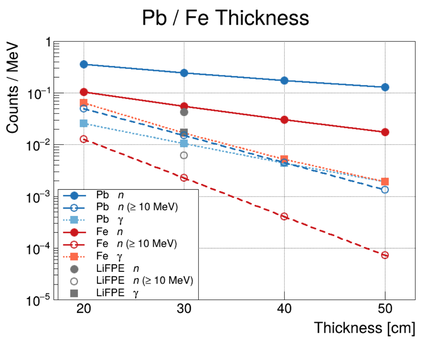
Pb



Fe



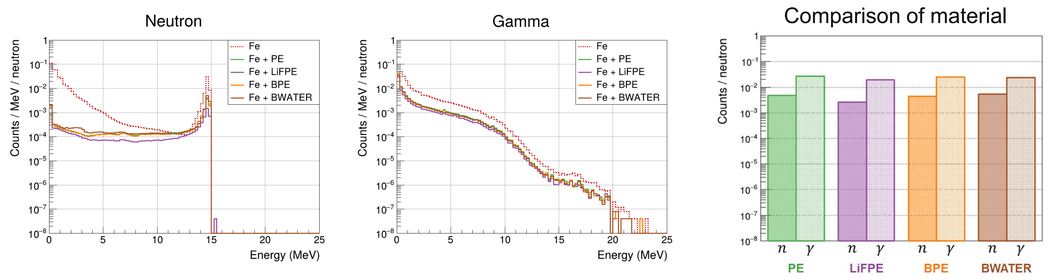
- ✓ Fe reduced high-energy neutrons more than Pb. (ref. https://doi.org/10.5611/hamon.28.4_208)
- ✓ Fe generates high-energy γ-rays.



- ✓ Shielding effectiveness of Fe and Pb increased linearly with increasing thickness.
- ✓ LiFPE 30cm, used in the 2024 beam test, neutron reduced 4e-2.

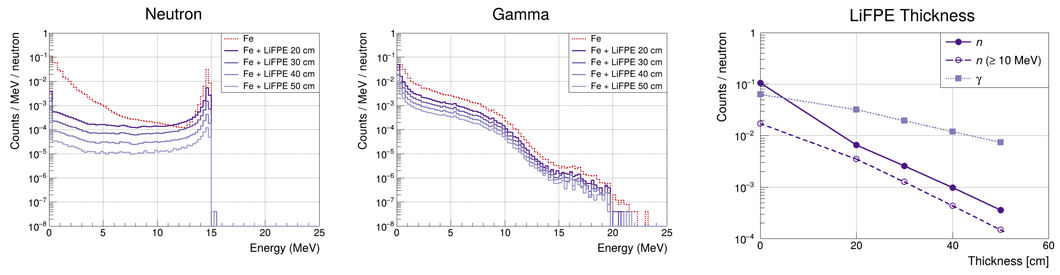
2. Evaluation of two composites

① Material selection: Fe 20cm + X 30 cm (X = PE, LiFPE, BPE, BWATER)



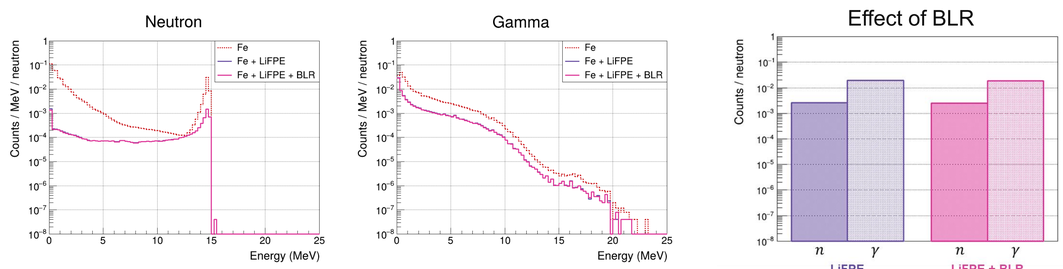
- ✓ LiFPE showed the highest shielding capability.

② Thickness Dependence: Fe 20cm + LiFPE x cm (x = 20, 30, 40, 50)



- ✓ LiFPE effectively shielded neutrons below 5-10 MeV.
- ✓ Shielding effect increased linearly with increasing thickness.

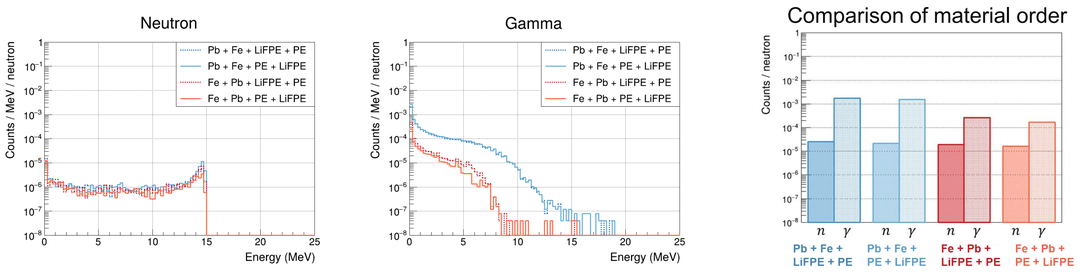
③ Boron-loaded rubber: Fe 20 cm + LiFPE 30 cm + BLR 5 mm



- ✓ Boron-loaded rubber (BLR) had little effect.

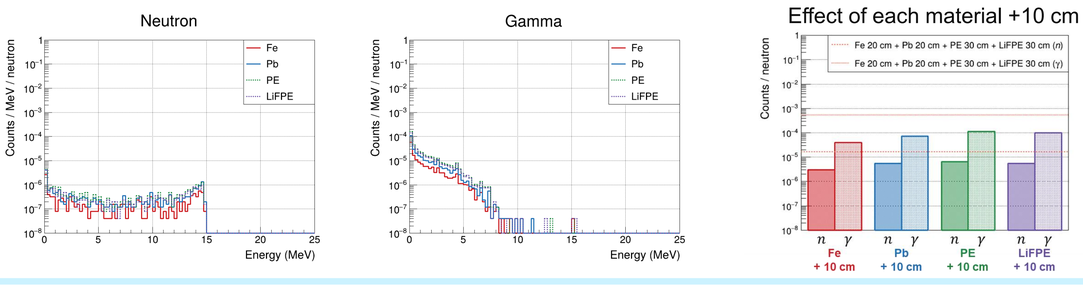
3. Evaluation of four composites

① Effect of layering order (Pb 20 cm, Fe 20 cm, PE 30 cm, LiFPE 30 cm)



- ✓ For Pb and Fe, the Fe → Pb order is more effective.
- ✓ For PE and LiFPE, the PE → LiFPE order is more effective.

② Thickness impact of each material (Base: Fe 20 cm + Pb 20 cm + PE 30 cm + LiFPE 30 cm)



- ✓ When increasing the thickness of only 1 of the 4 materials, Fe gave the most effective enhancement in shielding.

Summary

- ✓ Neutron shielding was evaluated using Geant4 simulations
- ✓ Fe was suitable as a degrader for high-energy neutrons and LiFPE was the most effective material to pair with Fe.
- ✓ Using 4 material, the configuration Fe → Pb → PE → LiFPE showed the best performance.
- ✓ Neutron was reduced 1 in 10^5 when Fe 30 cm + Pb 20 cm + PE 30 cm + LiFPE 30 cm.
- ✓ The reduction with LiFPE 30 cm (used 2024 beam test) was 4e-2. → Roughly 4e-7 reduction is required for the Migdal search.