Direct observation of Migdal effect

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MigdAl pRocess Validation by nEutruaL scattering

on behalf of MARVEL group

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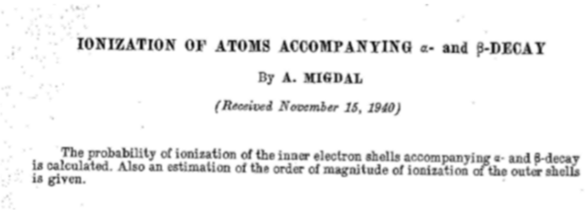
Outline

- Motivation
- MARVEL experiment proposal
- Detector performance
- Experimental setup
- Simulation & comparison
- Event selection algorithm
- Background analysis
- Summary and outlook

The Migdal effect

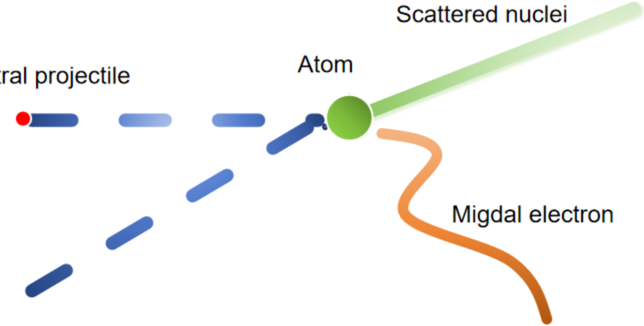
Also see Jianglai Liu's and Suerfu Burkhant's talk


IONIZATION OF ATOMS ACCOMPANYING α- and β-DECAY

By A. MIGDAL

(Received November 15, 1940)

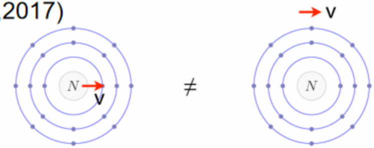
The probability of ionization of the inner electron shells accompanying α- and β-decay is calculated. Also an estimation of the order of magnitude of ionization of the outer shells is given.



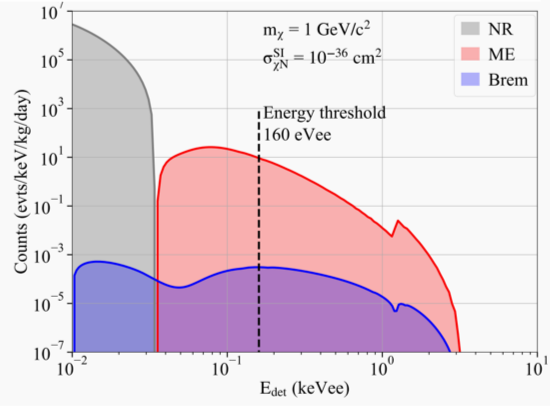
Energy deposition = nuclear scattering + Migdal effect electron

✓ In reality, it takes some time for the electrons to catch up…

(Ibe,IBS,2017)

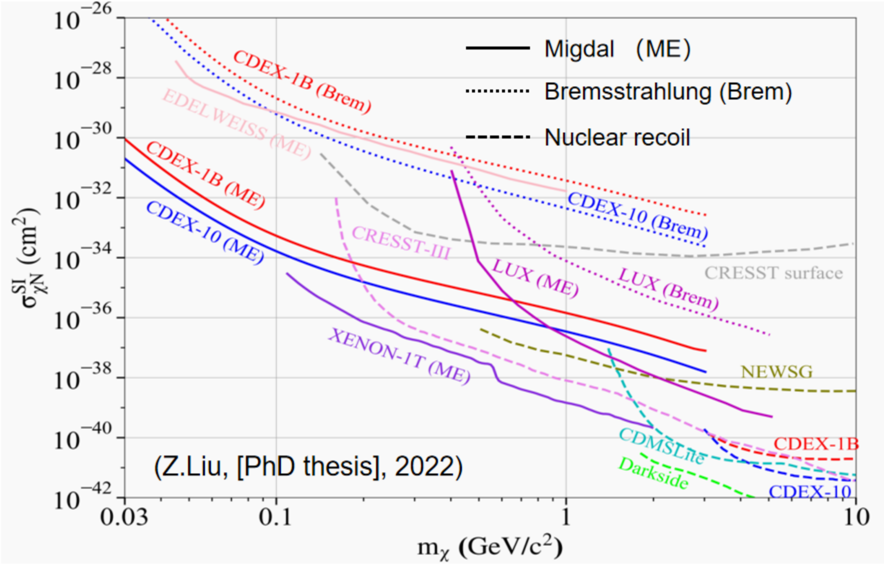


✓ The process to catch up causes electron excitations/ionizations!



Migdal effect in a Germanium detector

Sensitivity with & without Migdal effect



The Migdal effect enhanced the sensitivity of many existing direct dark matter detection experiments to the sub-GeV range.

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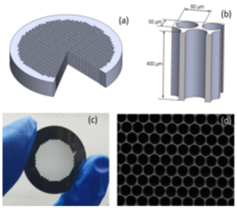
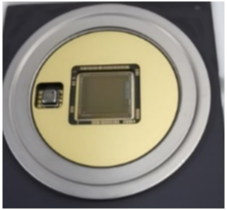
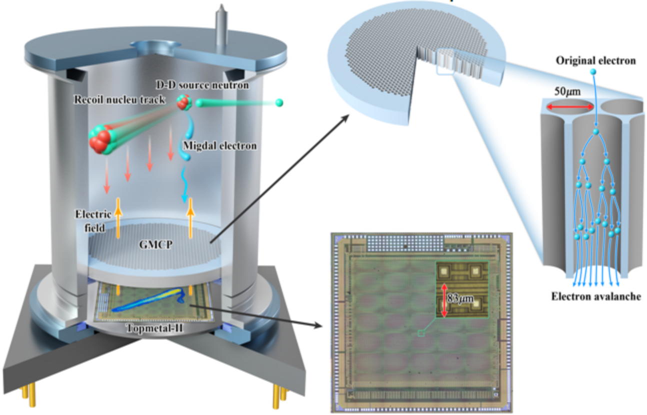
Experiment proposal

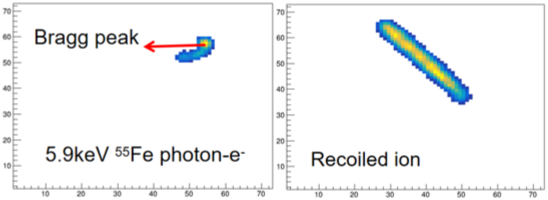


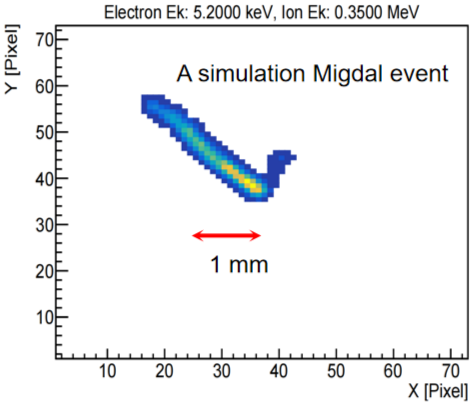
GMCP



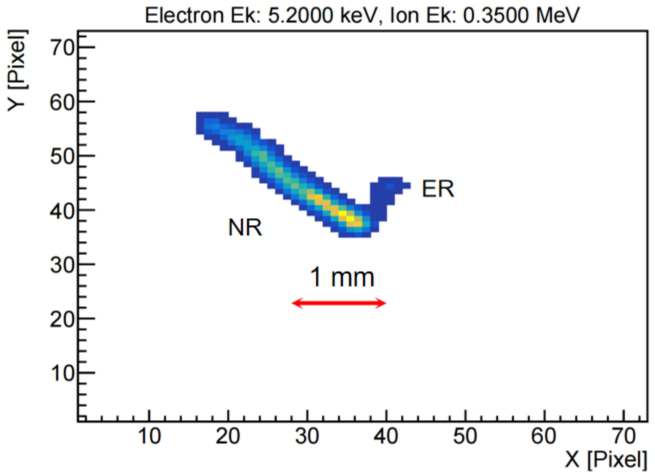
Topmetal







Characteristics of Migdal Events and Detector Requirements



- **ER~keV, NR~hundreds keV**
  - Good energy resolution
  - Large dynamic range.
- **ER shares vertex with NR**
  - Good vertex resolution
- **Reduce possible background**
  - Good time resolution

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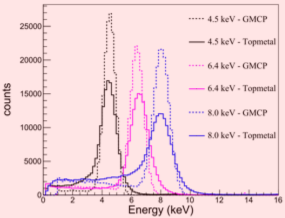
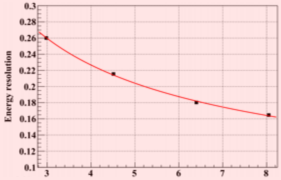
doi:10.1007/s41365-021-00903-0;
10.1088/1748-0221/18/08/P08012;
10.1016/j.nima.2023.168499;
10.1088/1748-0221/19/04/P04039

Detector performance

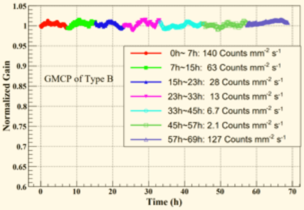
Energy

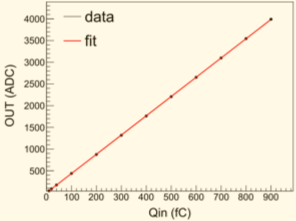




- Good linear energy response
- 20%-30% energy resolution(FWHM)
- Energy resolution follows the relationship ~ $1/\sqrt{E}$

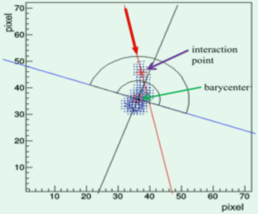
Dynamic range

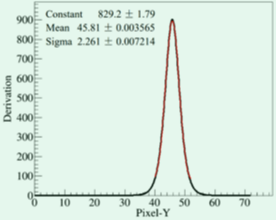




- Stable gain under different count rates(no charge pile up)
- Good linearity in charge response

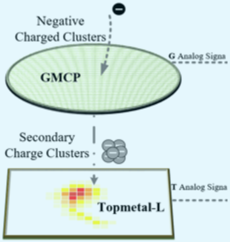
Vertex resolution

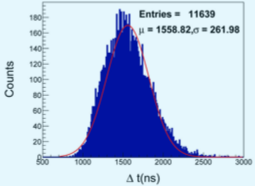




- ~200 μm vertex resolution @ 6.4 keV

Time resolution





- ~262 ns time resolution

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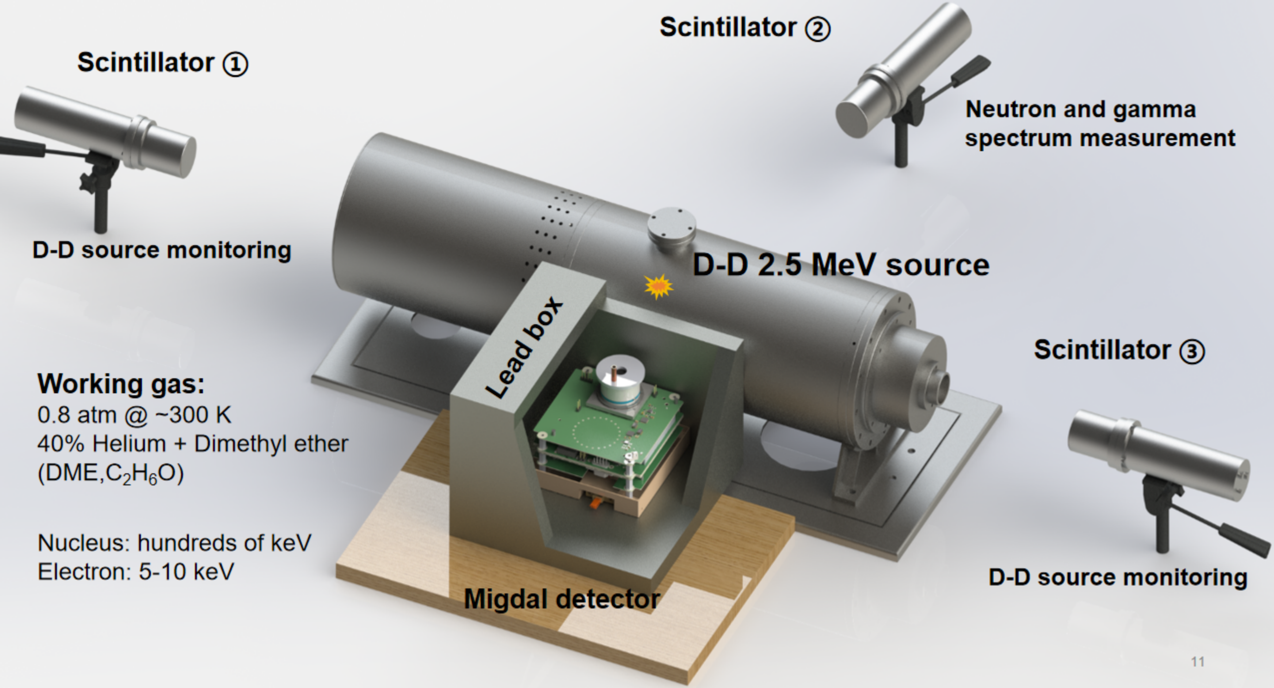

Working gas:
0.8 atm @ ~300 K
40% Helium + Dimethyl ether (DME, C_2H_6O)

Nucleus: hundreds of keV
Electron: 5-10 keV

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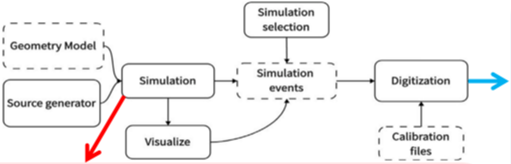
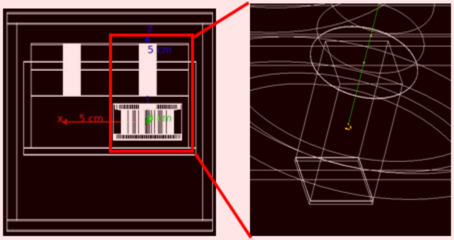
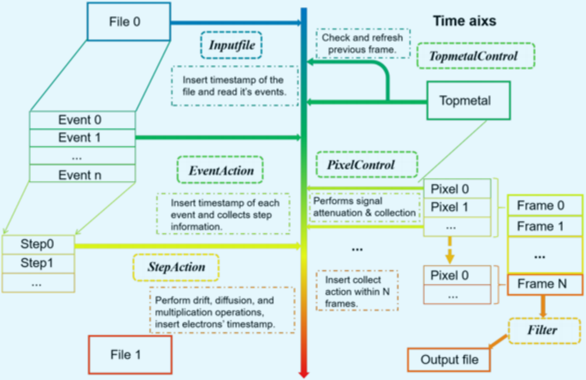
Simulation Framework

https://github.com/ElsevierSoftwareX/SOFTX-D-23-00679





- ✓ Simulate Migdal effect interaction with detector
- ➢ Simulate different interaction
- ➢ Provide energy deposit



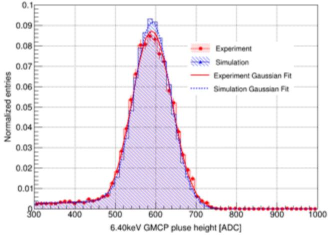
Parameters： MCP aperture, spacing, entry efficiency, multiplication factor, Fano factor; TopMetal pixel size, number, readout time interval, electron collection efficiency, ADC response,electron reception efficiency, noise, baseline,pixel signal attenuation...

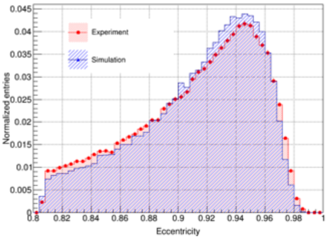
- ✓ Analog detector digital readout
- ➢ Simulate electron drifts, multiplies, collected procession
- ➢ Output file for data analysis and reconstruction algorithm

Consistency Between Simulation and Experiment

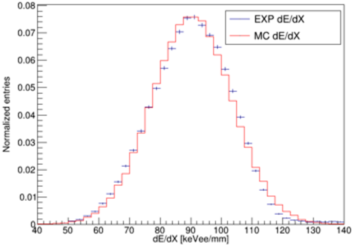
The consistency with experimental data nicely

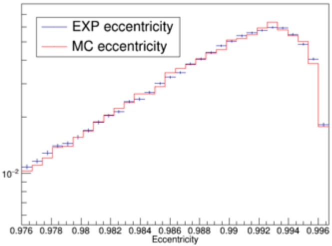
For **electron**: 6.4 keV photonelectron





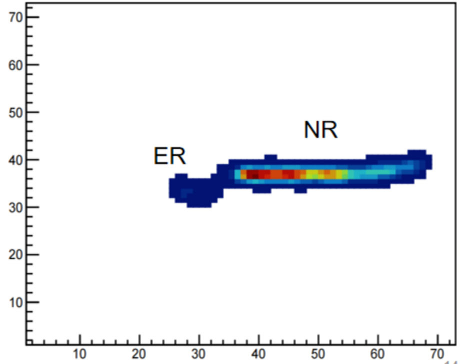
For **ion**(Alpha ray): ^{241}Am





Eccentricity, as a structural feature of images, takes into account the geometric shape of the tracks as well as the distribution of energy deposition.(NIM A,880 (2018), pp.188-193)

Electron Ek: 5.2500 keV, Ion Ek: 0.2300 MeV



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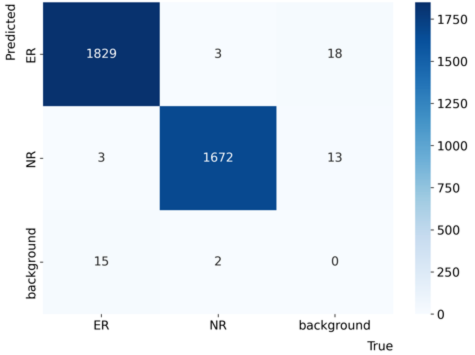
Event selection

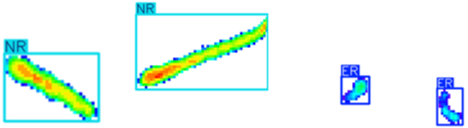
Data → YOLO*1 preselection → NR reconstruction → ER reconstruction → Vertex cut

Labeling

Dataset		Training	Validation
Experiment	^{55}Fe	3000	1493
	D-D	2994	1354
Simulation	ER	1200	301
	NR	1200	301
Total		8394	3449

Training →





NR, ER recognition result of the trained model

*1 https://github.com/ultralytics/ultralytics

Event selection

Data → YOLO*[1] preselection → NR reconstruction → ER reconstruction → Vertex cut

1. Search for the NR vertex through recursive iteration:

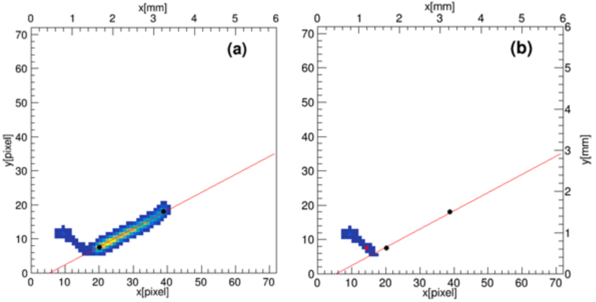
$$(x_0,y_0) \xrightarrow{\text{ADC}\cdot exp\,(d/d_0)} (x_n,y_n)$$

2. Fit the NR(direction, diffusion σ) and subtract it from the image.

3. Search for the electron vertex using **adaptive cutting algorithm**(doi:10.1007/s41365-021-00903-0).

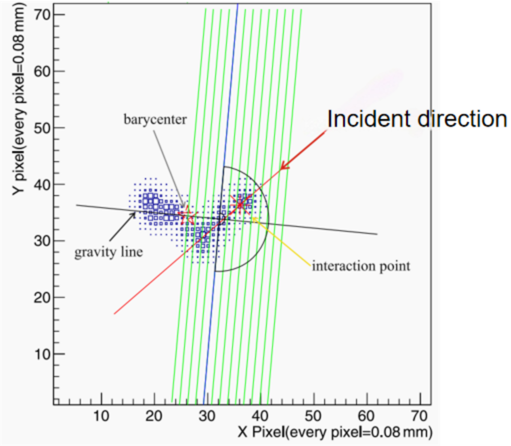
4. Determine whether the electron vertex is adjacent to the nucleon vertex.

$$R = \frac{D - 4\sigma}{L_{\text{ER}}} < 0.5$$



Adaptive cutting algorithm

- Determine the economic center of gravity and its trajectory based on ignition point and energy deposition.
- Calculate the sign of, M_d, $M_d = \sum_{point} (d^3 \times q)$, determine the head and tail(Bragg peak) of the trajectory
- Slide a perpendicular line along the center of gravity, compute the second-order moment M_2 to measure trajectory curvature, and truncate at the point of maximum M_2 change for a straightened path.
- Recalculate the center of gravity and its line for the truncated trajectory to identify the photoelectric interaction point and emission direction.



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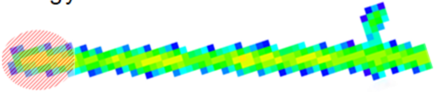
Background Component	Description	Expectation value (5 - 10 keV)
Recoil induced δ ray	δ electron near NR track origin	0.035 ± 0.023(stat.) ± 0.0068(sys.)
Particle Induced X-ray Emission		
X-ray emission	Photoelectron near NR track origin	0
Auger electrons	Auger electron near NR track origin	0
Bremsstrahlung processes		
Quasi-Free Electron (QFEB)	Photoelectron near NR track origin	≈ 0
Secondary Electron (SEB)	Photoelectron near NR track origin	≈ 0
Atomic (AB)	Photoelectron near NR track origin	≈ 0
Nuclear (NB)	Photoelectron near NR track origin	≈ 0
Random track coincidences	Photo-/Compton electron near NR track	0.180 ± 0.022(stat.) ± 0.042(sys.)
Muon induced δ ray	δ electron near NR track origin	0.013
Gas radioactivity		
Trace contaminants	Electron from decay near NR track origin	0.001 ± 0.00087(sys.)
Neutron activation	Electron from decay near NR track origin	≈ 0
Secondary nuclear recoil fork	NR track fork near track origin	≈ 0
Total background		0.229 ± 0.032(stat.) ± 0.043(sys.)

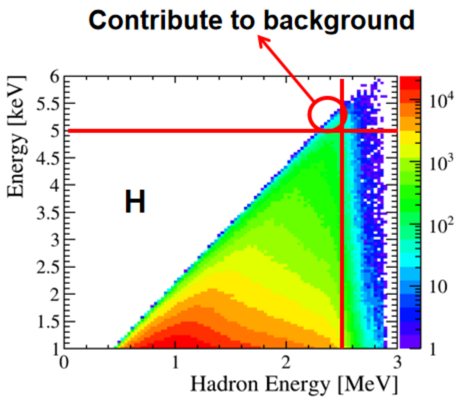
PRELIMINARY

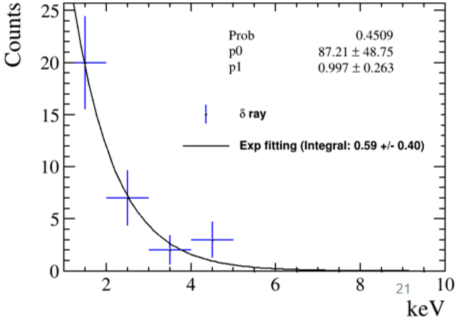
Recoil induced δ electron

- The δ-electron energies of C, O, and He are significantly lower than 5 keV, and only H can contribute to the background.
- Select δ-electrons located > 0.5 mm away from the nucleon vertex and fit their energy distribution.



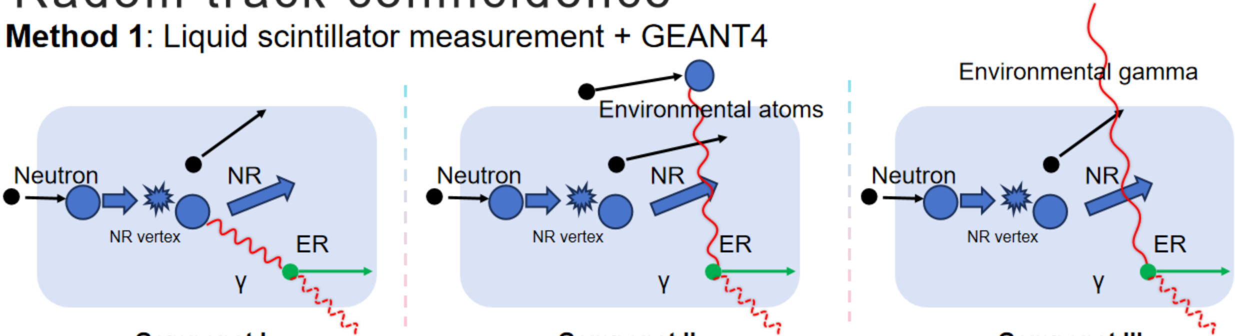
- No δ-electrons above 5 keV were found. By fitting an exponential function and extrapolating, the number of δ-electrons in the 5-10 keV range is estimated to be 0.59±0.40
- The ratio of the selection efficiency for δ-electrons near the vertex (<0.5 mm) to those at other positions (>0.5 mm), obtained using GEANT4 simulation and YOLO： 6%.
- Finally get: 0.035±0.023(stat.)



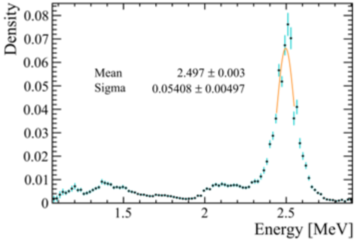


Radom track conincidence

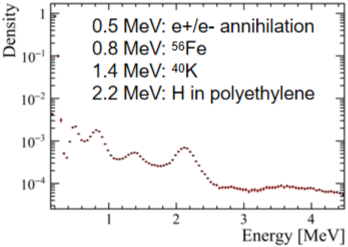
Method 1: Liquid scintillator measurement + GEANT4



Componet I **Componet II** **Componet III**



Neutron spectrum



Gamma spectrum

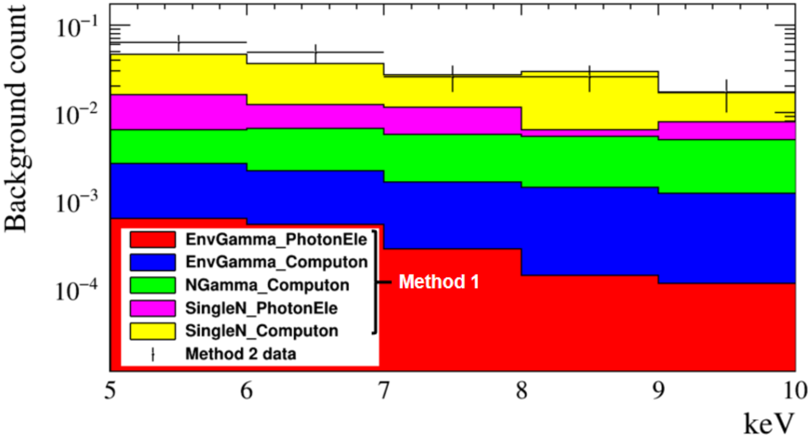
A trillion neutron + 50 billion gamma simulation gives:

Componet	NR	Compton e⁻	photonEle
I	1	4.32×10^{-5}	1.06×10^{-5}
II	1	6.06×10^{-6}	$\sim 3.63 \times 10^{-8}$
III	1	3.11×10^{-6}	7.15×10^{-7}

The expected background contribution of the 3 components in total is: 0.16±0.01(stat.)

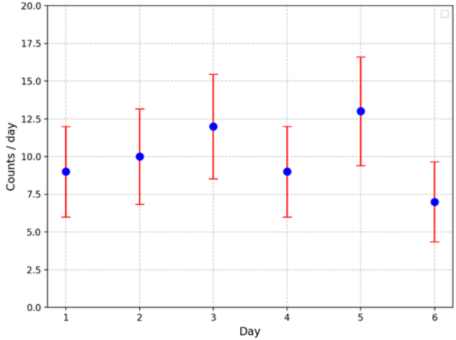
Radom track conincidence

- **Method 2:** Data from Migdal detector
  - Get the number of electron tracks within the 5-10 keV energy range that appear in the same frame as the nucleon tracks. Considering the accidental coincidence of NR and ER with a vertex selection efficiency, the final expected background value is 0.180±0.022(stat.)±0.042(sys.)

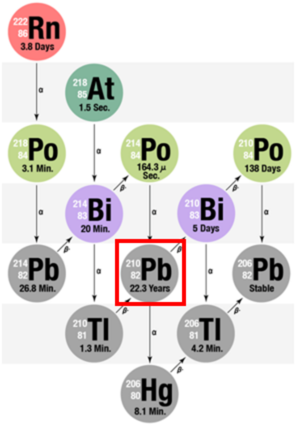


The results from the liquid scintillation + GEANT4 are **consistent** with the direct measurements obtained from the Migdal detector.

Trace contaminants



The detector's alpha decay count rate



The decay chain of ^{222}Rn

- The working natural abundance:
  - ^{3}H:$(6.38 \pm 6.38)\times 10^{-8}$ Bq
  - ^{14}C:$(4.58 \pm 4.58)\times 10^{-5}$ Bq
- β decay between 5-10 keV:
  - ^{3}H:$(2.29 \pm 2.29)\times 10^{-8}$ /s
  - ^{14}C:$(2.59 \pm 2.59)\times 10^{-6}$ /s

β decay between 5-10 keV contributed by the ^{222}Rn decay chain:

- $(7.25 \pm 0.94) \times 10^{-7}$ /s

Combined with the natural abundance values of the working gas:

- $(3.34 \pm 2.71) \times 10^{-6}$ /s

GEANT4 simulation of trace radioactivity generating 5-10 keV pseudo-Migdal events yields a selection efficiency of 11.4%

The final expectation for the background contribution from trace radioactivity is: 0.001 ± 0.001.

Assuming:

- All alpha rays are attributed to the decay chain of ^{222}Rn.
- The secondary nuclides with a half-life of less than 1 year have completely decayed.
- Decay process ultimately ceases at ^{210}Pb.

- The Migdal effect plays a very important role in light dark matter research.
- However this effect has not been observed with the neutral projectile.
- Gas pixel detector designed to find Migdal electron.
- Simulation, reconstruction, background analysis has been done.
- Phase I experiment has been successfully completed.
- Detector upgrades and the Phase II experiment are currently in preparation.

Thanks for your attention!