MigdAl pRocess Validation by nEutruaL scattering

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on behalf of MARVEL group

May 9, 2024

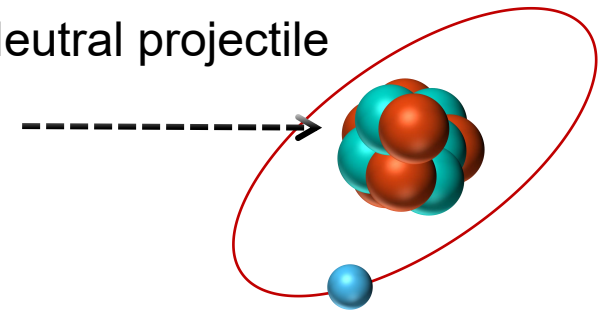
Xichang, Si Chuan

Outline

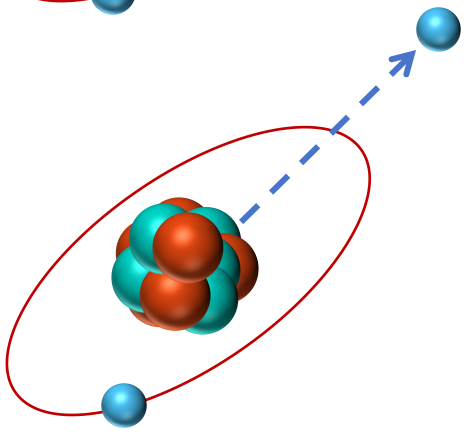
- Motivation
- MARVEL experiment proposal
- Simulation & reconstruction
- Background analysis
- Summary and outlook

What happens in neuclear recoil?

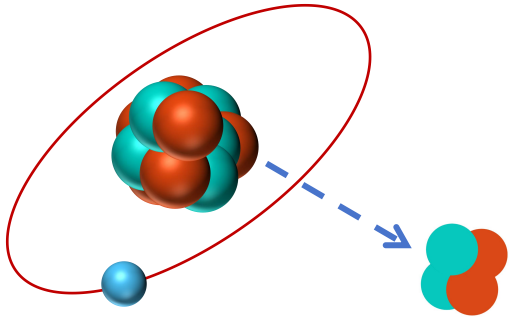
Neutral projectile



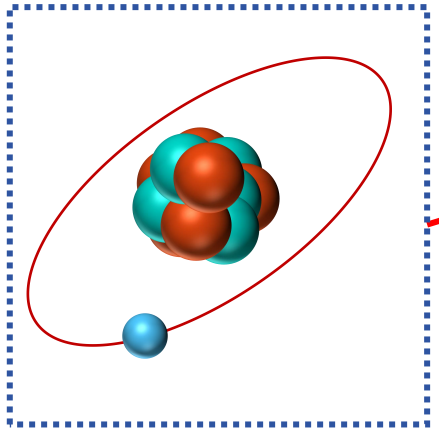
β decay



α decay



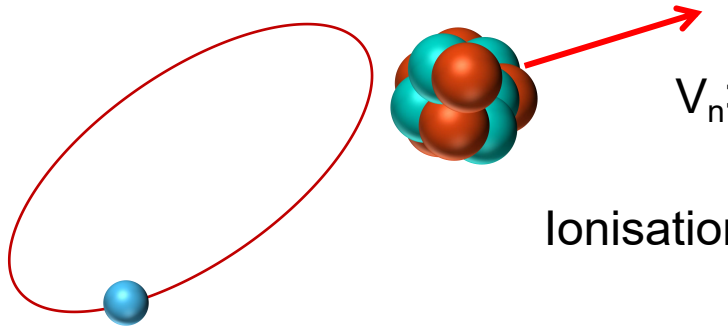
1. Low energy transition



$V_n << \alpha c$

The entire atom moves together

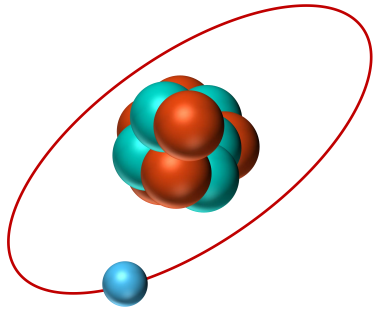
2. High energy transition



$V_n >> \alpha c$

Ionisation

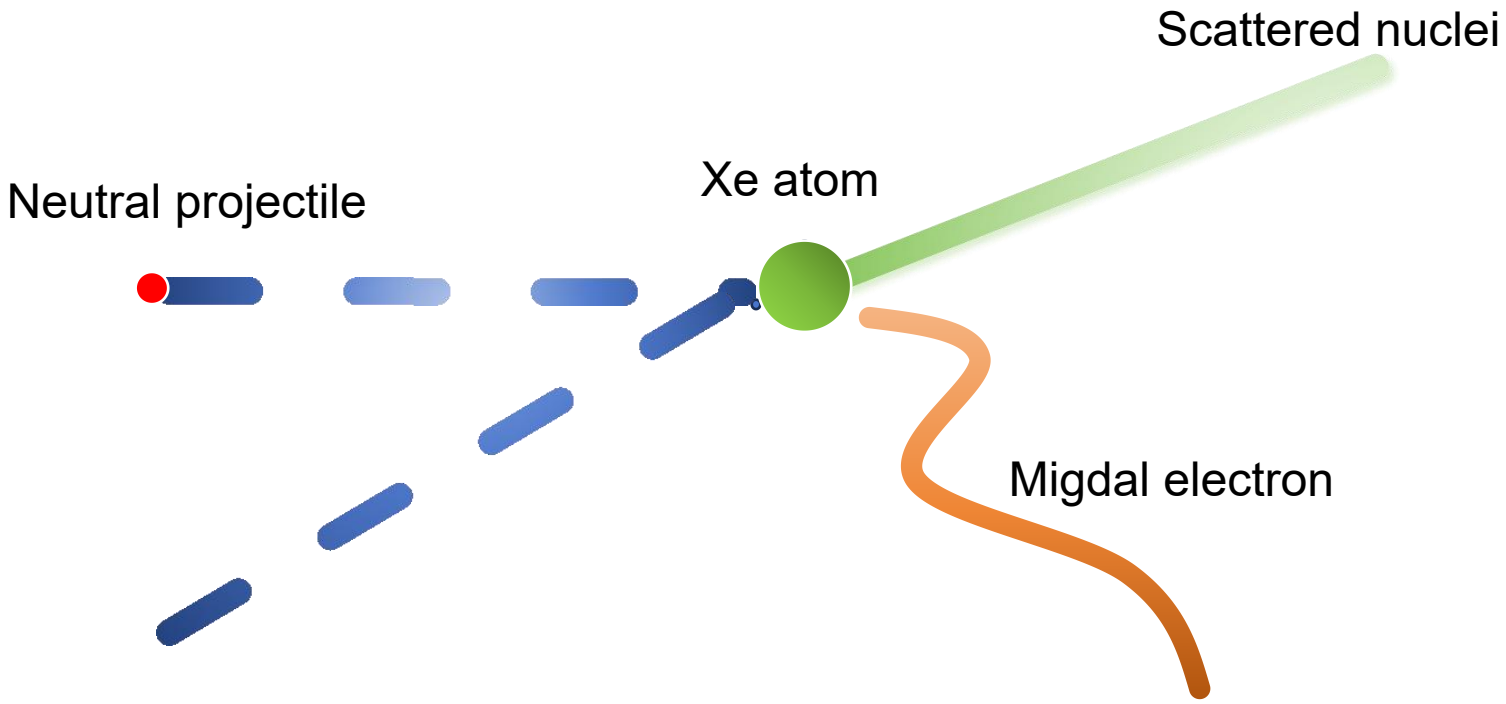
2. Middle energy transition

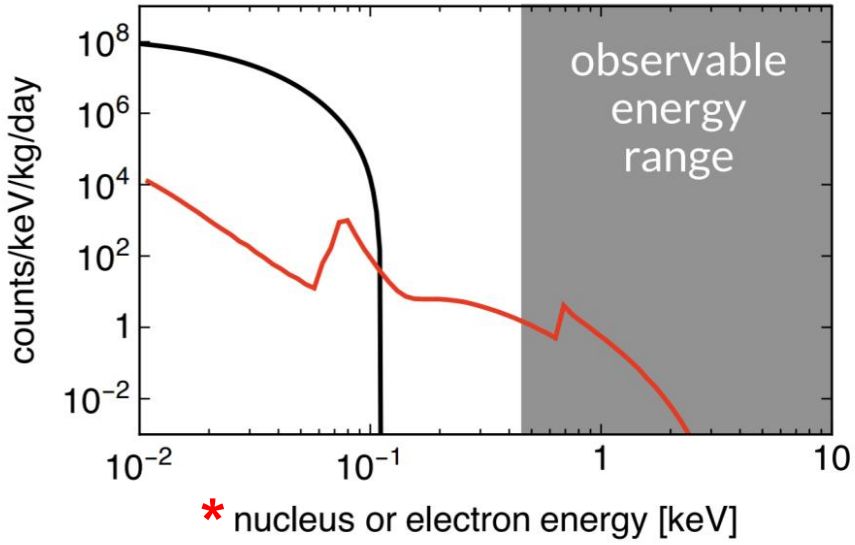


?

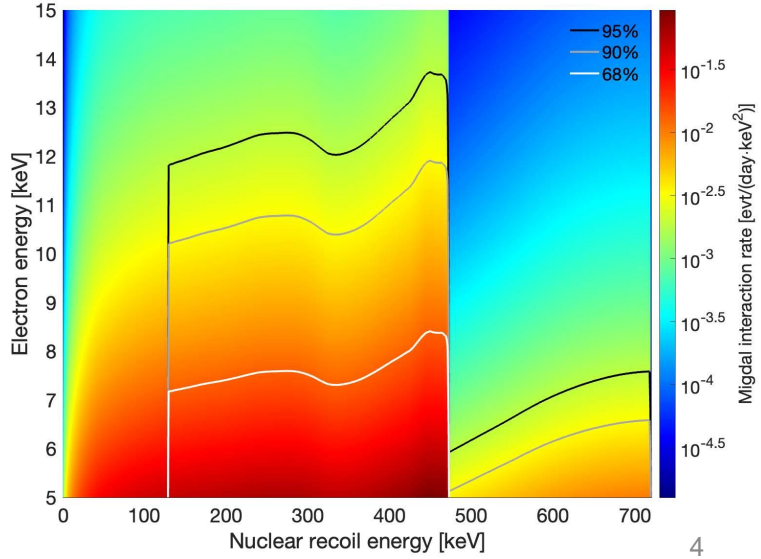
$V_n \approx \alpha c$

The Migdal effect?





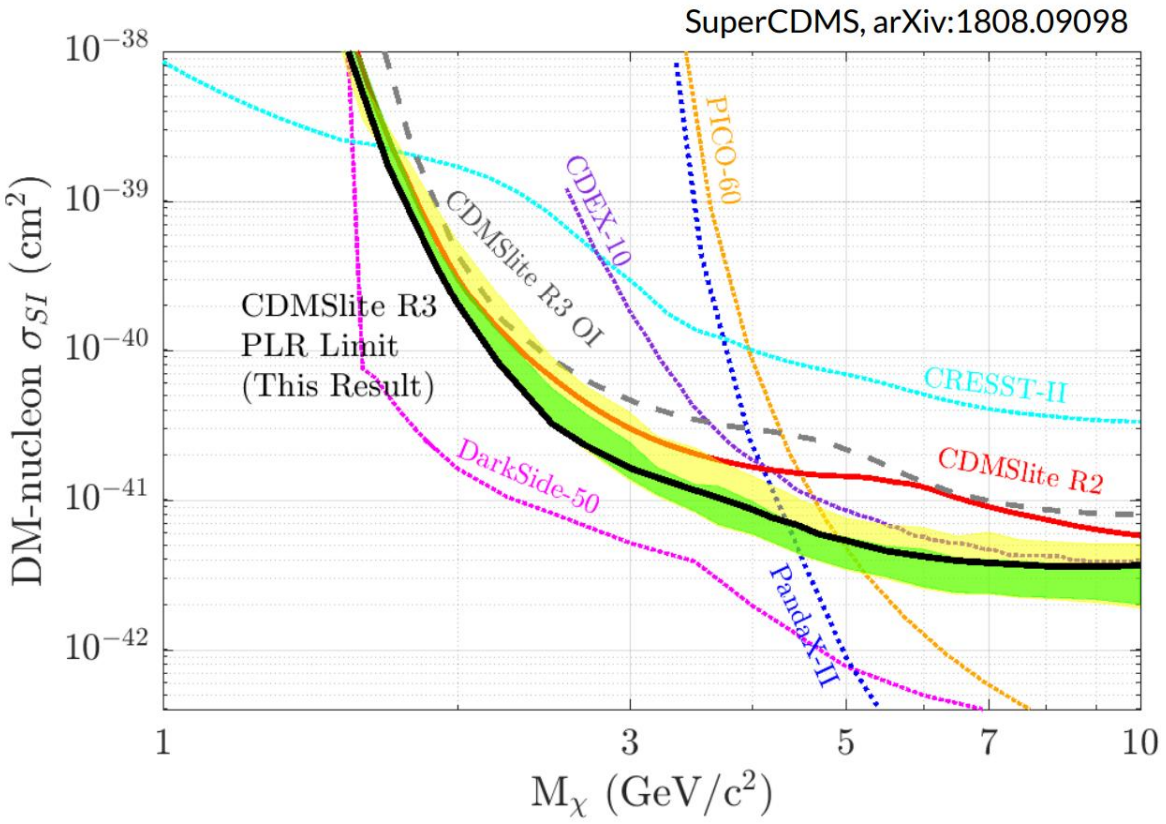
astropartphys.2023.102853

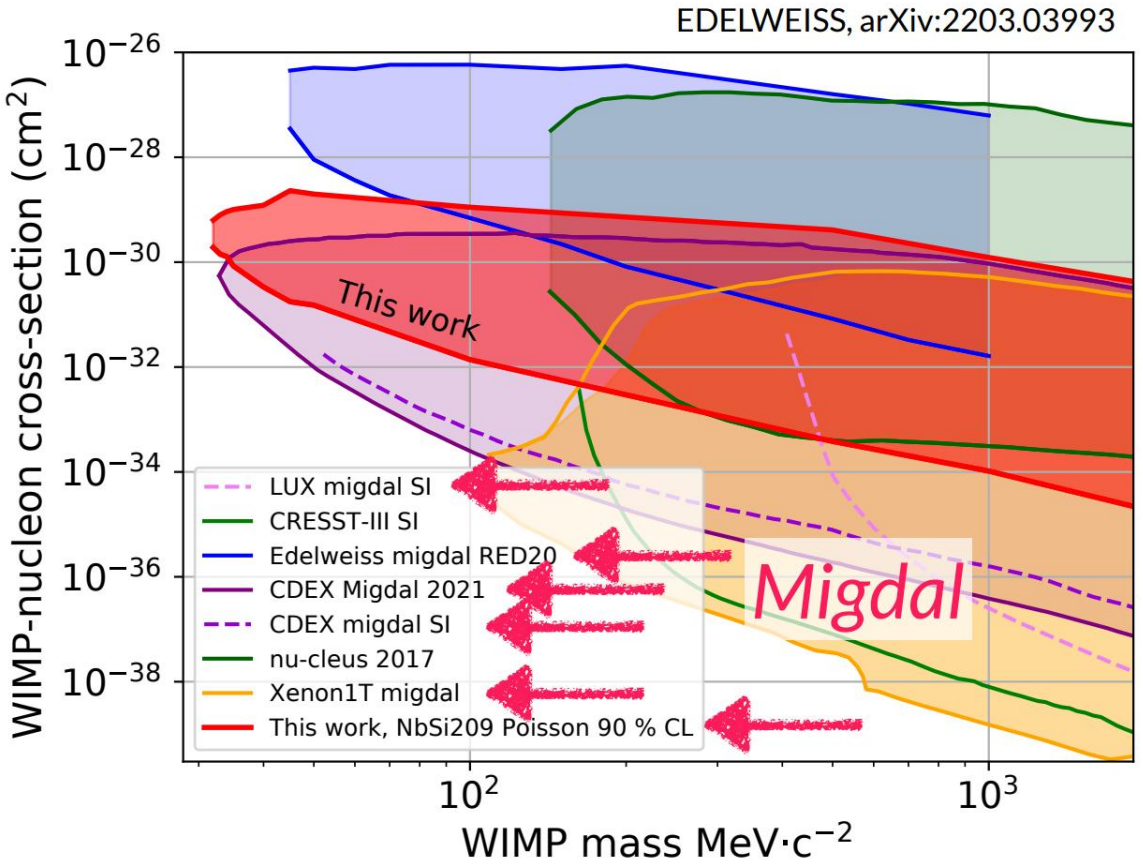


- Energy deposition = nuclear scattering + Migdal effect electron
- Without the uncertainty of quenching factor

*Particle Avenues in the Dark Universe Arena (PADUA): Light dark sectors, 6 September 2023

Sub-GeV searches increasingly dominated by Migdal





Pre-2018
No Migdal limits

Migdal effect in dark matter direct detection experiments, Ibe et al arXiv:1707.07258

Today
Dominated by Migdal

The Migdal effect?

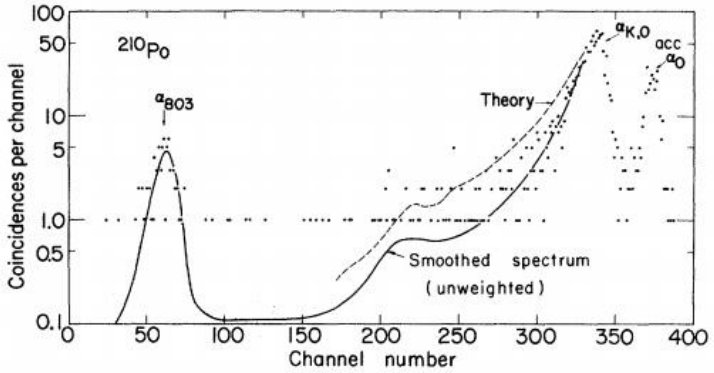
Predicted by A.Migdal date back to the 1940s

Predicted effect in:

1. α， β decay

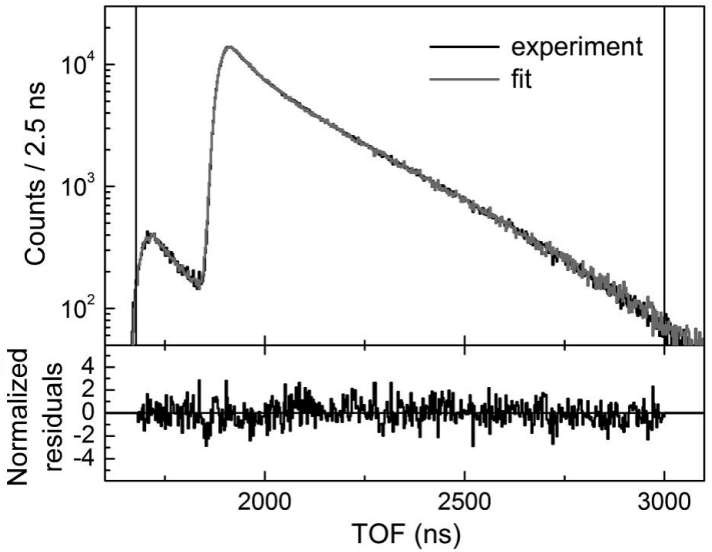
2. Neutral scattering

oberved in β decay

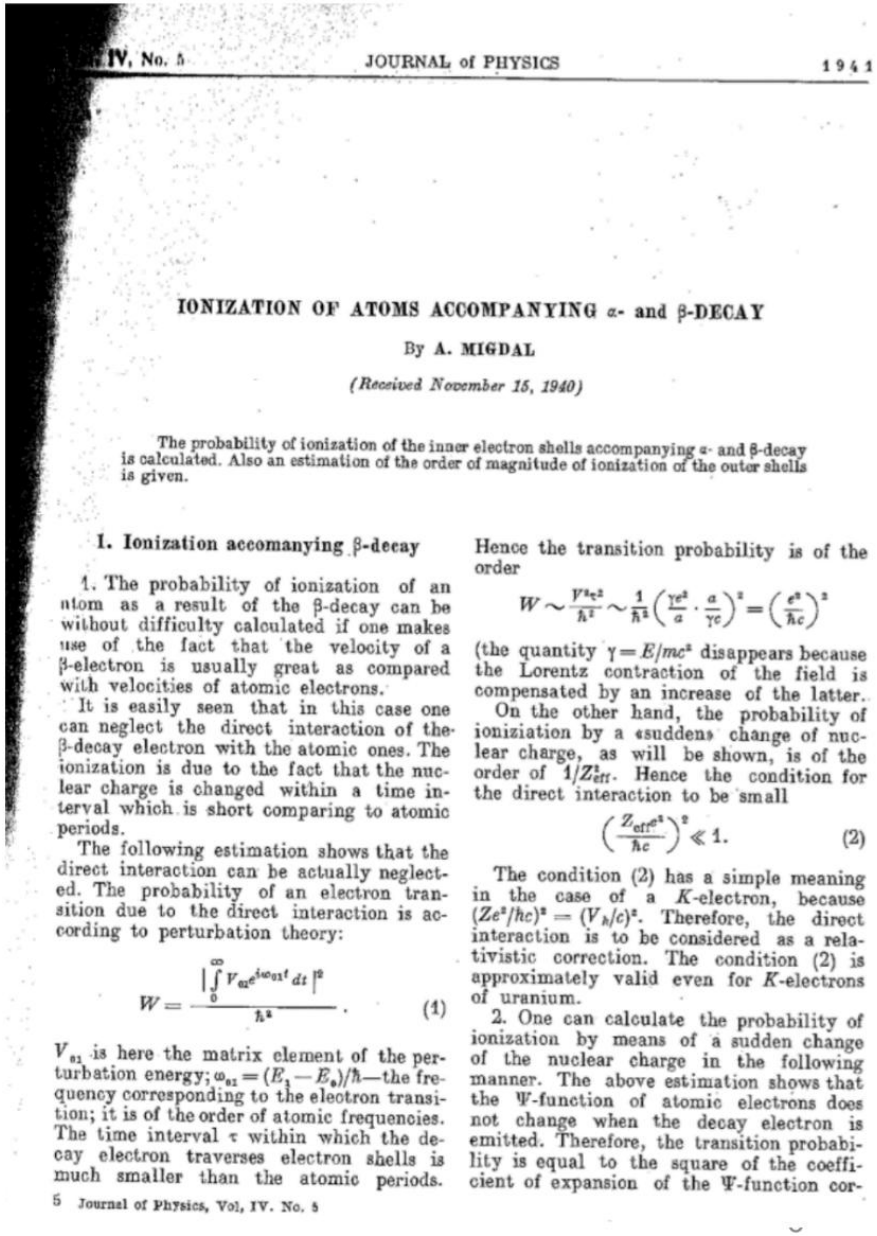


PhysRevC.11.1740

oberved in α decay



PhysRevLett.108.243201



IV, No. 5 JOURNAL of PHYSICS 1941

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.

1. Ionization accomanying β-decay

1. The probability of ionization of an atom as a result of the β-decay can be without difficulty calculated if one makes use of the fact that the velocity of a β-electron is usually great as compared with velocities of atomic electrons.

It is easily seen that in this case one can neglect the direct interaction of the β-decay electron with the atomic ones. The ionization is due to the fact that the nuclear charge is changed within a time interval which is short comparing to atomic periods.

The following estimation shows that the direct interaction can be actually neglected. The probability of an electron transition due to the direct interaction is according to perturbation theory:

$$W = \frac{\left|\int_0^\infty V_{01} e^{i\omega_{01} t}\, dt\right|^2}{\hbar^2}. \qquad (1)$$

V_{01} is here the matrix element of the perturbation energy; $\omega_{01} = (E_1 - E_0)/\hbar$—the frequency corresponding to the electron transition; it is of the order of atomic frequencies. The time interval τ within which the decay electron traverses electron shells is much smaller than the atomic periods. Hence the transition probability is of the order

$$W \sim \frac{V^2\tau^2}{\hbar^2} \sim \frac{1}{\hbar^2}\left(\frac{Ze^2}{a}\cdot\frac{a}{\gamma c}\right)^2 = \left(\frac{e^2}{\hbar c}\right)^2$$

(the quantity $\gamma = E/mc^2$ disappears because the Lorentz contraction of the field is compensated by an increase of the latter.

On the other hand, the probability of ionization by a «sudden» change of nuclear charge, as will be shown, is of the order of $1/Z_{eff}^2$. Hence the condition for the direct interaction to be small

$$\left(\frac{Z_{eff}e^2}{\hbar c}\right)^2 \ll 1. \qquad (2)$$

The condition (2) has a simple meaning in the case of a K-electron, because $(Ze^2/\hbar c)^2 = (V_k/c)^2$. Therefore, the direct interaction is to be considered as a relativistic correction. The condition (2) is approximately valid even for K-electrons of uranium.

2. One can calculate the probability of ionization by means of a sudden change of the nuclear charge in the following manner. The above estimation shows that the Ψ-function of atomic electrons does not change when the decay electron is emitted. Therefore, the transition probability is equal to the square of the coefficient of expansion of the Ψ-function cor-

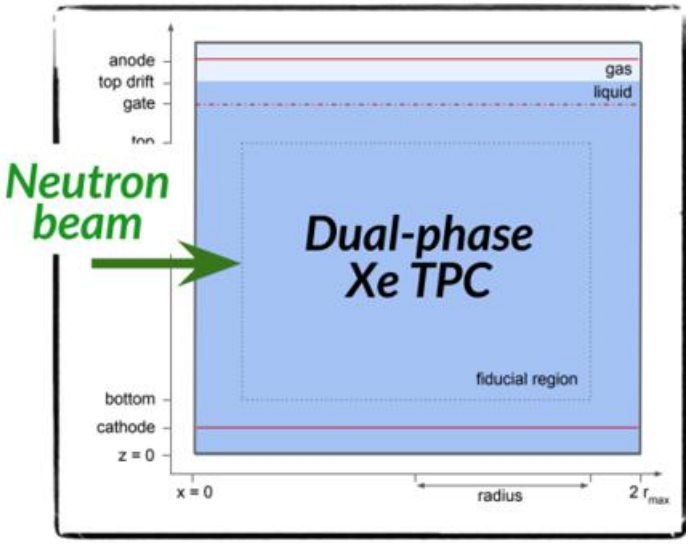
5 Journal of Physics, Vol. IV. No. 5

Haven’t been oberved in Neutral scattering

Migdal electron haven’t been oberved directly

Proposed MIGDAL experiment

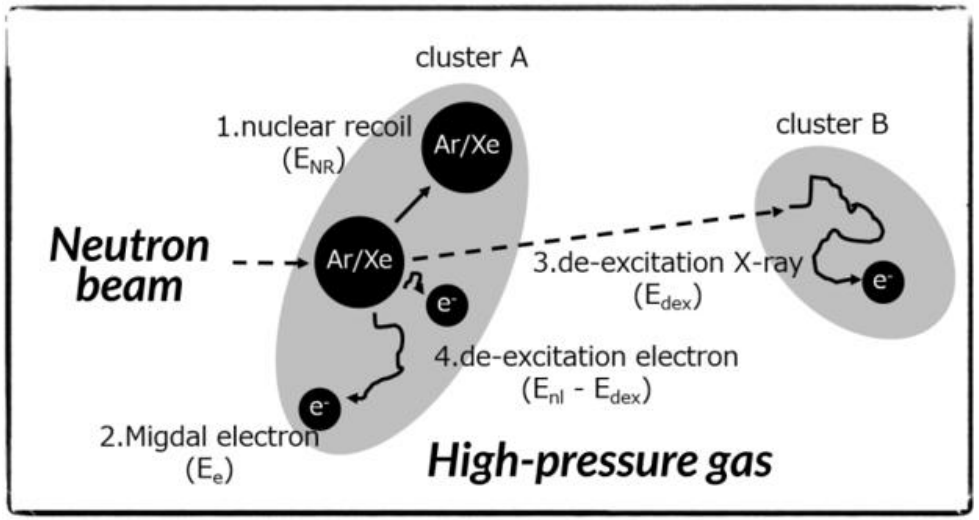
Bell et al, arXiv:2112.08514
Xu et al, arXiv:2307.12952



$E_{\text{neutron}} \sim 15 - 15000$ keV

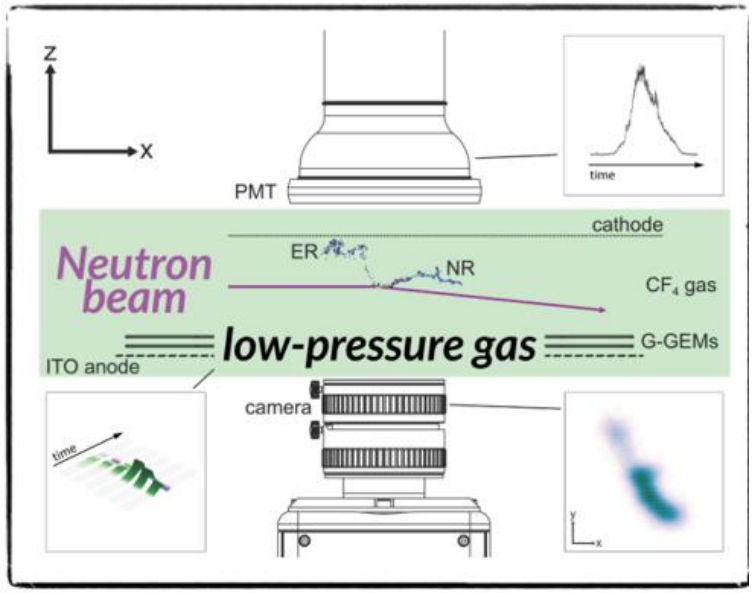
S1/S2

Nakamura et al, arXiv:2009.05939



$E_{\text{neutron}} \sim 500$ keV

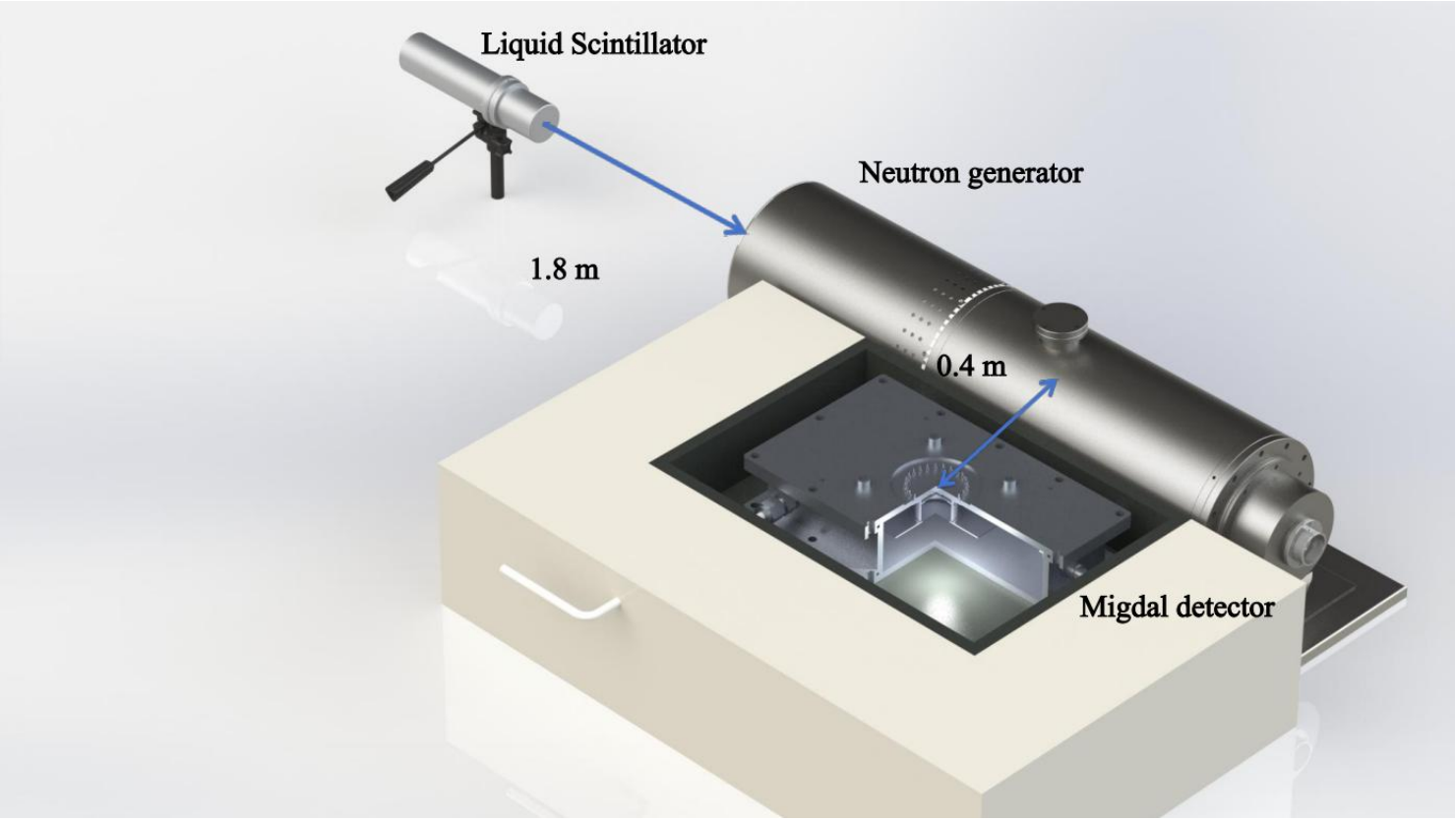
Araújo et al (MIGDAL), arXiv:2207.08284



$E_{\text{neutron}} \sim 2500 - 15000$ keV

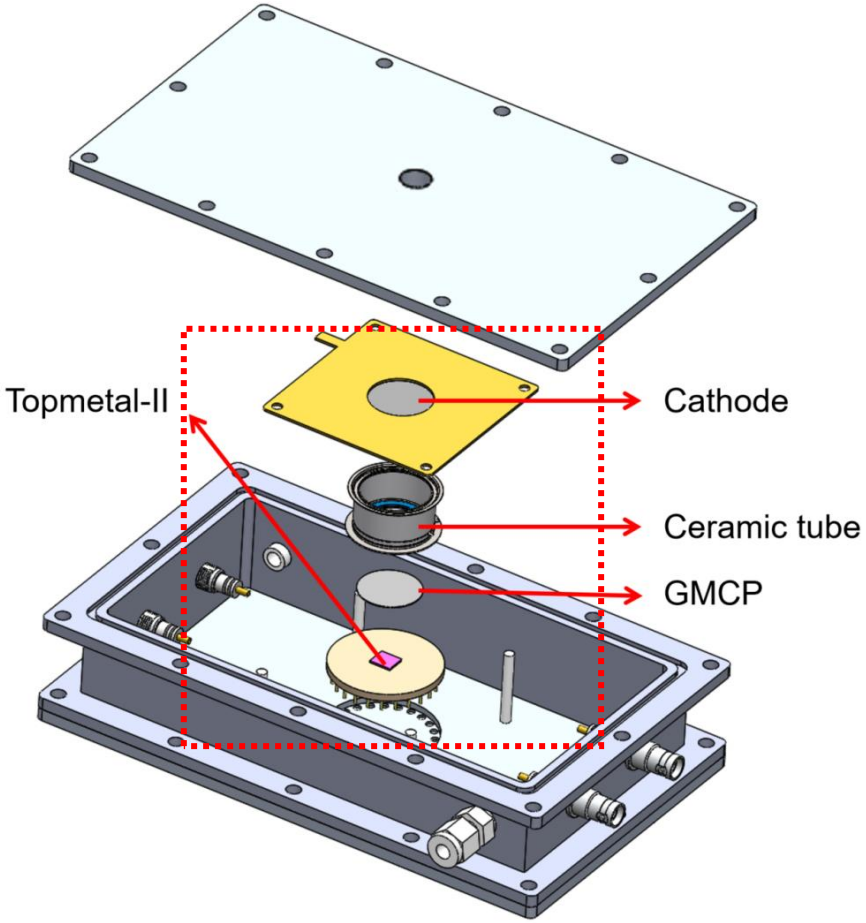
Optical TPC

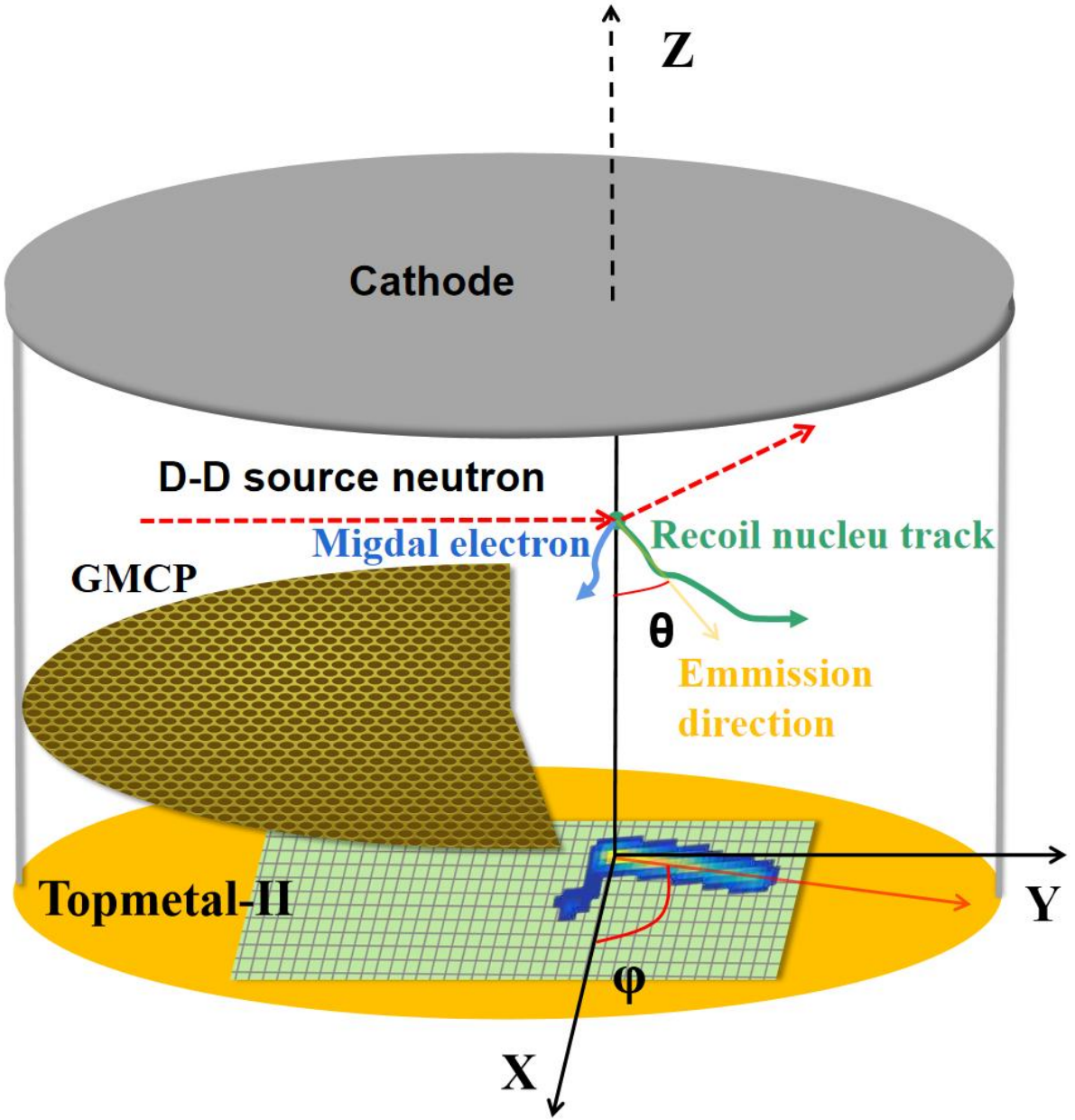
MARVEL experiment



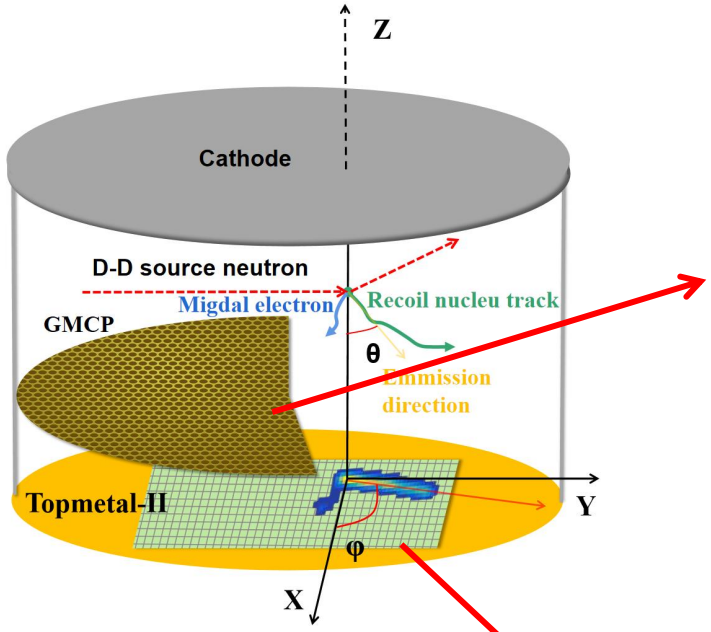
- Mixture of dimethyl ether(DME,C_2H_6O) and helium gas at 1 atm
  - High efficency
  - low diffusion coefficient
  - relativly long electron track
- Gas Microchannel Plate(GMCP) amplification
  - High gain upto~10^4
  - Fine granularity
  - Stable gain coefficient
- Topmetal Charge-sensitive chip imaging
  - Fine granularity
  - High resolution

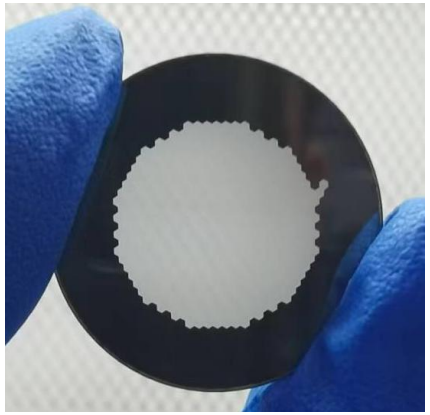
Detector construction





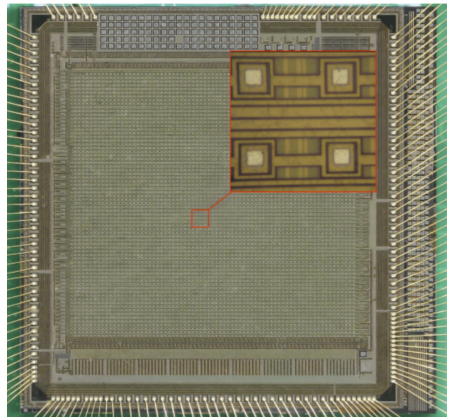
Working principle





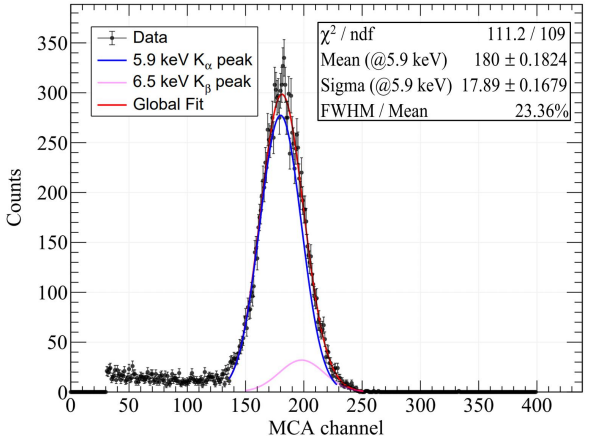
Topmetal-II-:

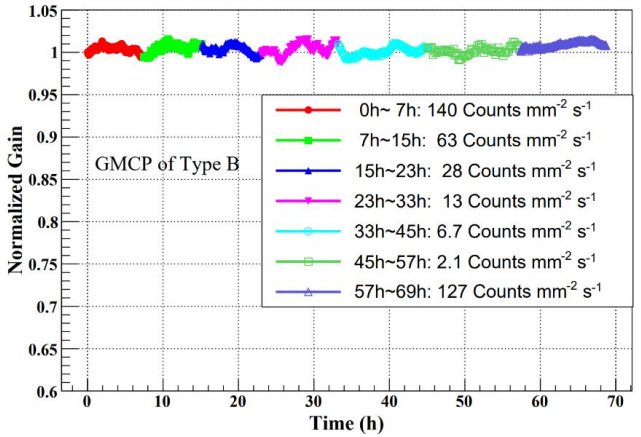
- 83 um pitch
- 2.5 ms time resolution
- noise 13.9e-

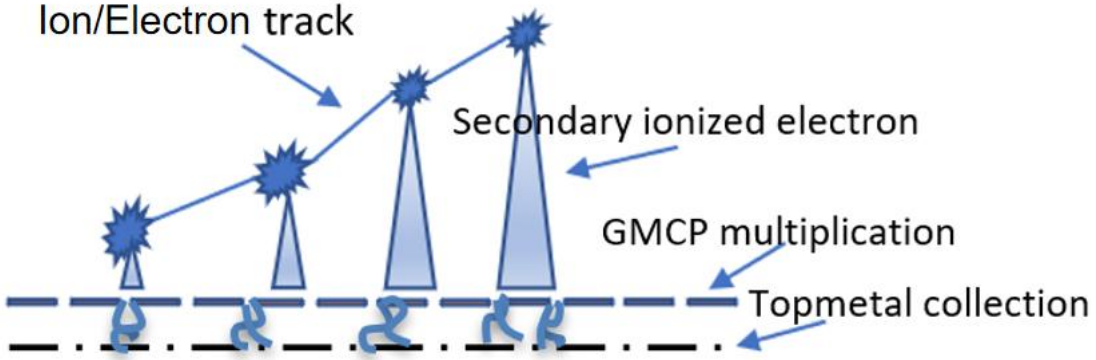


GMCP:

- 50 um diameter, 60 um pitch
- High energy resolution
- Stable gain coefficient

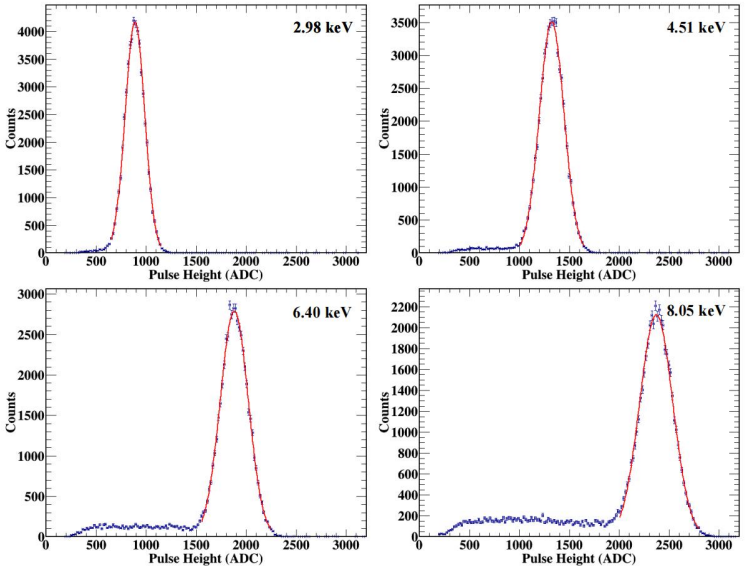


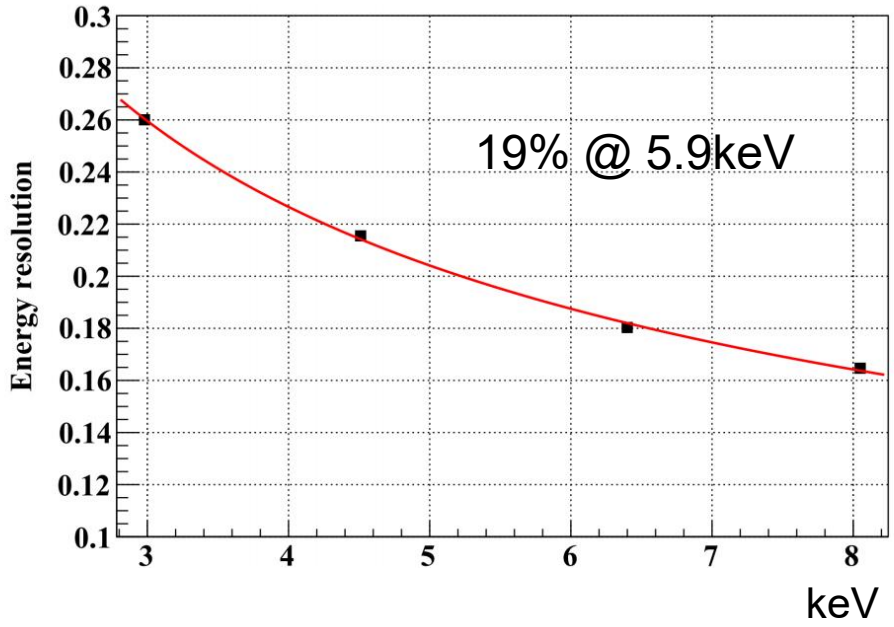




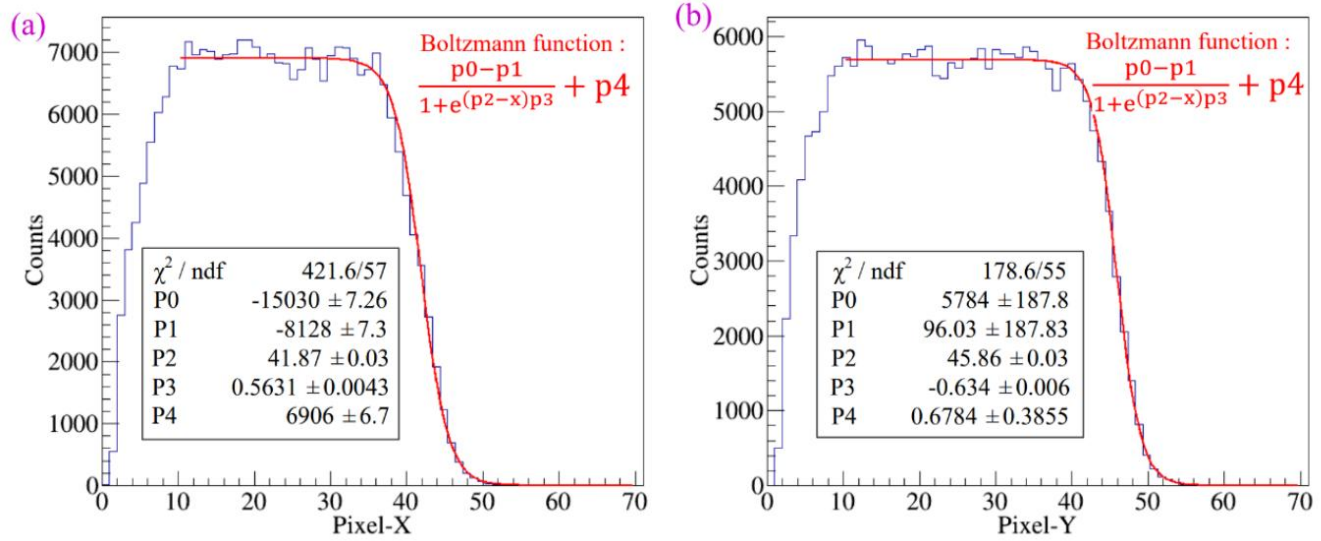
Detector Calibration

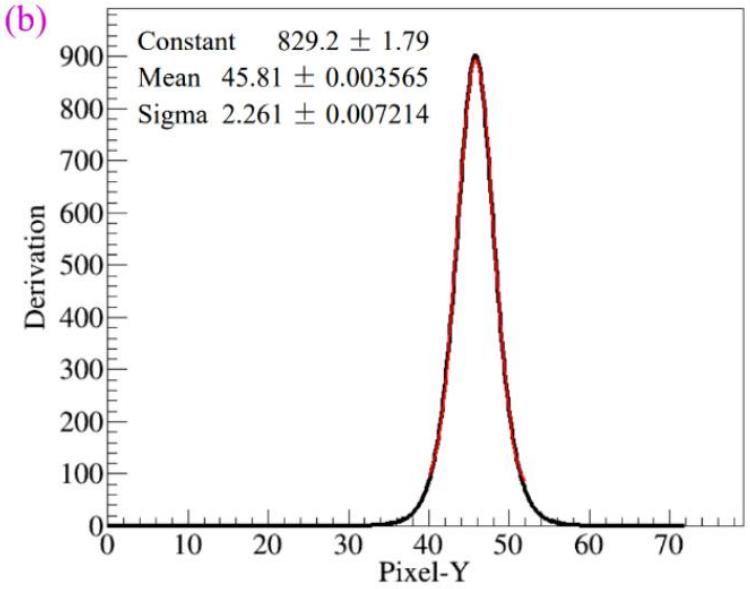
Energy resolution:





Position resolution:





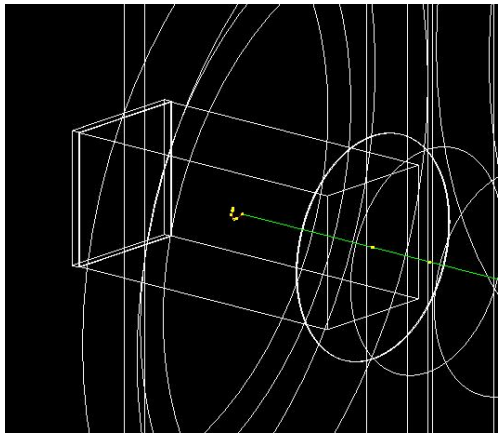
~180 um
position resolution

Simulation Framework

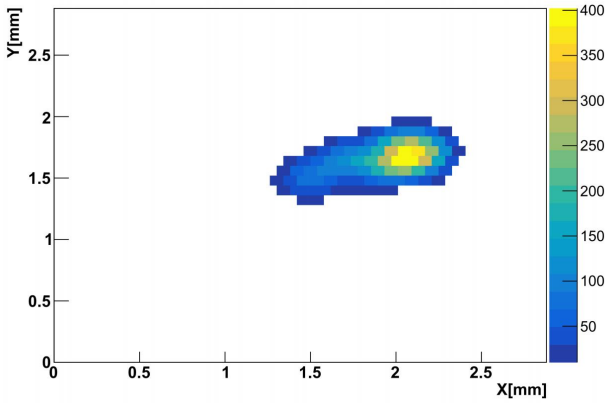
- Motivation:
  Establish a framework for Migdal electron and Ion measurement simulation and offline data analysis

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

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



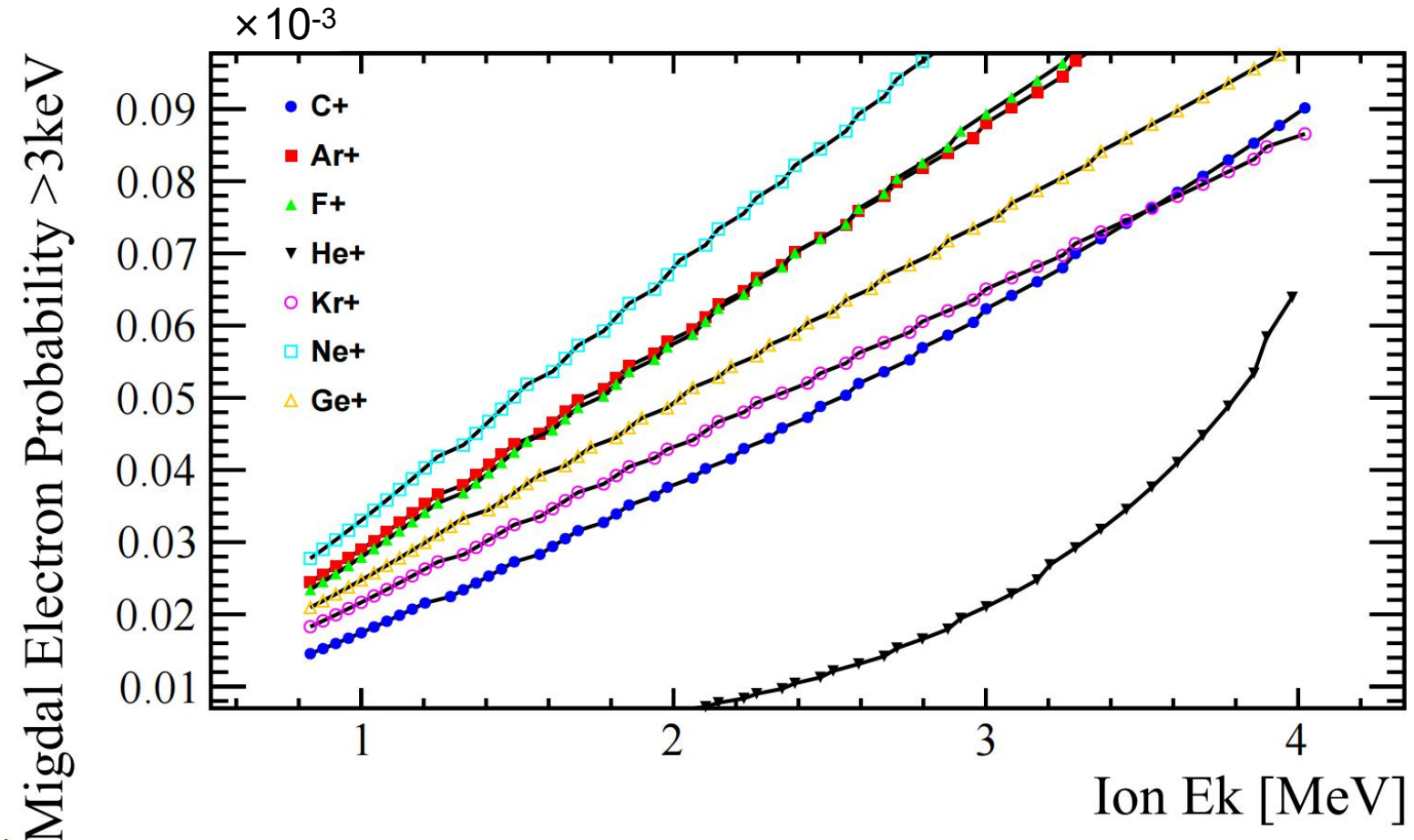
Detector modeling



Track simulation

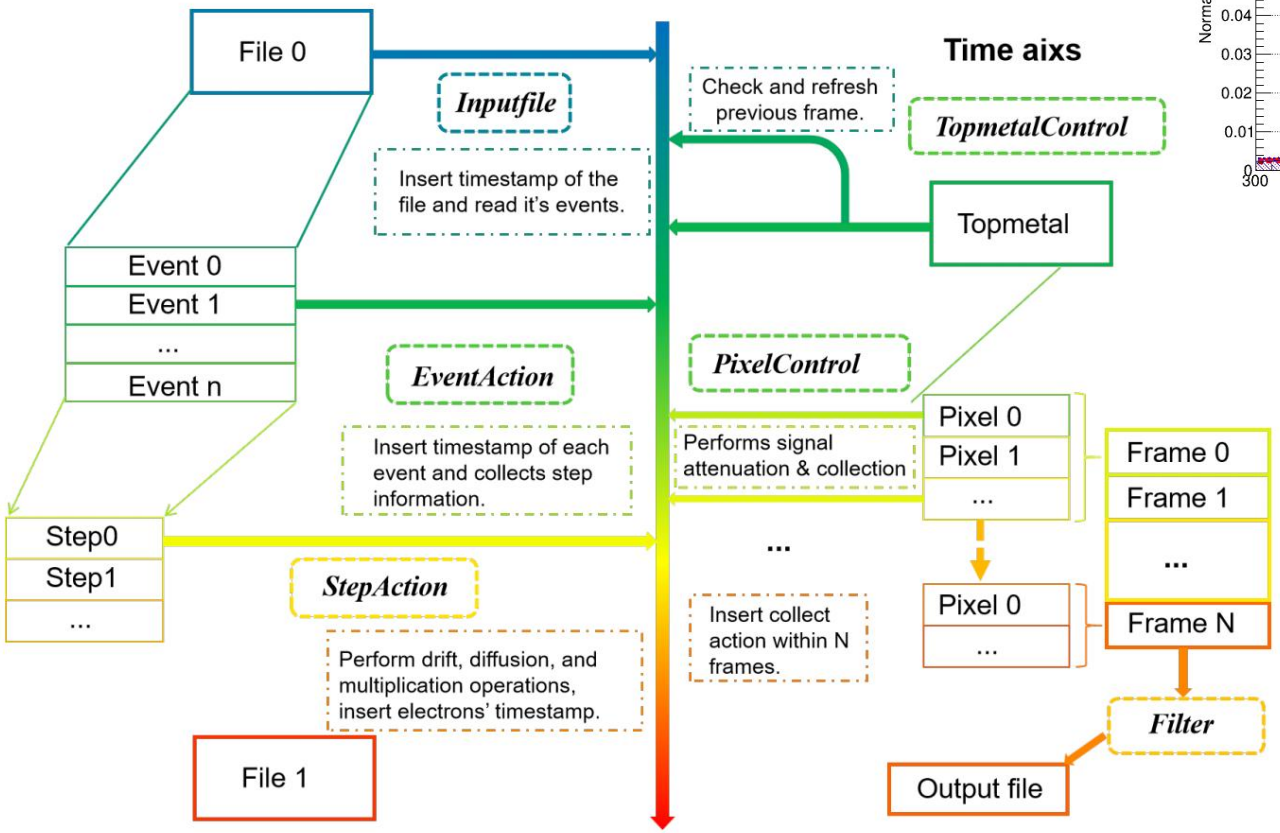
Simulation

- **The cross sections for nuclear interaction and electromagnetic interaction are from Geant4**
- **The theoretical Migdal cross sections for Ar/C/F/Ge/He/Kr/Ne/Si/Xe nuclei are available.**

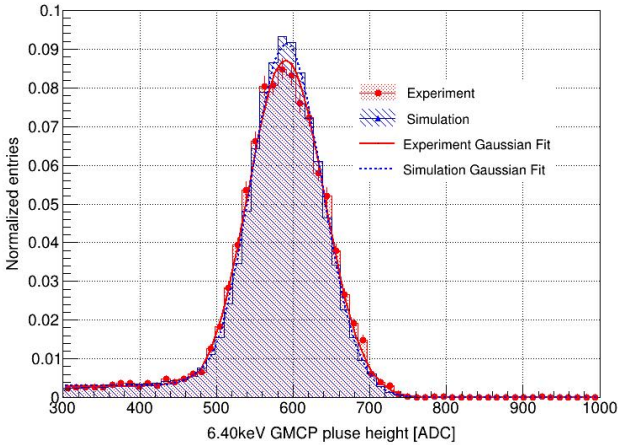


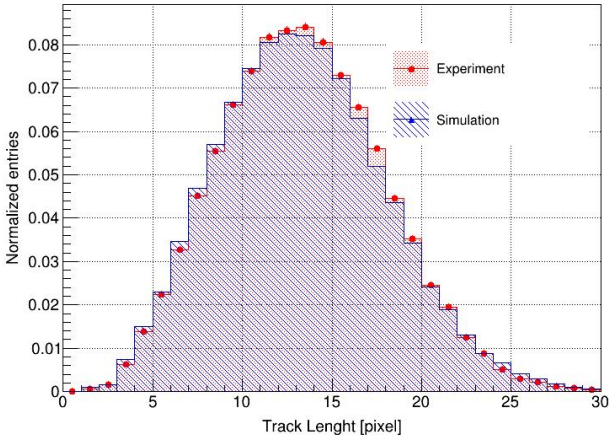
Digitization

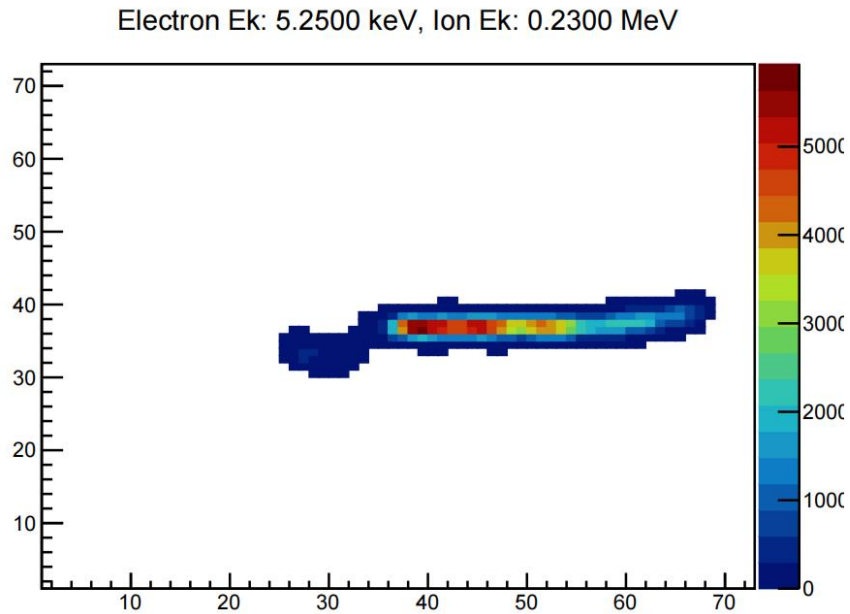
- The digitization is entirely based on the electronic readout logic design.



The consistency with experimental data nicely



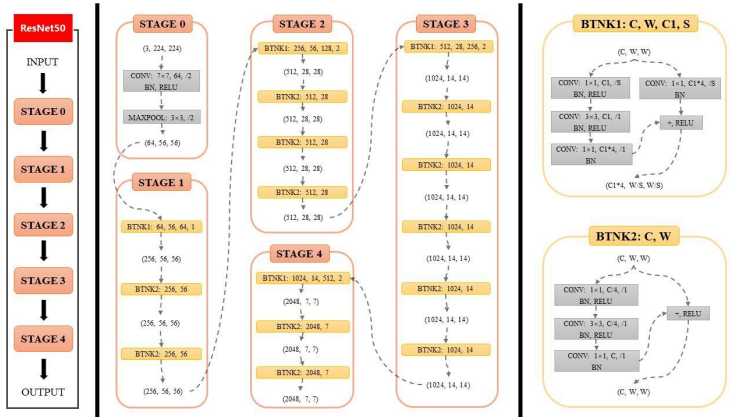


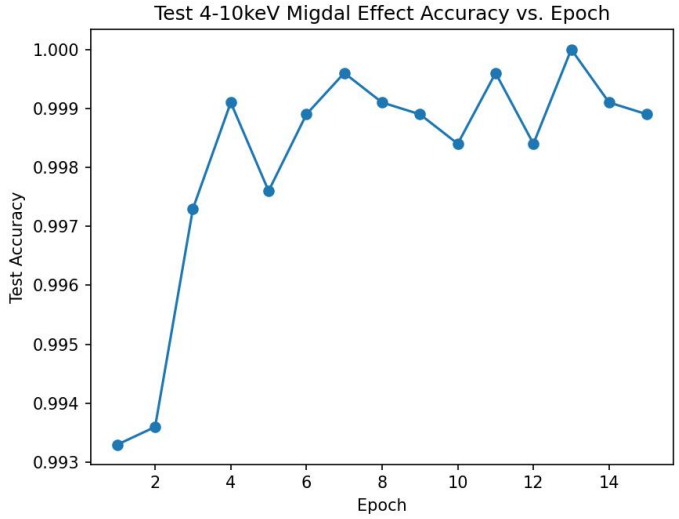


A simulation example

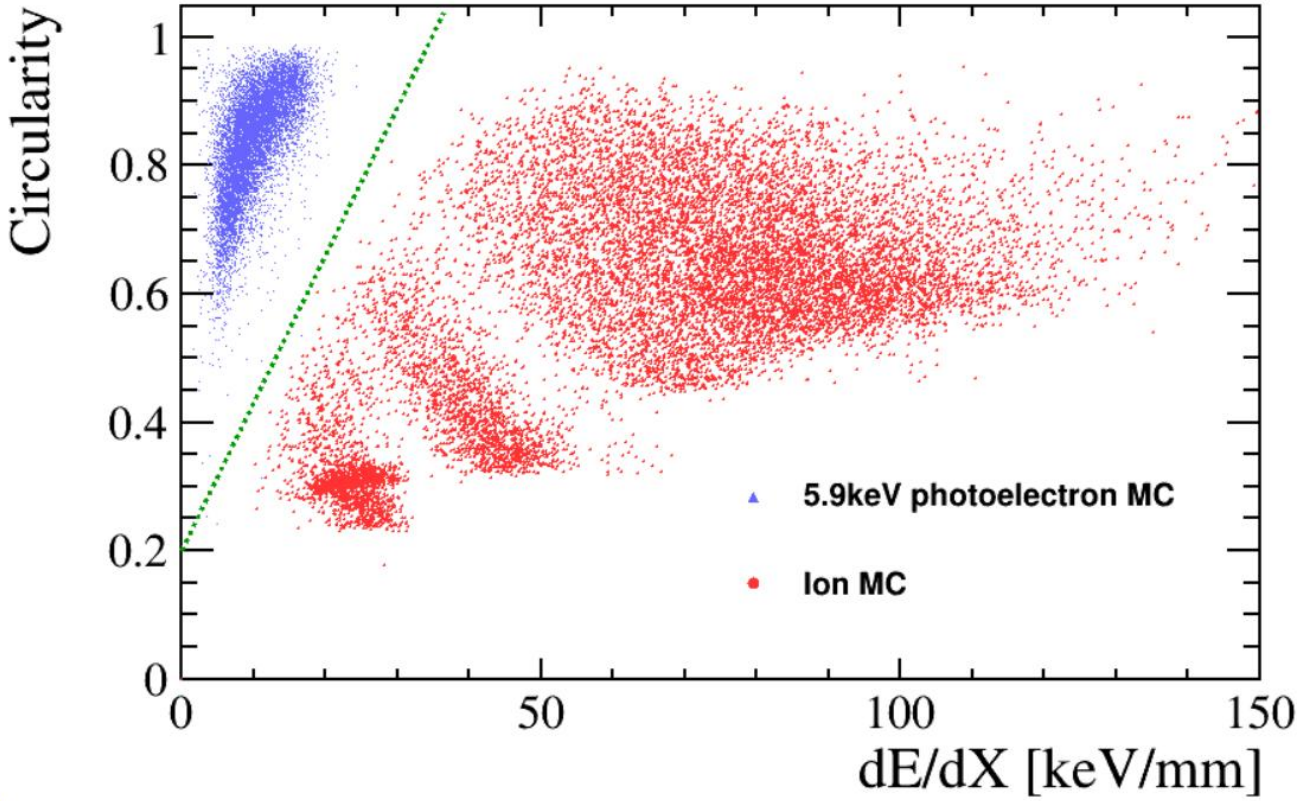
Reconstruction& Selection

- ResNet50 neural network trained based on simulated data for Migdal instance identification.





- A few keV electrons and recoiling nuclei bear distinguished features in circularity and dE/dx.



Backgrounds Analysis

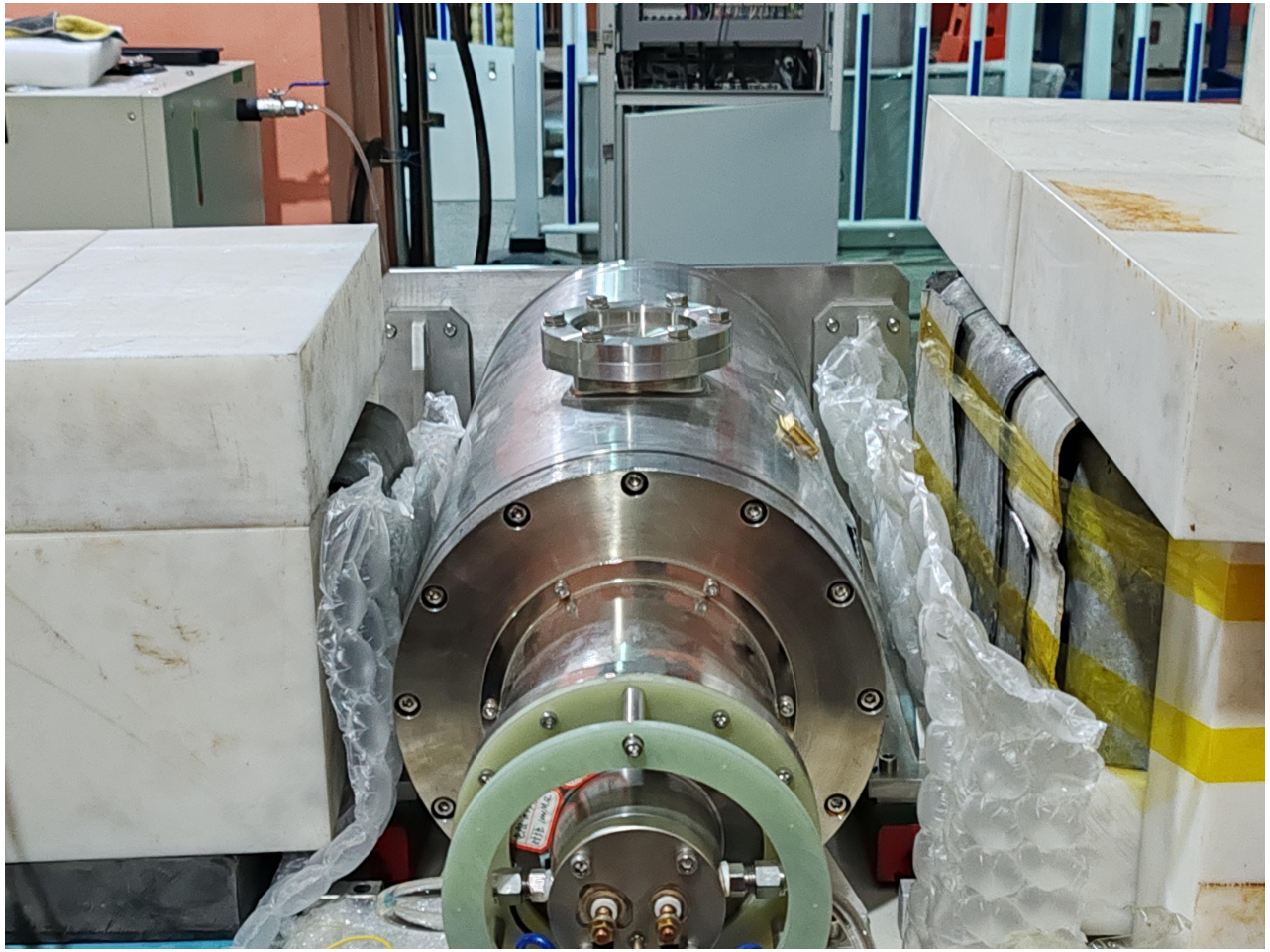
Backgrounds in 1 million neuclear recoil events

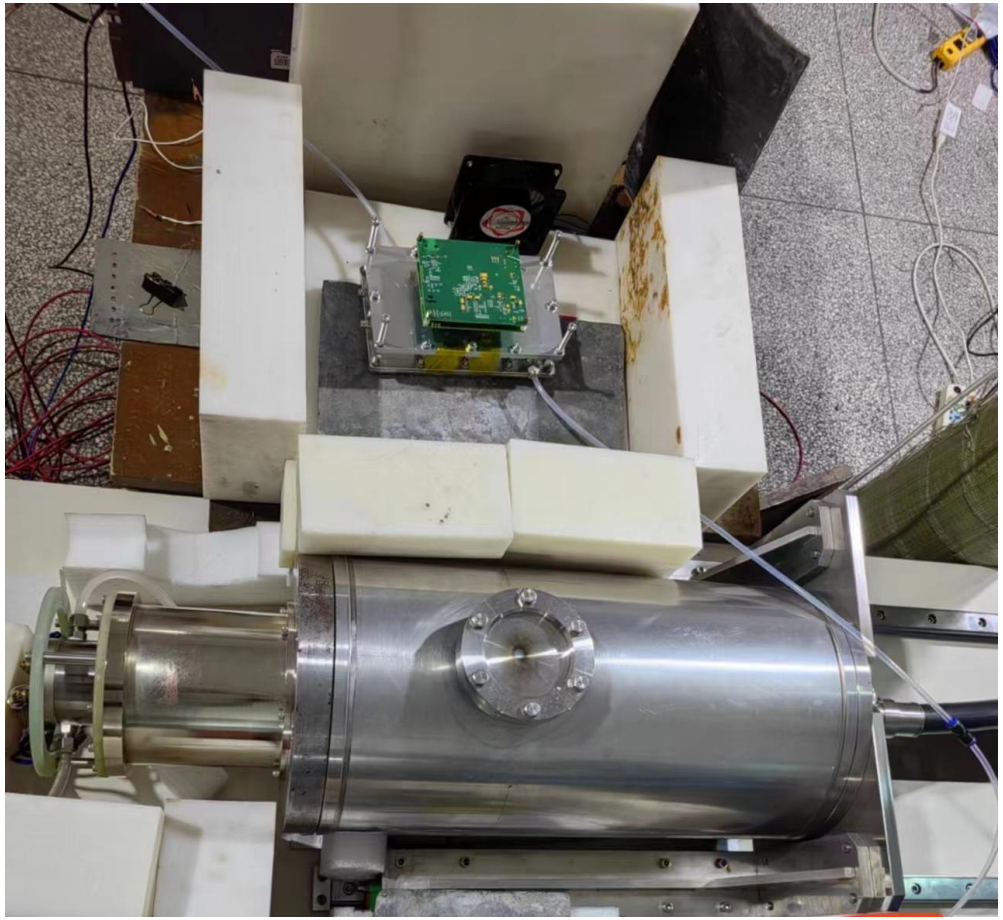
Background Component	Description	>0.5keV	5keV-15keV
Recoil induced δ ray	δ electron near (200 μm) NR track origin	1.4×10^{3}	≈0
Particle-Induced X-ray Emission (PIXE)			
X-ray emission	Photoelectron near NR track origin	0.3	0
Auger electrons	Auger electron near NR track origin	3.1×10^{3}	0
Bremsstrahlung processes			
Quasi-Free Electron (QFEB)	Photoelectron near NR track origin	4	≈0
Secondary Electron (SEB)	Photoelectron near NR track origin	1.3	≈0
Atomic (AB)	Photoelectron near NR track origin		≈0
Nuclear (NB)	Photoelectron near NR track origin		≈0
Neutron inelastic γ-rays			
Compton Electron	Compton electron near NR track origin	2.1	$(3.3\pm0.37)\times10^{-1}$
Photoelectron	Photoelectron near NR track origin	4.2	≈0
Random track coincidences	Photo-/Compton electron near NR track	-	$(1.7\pm0.11)\times10^{-2}$
Muon induced δ ray	δ electron near NR track origin	10	$(7.0\pm0.71)\times10^{-1}$
Gas radioactivity			
Trace contaminants	Electron from decay near NR track origin	0.91	$(1.8\pm0.2)\times10^{-2}$
Neutron activation	Electron from decay near NR track origin	-	≈0
Secondary nuclear recoil fork	NR track fork near track origin	-	≈0
Total background		4.6×10^{3}	1.1 ± 0.080

Theoretical Migdal electron > 5keV probably: ~ O(10^{-5})

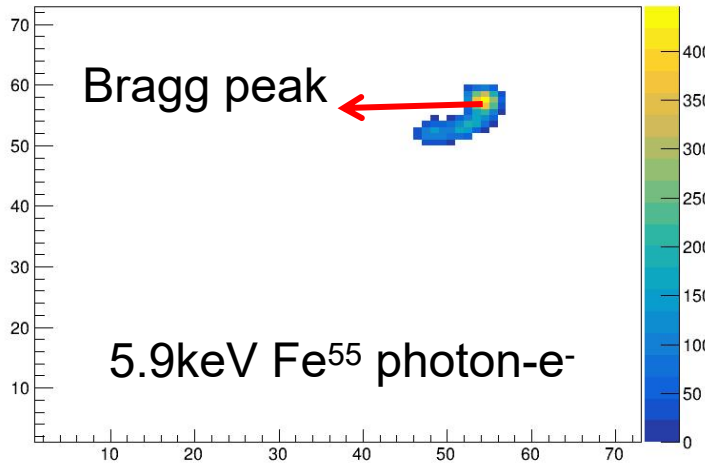
tens of Migdal electron should be found per million

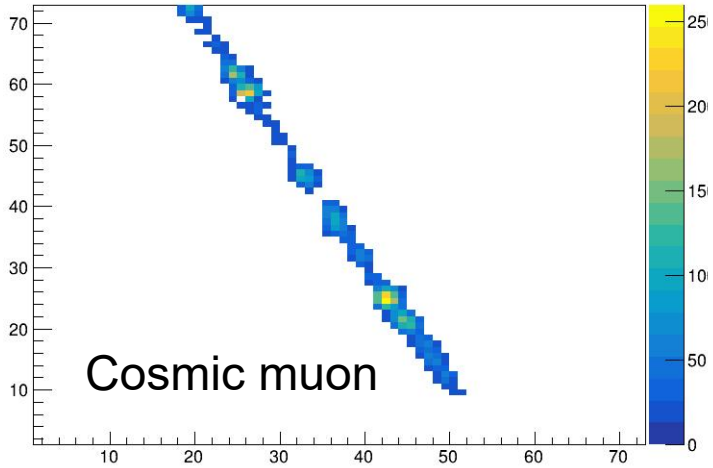
Pre-test & Placement

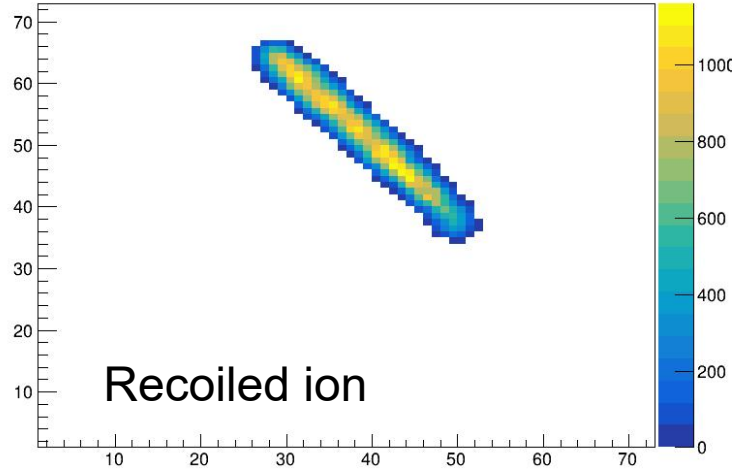


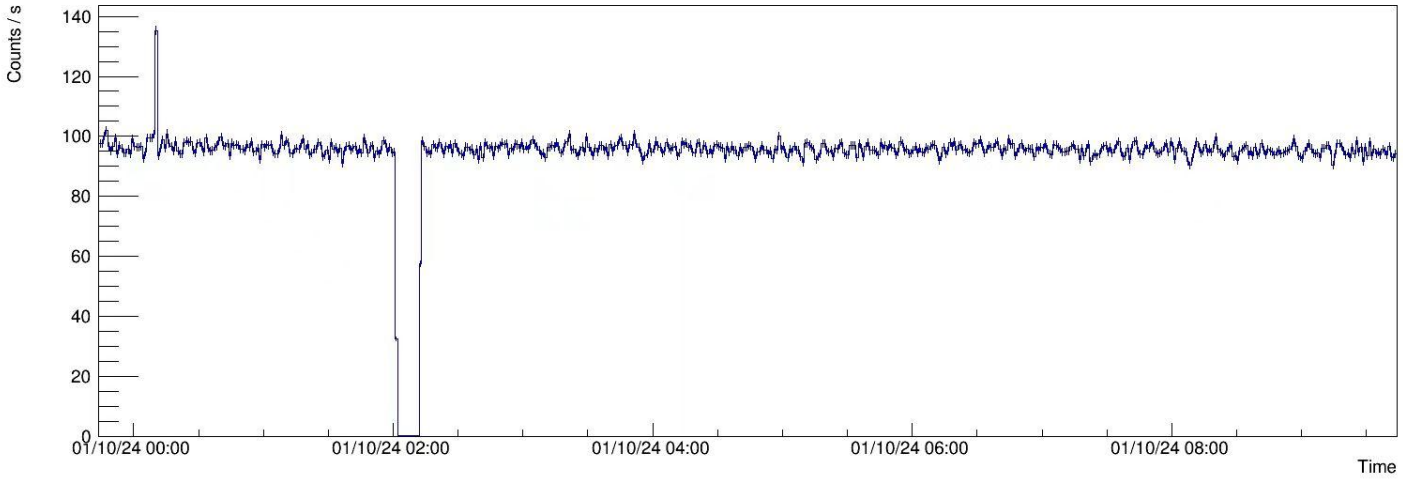


Track Imaging

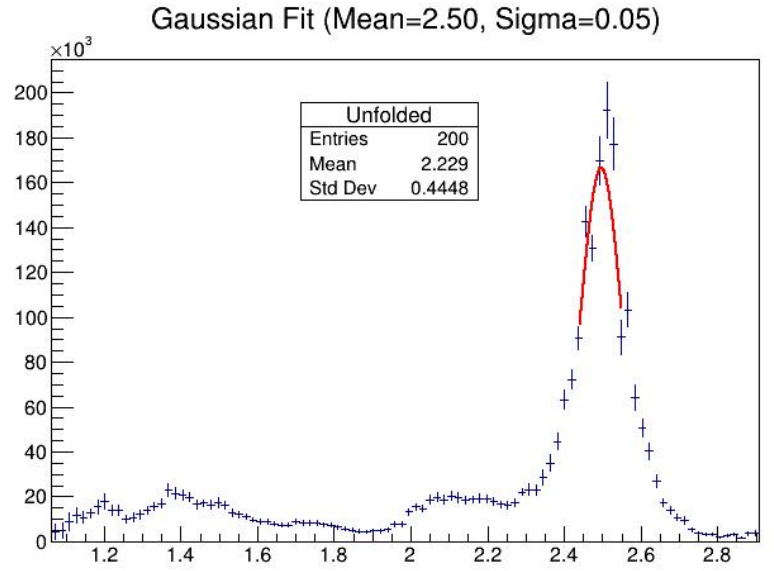








Neutron flux monitor



Neutron spectrum

- The Migdal effect plays a very important role in light dark matter research.
- However this effect has not been observed with the neutral projectile.
- Many experiments have been proposed.
- The capability of the GMCP detector to measure the Migdal effect is being discussed.
- Simulation and reconstruction is ready.
- Background analysis has been done.
- More work is currently in progress.

Experiment is ready,
Looking forward to results!

Thanks for your attention!