The MIGDAL experiment: Towards observation and measurement of the Migdal effect to help low mass WIMP searches.

Pawel Majewski
(STFC/Rutherford Appleton Laboratory)
for the MIGDAL collaboration

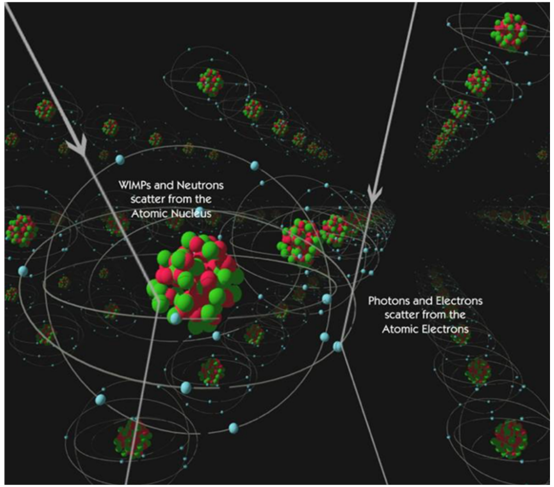
17th International Conference on Topics in Astroparticle and Underground Physics (TAUP 2021)

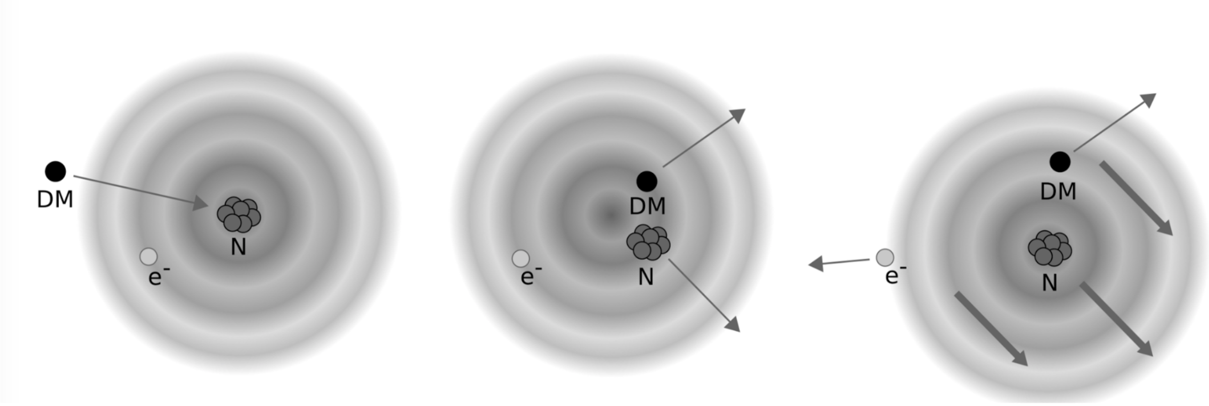
Outline

MIGDAL
Migdal In Galactic Dark mAtter expLoration

1. The Migdal effect and Dark Matter
2. Observation of the Migdal effect in radioactive decays
3. The MIGDAL experiment
4. Optical-TPC filled with CF_4 at 50 Torr
5. Tests with low energy electrons
6. Simulations
7. Conclusions

What the Migdal effect is and why it matters in DM searches ?



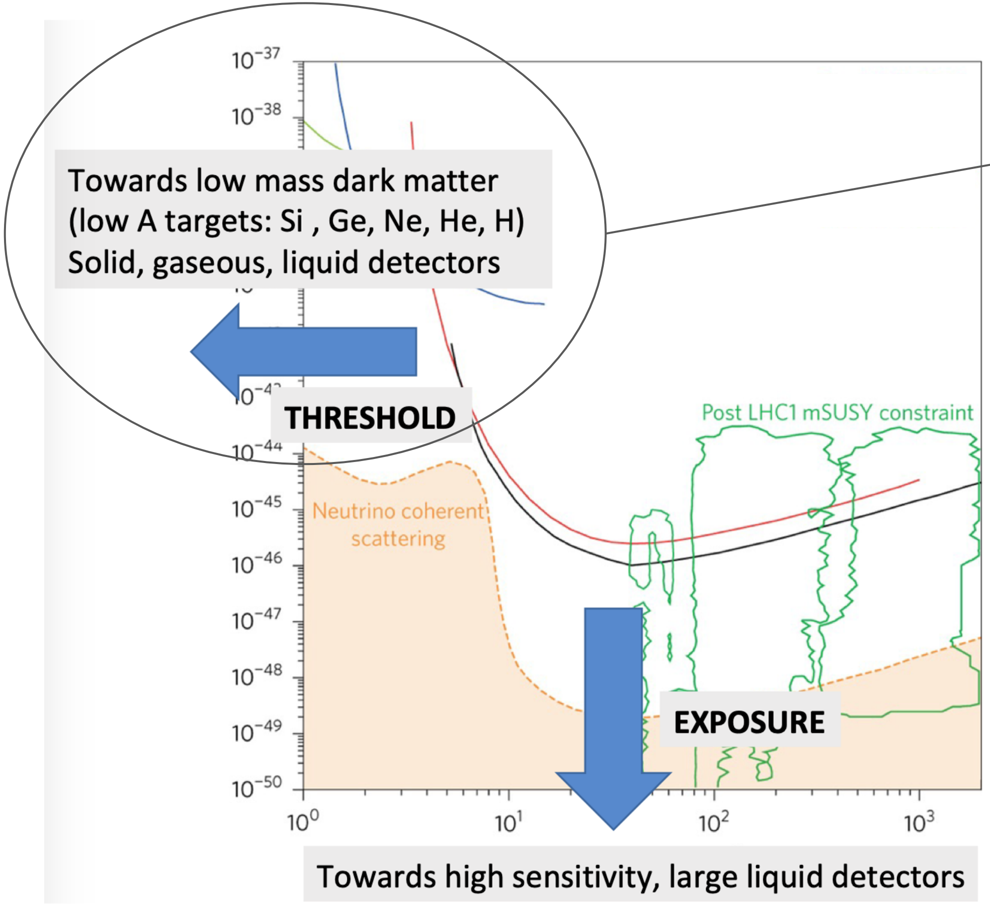


Migdal Effect - nucleus moves relative to the electron cloud. Individual electron might be ejected leading to ionisation.

DM searches use signal from nuclear recoils as a signature of the DM interaction with the detector medium.

- M. J. Dolan et al., *Directly detecting sub-GeV dark matter with electrons from nuclear scattering;* *Phys. Rev. Lett. 121, 101801 (2018)*
- M. Ibe et al., *Migdal Effect in Dark Matter Direct Detection Experiments;* *J. High Energ. Phys. 2018, 194 (2018)*

Why Migdal effect matters in DM searches ?



Parameter space reachable exclusively by the detectors with a low mass target material

BUT not any longer

if the Migdal experimentally is confirmed in elements such as Xe and Ar

and as a bonus it comes for free !

Ionisation electrons treated so far as background can therefore become a signature of the signal from the low mass dark matter particles.

Huge attention of the DM community to the Migdal Effect

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Migdal effect in dark matter direct detection experiments

Masahiro Ibe,[a,b] Wakutaka Nakano,[a] Yutaro Shoji[a] and Kazumine Suzuki[a]
[a] *ICRR, The University of Tokyo, Kashiwa, Chiba 277-8582, Japan*
[b] *Kavli IPMU (WPI), UTIAS, The University of Tokyo, Kashiwa, Chiba 277-8583, Japan*
E-mail: ibe@icrr.u-tokyo.ac.jp, m156077@icrr.u-tokyo.ac.jp, yshoji@icrr.u-tokyo.ac.jp, ksuzuki@icrr.u-tokyo.ac.jp

So far ~ 100 citations of the Ibe's paper.

Migdal effect calculations reformulated by M. Ibe et al. with ionisation probabilities for atoms and recoil energies relevant to Dark Matter searches

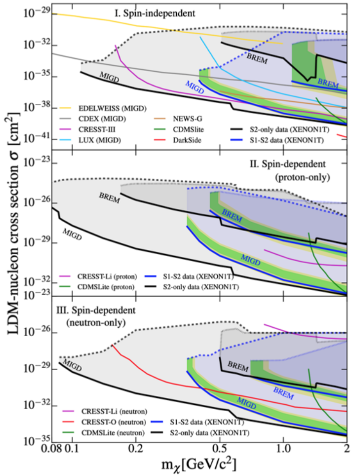
Papers in the past from: LUX, XENON1T, EDELWEISS,CDEX-1B, SENSEI

Including targets:

Ge, Si, Xe and Ar

and claiming sensitivity to WIMPs with mass below 1 GeV

Dark Matter searches and Migdal Effect
-> sensitivity extension to low mass region

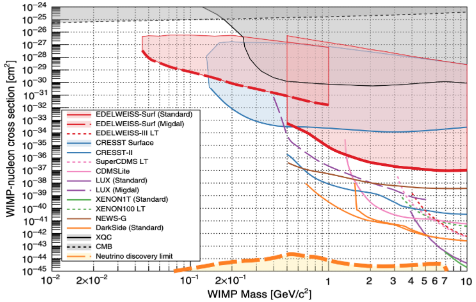


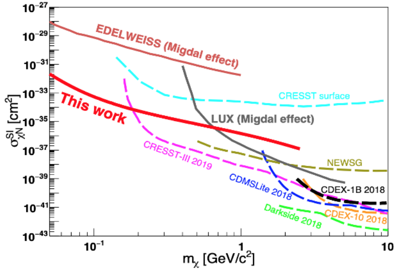
LUX (Xenon)
”Results of a Search for Sub-GeV Dark Matter Using 2013 LUX Data”
https://arxiv.org/pdf/1811.11241.pdf

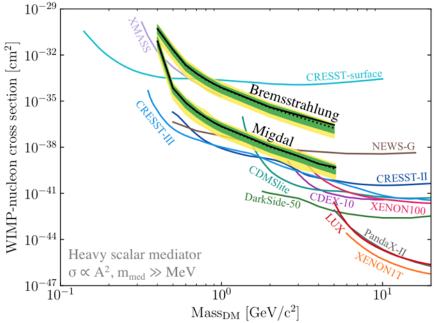
XENON1T (Xenon)
”A Search for Light Dark Matter Interactions Enhanced by the Migdal effect or Bremsstrahlung in XENON1T”
https://arxiv.org/pdf/1907.12771.pdf

EDELWEISS (Germanium)
”Searching for low-mass dark matter particles with a massive Ge bolometer operated above-ground”
https://arxiv.org/abs/1901.03588

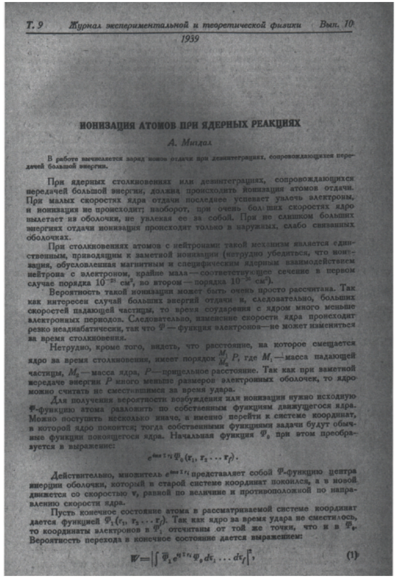
CDEX-1B (Germanium)
”Constraints on Spin-Independent Nucleus Scattering with sub-GeV Weakly Interacting Massive Particle Dark Matter from the CDEX-1B Experiment at the China Jin-Ping Laboratory”
https://arxiv.org/pdf/1905.00354.pdf







What do we already know about the Migdal effect ?



Т. 9 *Журнал экспериментальной и теоретической физики* Вып. 10

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ИОНИЗАЦИЯ АТОМОВ ПРИ ЯДЕРНЫХ РЕАКЦИЯХ

А. Мигдал

В работе вычисляется заряд ионов отдачи при дезинтеграциях, сопровождающихся передачей большой энергии.

При ядерных столкновениях или дезинтеграциях, сопровождающихся передачей большой энергии, должна происходить ионизация атомов отдачи. При малых скоростях ядра отдачи последнее успевает увлечь электроны, и ионизация не происходит; наоборот, при очень больших скоростях ядро вылетает из оболочки, не увлекая ее за собой. При не слишком больших энергиях отдачи ионизация происходит только в наружных, слабо связанных оболочках.

При столкновениях атомов с нейтронами такой механизм является единственным, приводящим к заметной ионизации (нетрудно убедиться, что ионизация, обусловленная магнитным и специфическим ядерным взаимодействием нейтрона с электроном, крайне мала — соответствующее сечение в первом случае порядка 10^{-28} см^2, во втором — порядка 10^{-30} см^2).

Вероятность такой ионизации может быть очень просто рассчитана. Так как интересен случай больших энергий отдачи и, следовательно, больших скоростей падающей частицы, то время соударения с ядром много меньше электронных периодов. Следовательно, изменение скорости ядра происходит резко неадиабатически, так что Ψ — функция электронов — не может измениться за время столкновения.

Нетрудно, кроме того, видеть, что расстояние, на которое смещается ядро за время столкновения, имеет порядок $\frac{M_1}{M_2}P$, где M_1 — масса падающей частицы, M_2 — масса ядра, P — прицельное расстояние. Так как при заметной передаче энергии P много меньше размеров электронных оболочек, то ядро можно считать не сместившимся за время удара.

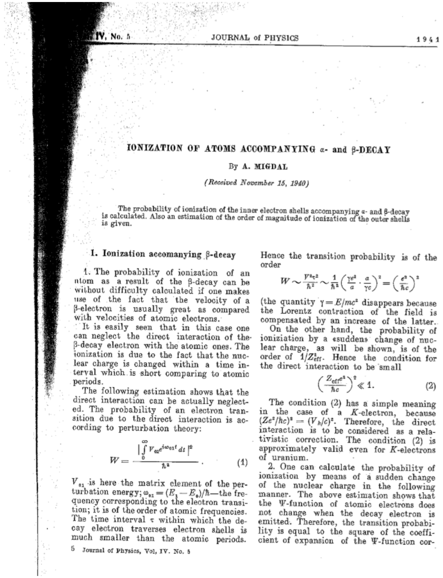
Для получения вероятности возбуждения или ионизации нужно исходную Ψ-функцию атома разложить по собственным функциям движущегося ядра. Можно поступить несколько иначе, а именно перейти к системе координат, в которой ядро покоится; тогда собственными функциями задачи будут обычные функции покоящегося ядра. Начальная функция Ψ_0 при этом преобразуется в выражение:

$$e^{imv\Sigma r_i}\Psi_0(\mathbf{r}_1, \mathbf{r}_2 \ldots \mathbf{r}_f).$$

Действительно, множитель $e^{imv\Sigma r_i}$ представляет собой Ψ-функцию центра инерции оболочки, который в старой системе координат покоился, а в новой движется со скоростью $\mathbf{v}$, равной по величине и противоположной по направлению скорости ядра.

Пусть конечное состояние атома в рассматриваемой системе координат дается функцией $\Psi_1(r_1, r_2 \ldots r_f)$. Так как ядро за время удара не сместилось, то координаты электронов в Ψ_1 отсчитаны от той же точки, что и в Ψ_0. Вероятность перехода в конечное состояние дается выражением:

$$W = \left|\int \overline{\Psi}_1 e^{iq\Sigma r_i} \Psi_0 \, d\tau_1 \ldots d\tau_f\right|^2, \quad (1)$$



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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.

I. 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:

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

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

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

(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 ioniziation by a «sudden» change of nuclear charge, as will be shown, is of the order of $1/Z^2_{eff}$. Hence the condition for the direct interaction to be small

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

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

A. Migdal publications:

- Ionisation in nuclear reactions [1]
- Ionisation in radioactive decays [2]

First observations of the Migdal effect in :

- Alpha decay [3,4]
- Beta decay [5]
- Positron decay [6]
- Nuclear scattering [ ]

Also in A.B. Migdal "Qualitative Methods in Quantum Theory" Advanced Book Classics CRC Press, 2000
L. Landau and E. Lifshitz "Quantum Mechanics : Non-relativistic Theory"

[1] A. Migdal *Ionizatsiya atomov pri yadernykh reaktsiyakh, ZhETF, 9, 1163-1165 (1939)*

[2] A. Migdal *Ionizatsiya atomov pri α- i β- raspade, ZhETF, 11, 207-212 (1941)*

[3] M.S. Rapaport, F. Asaro and I. Pearlman *K-shell electron shake-off accompanying alpha decay, PRC **11**, 1740-1745 (1975)*

[4] M.S. Rapaport, F. Asaro and I. Pearlman *L- and M-shell electron shake-off accompanying alpha decay, PRC **11**, 1746-1754 (1975)*

[5] C. Couratin et al. , *First Measurement of Pure Electron Shakeoff in the β Decay of Trapped $^6He^+$ Ions, PRL **108**, 243201 (2012)*

[6] X. Fabian et al., *Electron Shakeoff following the β^+ decay of Trapped $^{19}Ne^+$ and $^{35}Ar^+$ trapped ions, PRA, **97**, 023402 (2018)*

What do we already know about the Migdal effect ?

- Observation of the Migdal effect in α decay
  - Measured in ^{210}Po and ^{238}Pu decays measuring α particles in coincidence with X-rays emitted from K, $L_{I,II,III}$ and M-shell due to electron shake-off effect (emission of Migdal electron)
- Observation of the Migdal effect in β and β+ decay
  - Measured in $^{6}He^{+}$ (β- decay) and also in $^{19}Ne^{+}$ and $^{35}Ar^{+}$ (β+ decay) using an ion trap coupled to a TOF recoil-ion spectrometer detecting recoils of $^{6}Li^{2+}$ and also $^{19}F^{q+}$ and $^{35}Cl^{q+}$

None of the experiments observed Migdal electrons.

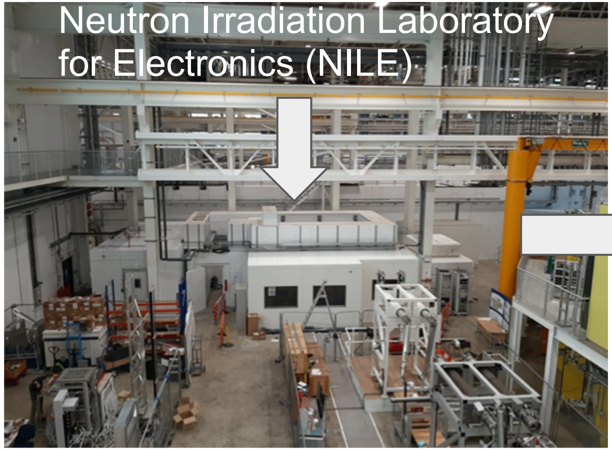
- Migdal effect in nuclear scattering
  - **Extremely challenging and awaiting first observation**

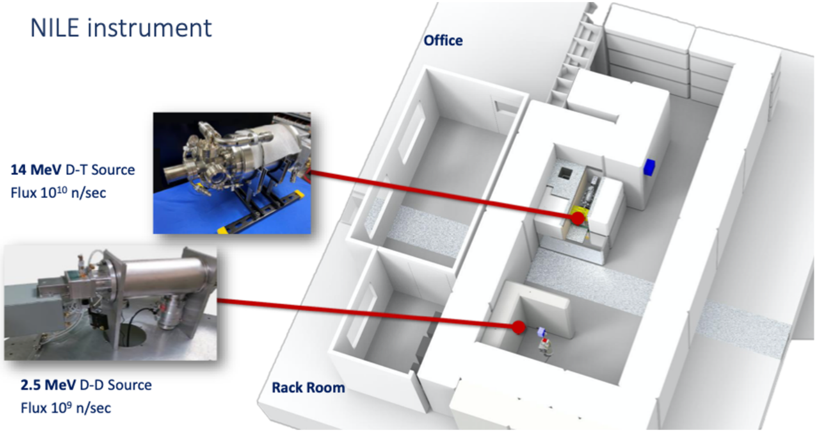
Migdal In Galactic Dark mAtter expLoration

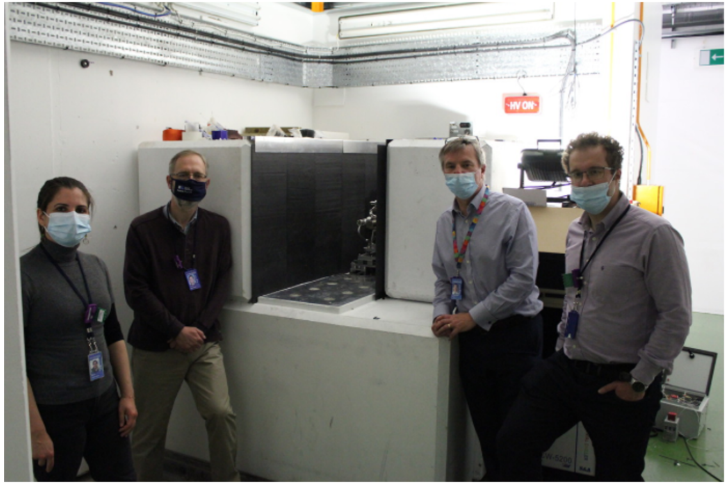
- Create a dedicated environment for an unambiguous first observation of the Migdal effect in nuclear scattering with a suppressed background
- Phase 1: Observe the effect in CF_4 in high energy recoils using a high flux D-T n-generator
- Phase 2: Observe the Migdal effect in CF_4 + noble gases using high flux D-D and D-T n-generators

⇨ This experiment is not designed for observation and measurement of the effect at DM energy scale.

Neutron **I**rradiation **L**aboratory for **E**lectronic facility at ISIS







- DT neutron generator:

  E_n=14.1 MeV, flux 10^{10} n/s
- DD neutron generator:

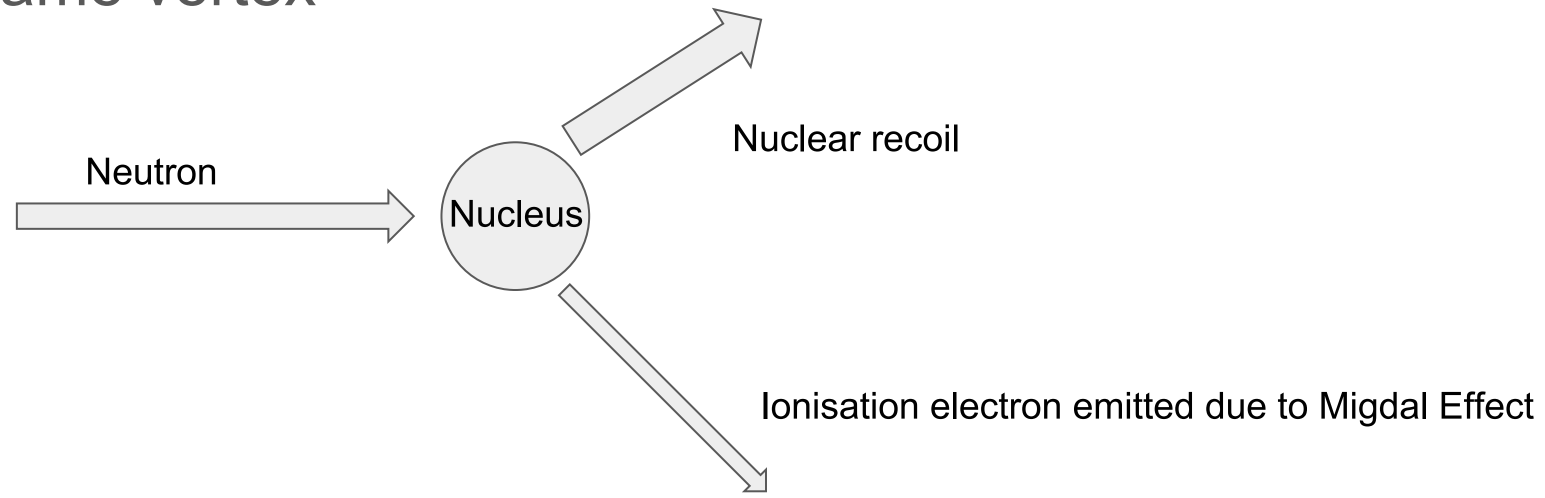
  E_n=2.45 MeV, flux 10^{9} n/s
- Both generators from Adelphi (USA)

Detector operation and the signal signature

- Use of CF_4 scintillating gas as a base gas for the experiment operating at low pressure
  - Advantages :
    - Well understood gas for gaseous detectors
    - Expertise operating O-TPCs with pure CF_4 and CF_4+ noble gases
    - Light atoms produce only low energy characteristic X-rays (below threshold)
    - Few mm long tracks of electrons and nuclear recoils can be captured by a fast low-noise digital camera
    - Long gamma absorption mean free path minimises the background
  - Disadvantages in rare event searches :
    - Low mass of the target requires operation in very high neutron flux environment
- Use of high energy neutrons from D-T generator
  - Advantages :
    - Long track of the recoils - easier to image
    - Increased yield of the Migdal Effect - easier to observe the effect
  - Disadvantages
    - Increased background rate

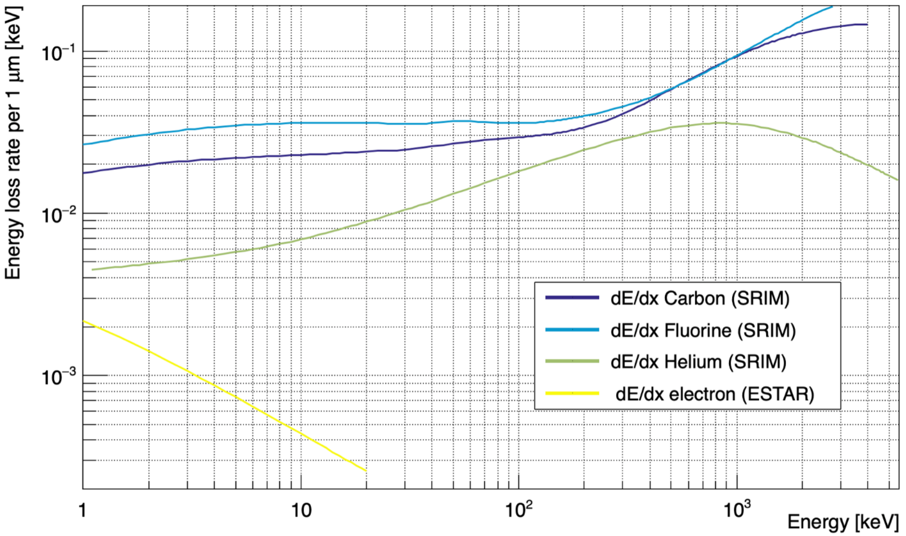
Experimental Goal

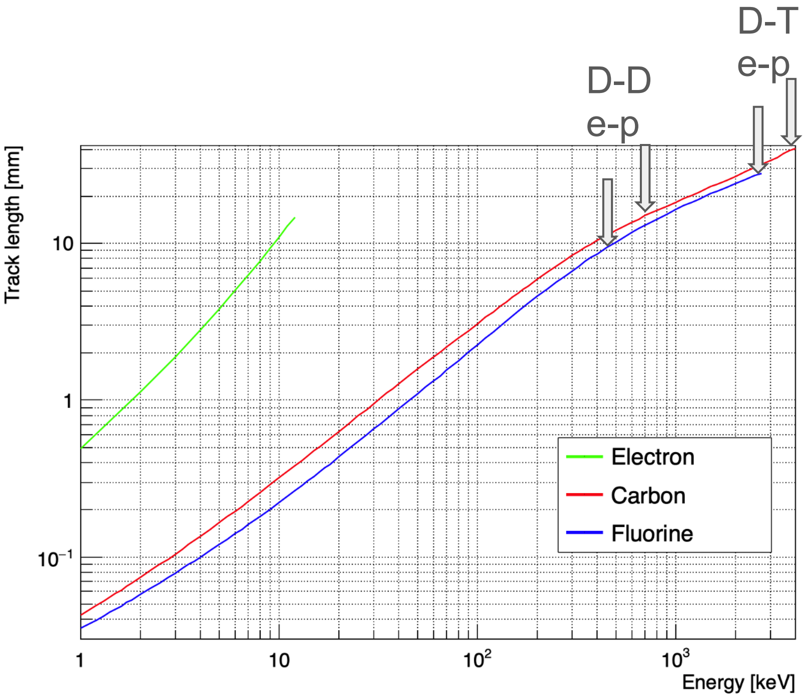
Observation of two simultaneously created tracks of the ionisation electron and the nuclear recoil originating from the same vertex



We propose first observation of the Migdal effect with detection of the Migdal electrons.

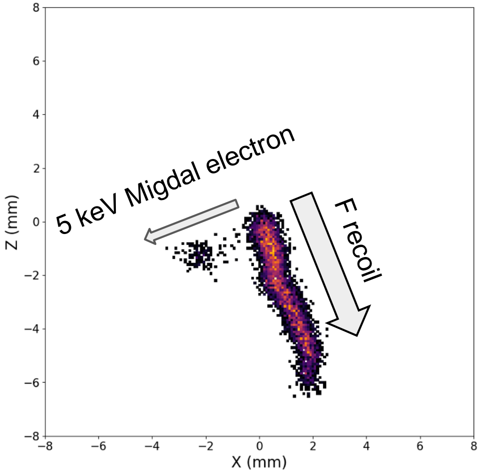
dE/dx distribution and track length for electrons and nuclear recoils in 50 Torr CF_4

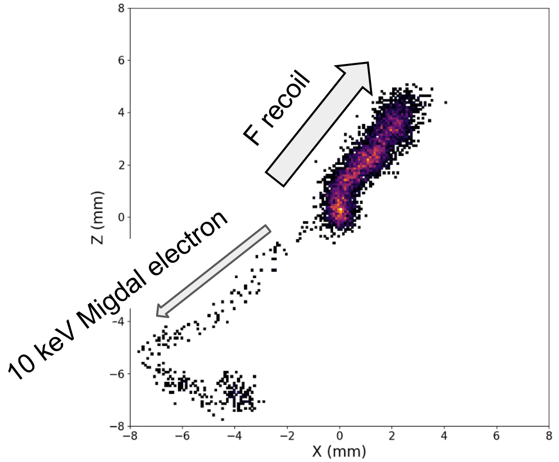




- dE/dx for the nuclear recoils decreases with the energy which is opposite for the electrons
- Electrons with energies 5 - 10 keV have track lengths between 4 - 10mm
- Nuclear recoils with energies E > 150 keV have track length > 4 mm

Detector operation and the signal signature



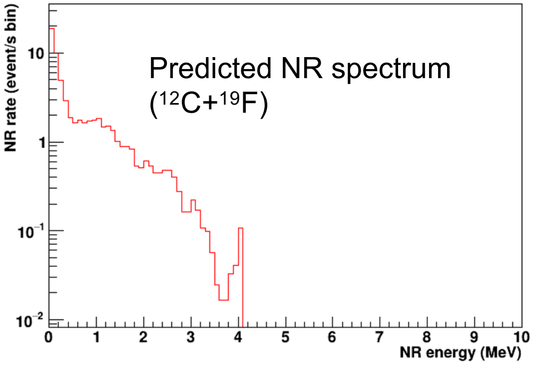


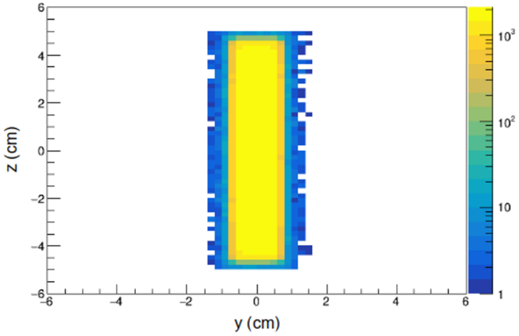
- Example of the Migdal effect with 250 keV Fluorine recoil & 5 (10) keV electron (after 10 mm of drift in CF_4 at 50 Torr)
- Simulated with SRIM and garf++ (recoil) and DEGRAD (electron)
- Clear "fork-like" topology
- Clear different dE/dx distribution for both tracks
  - Opposite head-and-tail ionisation distribution
- Clear different ionisation density for both tracks

➔ At this moment we do not assume any specific angular distribution of the Migdal electron emission. We will have capability to measure it.

Sources of background (1)

- Developed a Geant4 model of full experiment at the neutron's source facility
- Predicting 80 Hz of total NR rate in fiducial volume for D-T neutron source, of which 55 Hz are detected as isolated NRs (elastic, or inelastic + neutrals)
- Used simulation to optimize shielding and collimator:
    - Front shielding: 70 cm Fe+20 cm borated HDPE+10 cm Pb
    - Side and back shielding: 20 cm borated HDPE+10 cm Pb
    - Collimator defines a beam of 9 cm×1.4 cm section, and only contributes 8 Hz to total non-NR rate

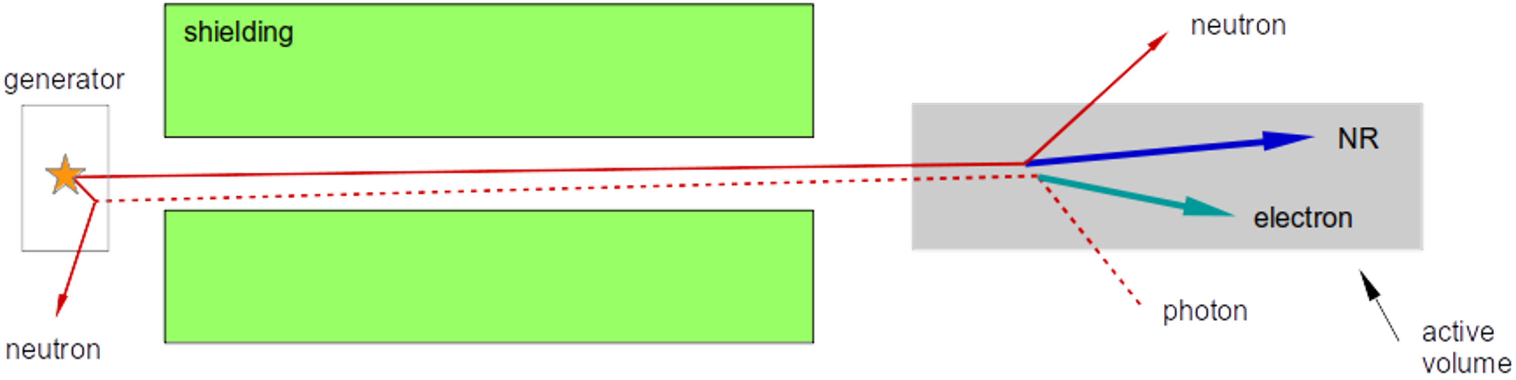




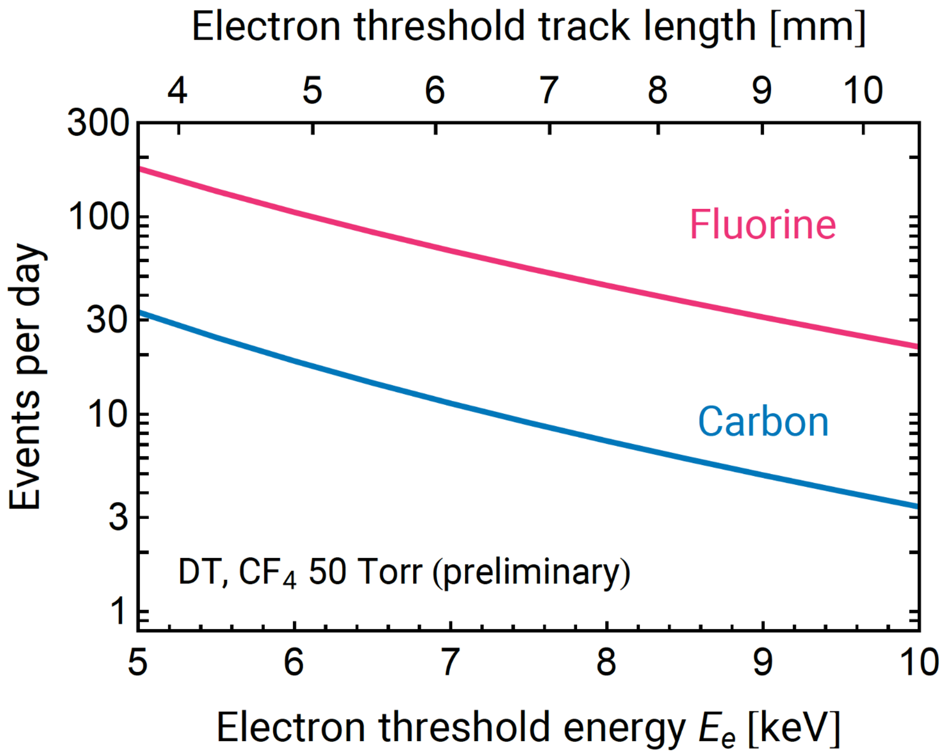
Beam section at entrance of active volume

Sources of background (2)

- Dominant background source (from G4 sims): random combination of NR+Compton electron track, in the same event
- Compton electrons in active volume are mostly produced by photons from inelastic interaction of primary neutrons with generator material
- Predicted rate from G4 sims: 5.4 ± 0.3 events/M NR
- If placing 1.3 cm Pb+1 cm Sn layers between neutron generator and active volume, this background rate can be lowered to 2.1 ± 0.1 events/M NR

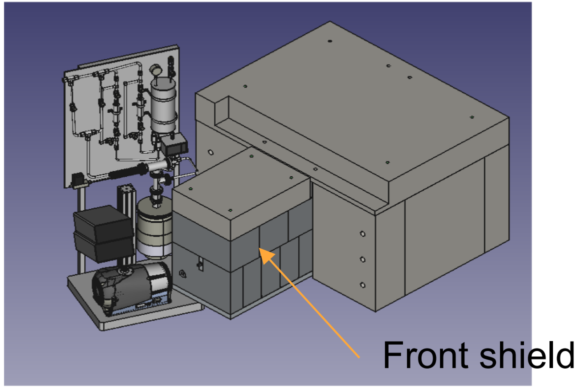


Expected number of Migdal events in CF_4 using DT generator

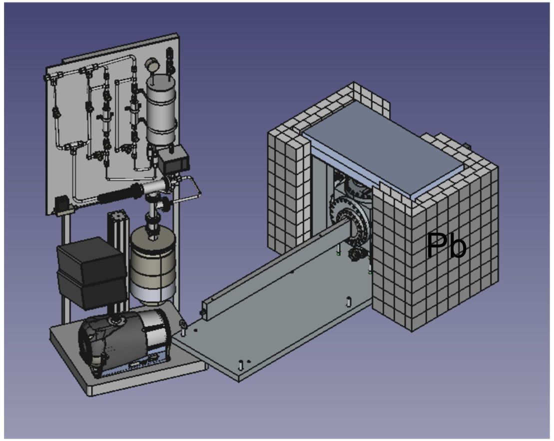


Taking into account energy distribution and rates of the events with C and F recoils in the fiducial region over one day of exposure to neutron from DT generator.

Shield and collimator

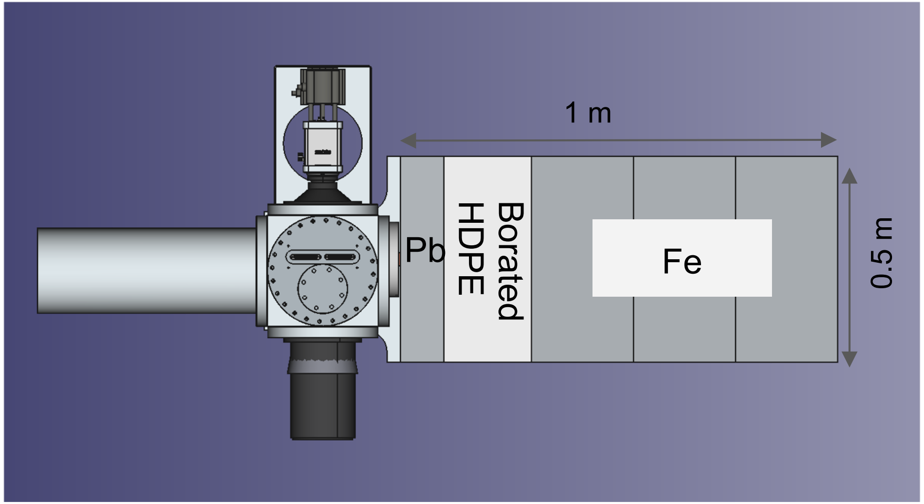


Plastic shield

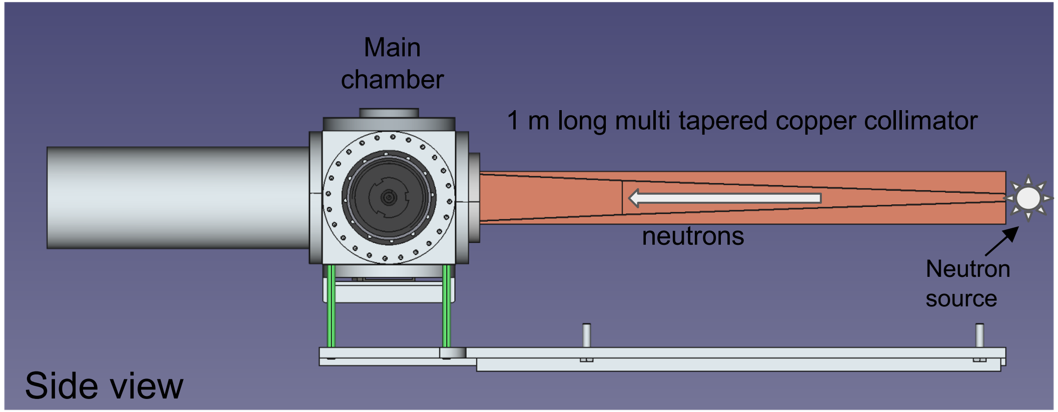


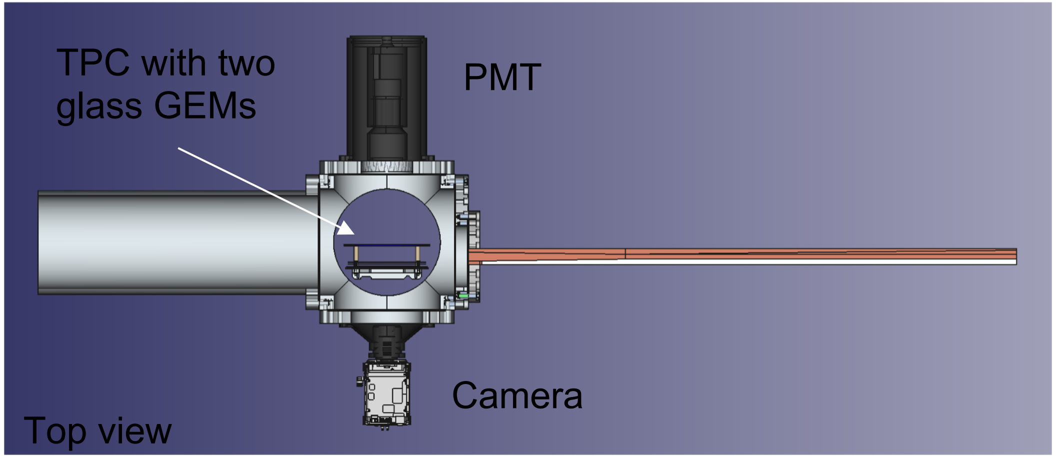
Lead shield

- Fe - slows down fast neutrons
- Borated HDPE - captures neutrons
- Pb - stops gamma rays
- Reduction of neutron flux : ~ 1E6



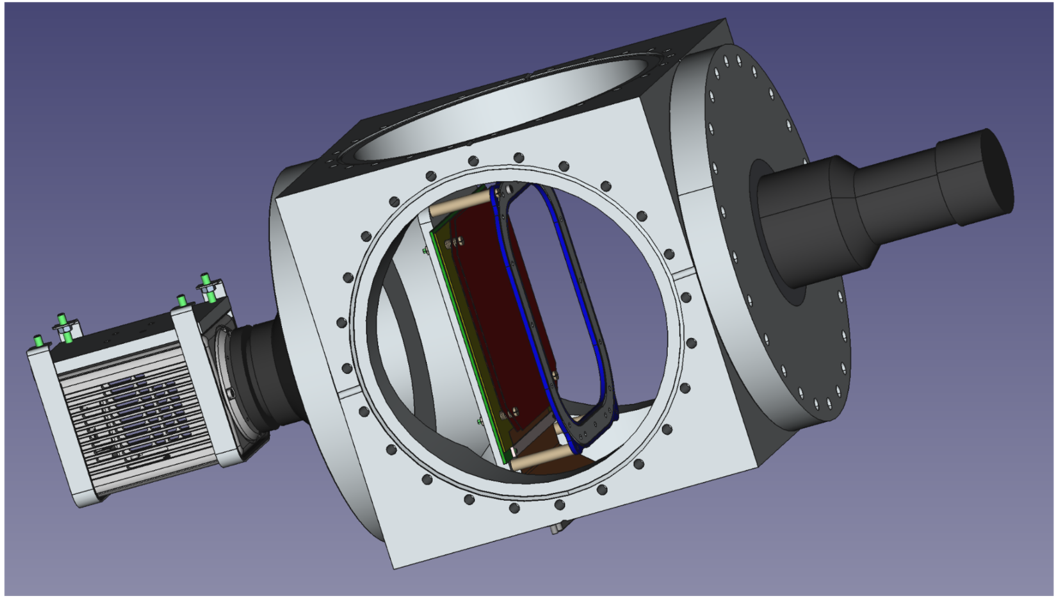
DT and DD neutron generators, beam collimation and shielding

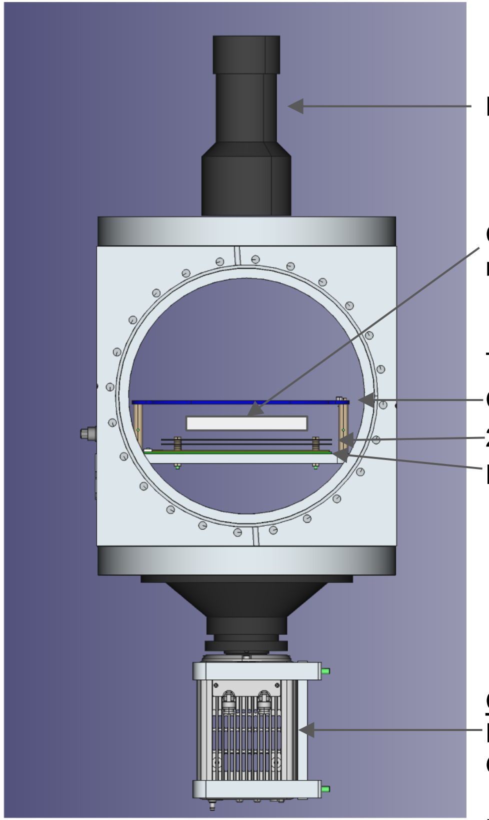




- Collimator length: 1 m
- Material: copper
- Rate of neutrons from DT generator at the front of the TPC: ~ 400 kHz
- Events rate in the TPC ~ 80 Hz

Optical Time Projection Chamber

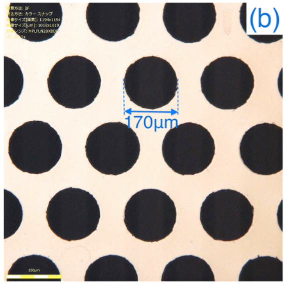




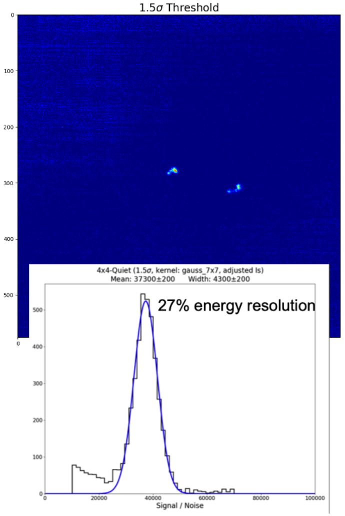
- Aluminium chamber: 25.4 cm
- TPC active area: 10 cm x 10 cm
- Drift gap: 3 cm
- Amplification with 2 x standard glass GEM (2 mm gap)
- ITO plate 15 cm x 15 cm with 120 readout strips (2 mm induction gap)

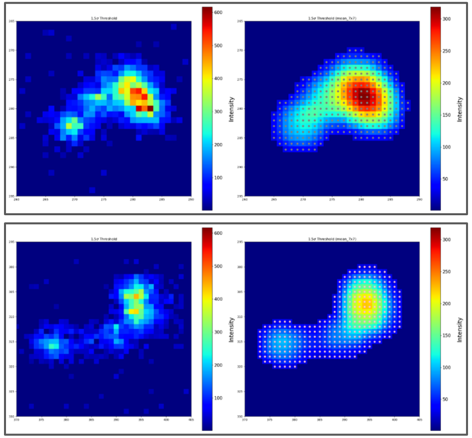
Low energy electrons generated by ^{55}Fe source (test at CERN)

Glass GEM

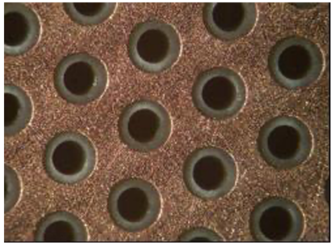


0.55 mm thick glass with 2 um copper on both sides. Distance between holes 280 um and hole diameter : 170 um





Thick GEM



1 mm thick PCB with 20 um copper on both sides. Distance between holes 700 um and hole diameter : 400 um

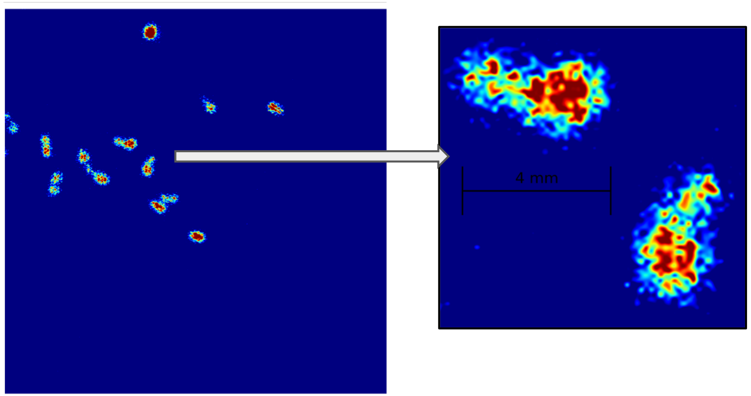
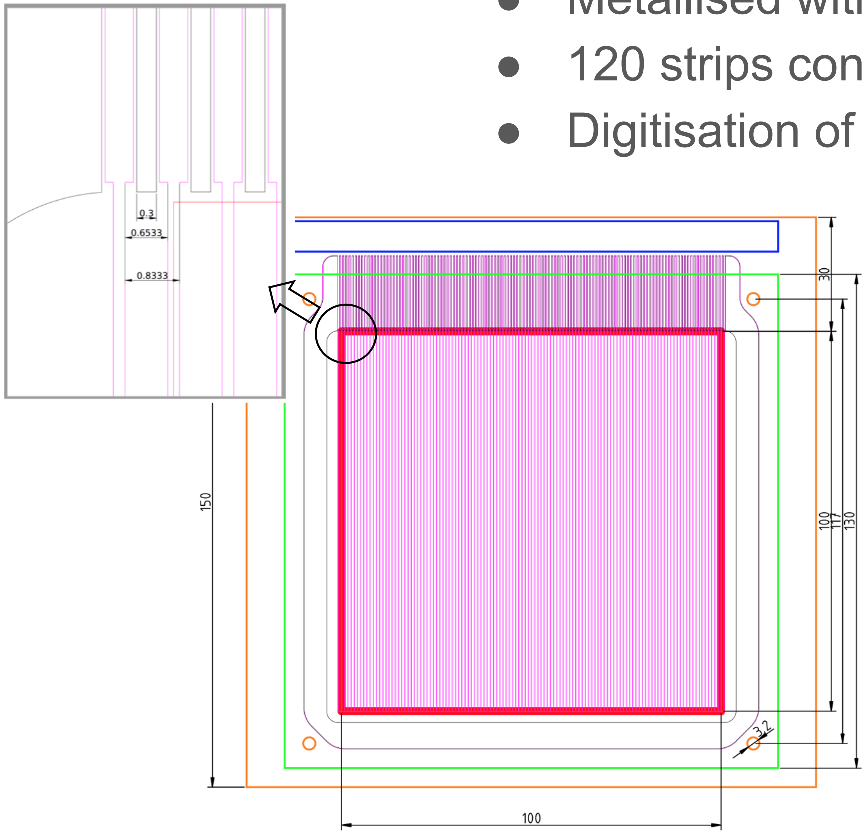
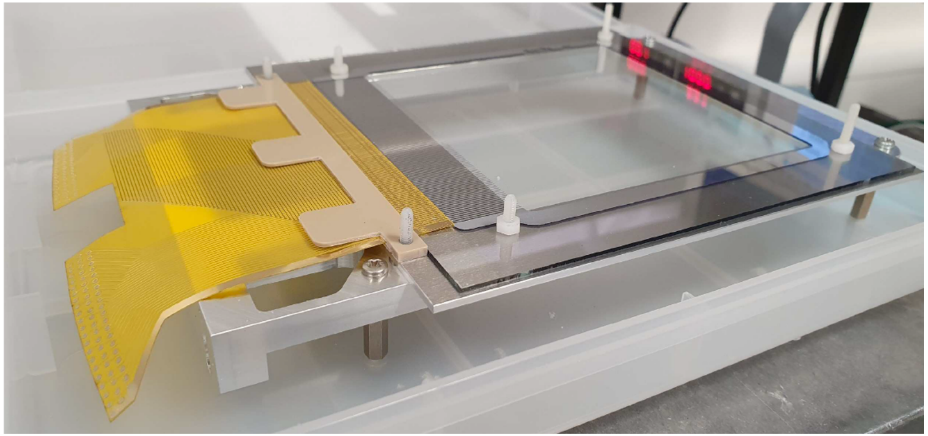


Image of low energy electron tracks from ^{55}Fe source in 50 Torr CF_4. Tracks' head and tail structure is clearly resolved.

ITO strips

- 1.1 mm thick ITOGLASS 04, resistance 4 Ohm/square
- Metallised with Cr and Aluminium for wire bonding
- 120 strips connected to Acqiris 60 channel digitizer
- Digitisation of pulses with 2 ns sampling rate

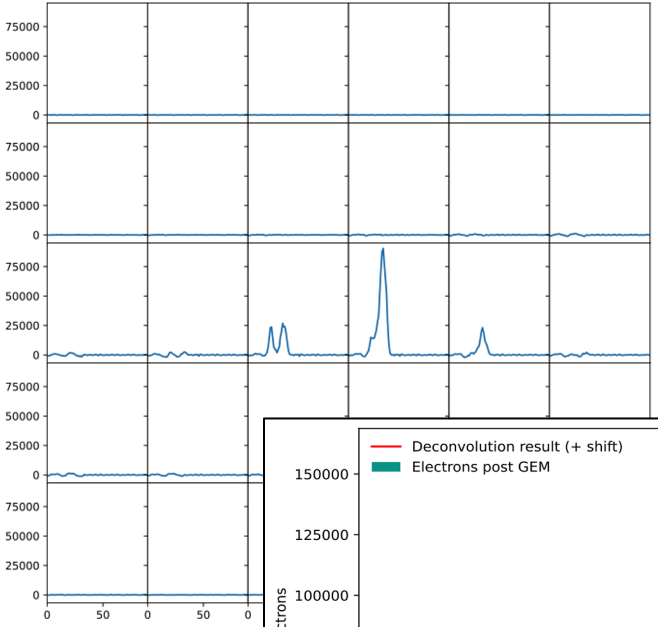


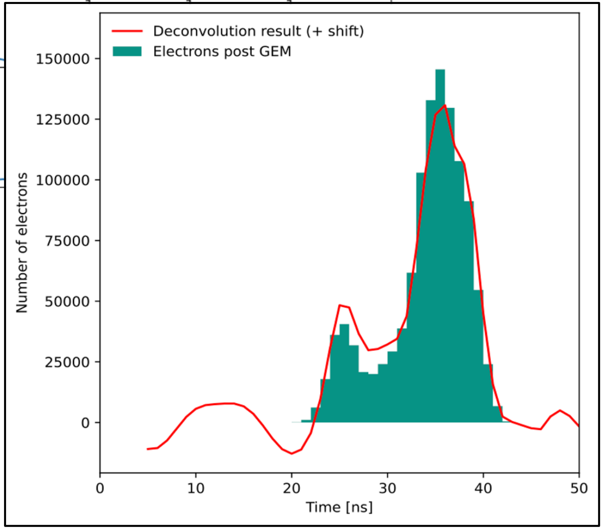


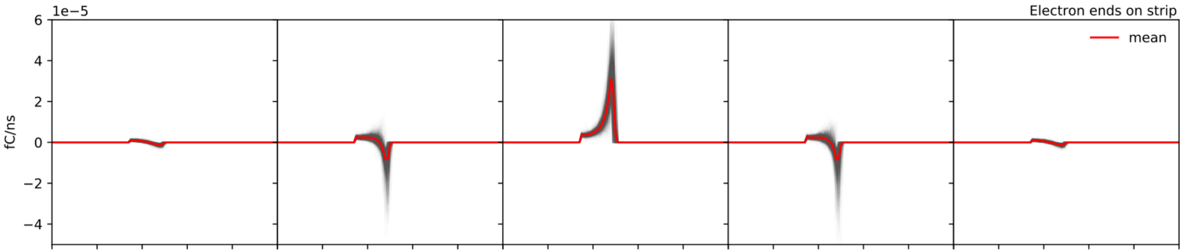
GEM+ITO simulations

- Two-dimensional deconvolution (a la MicroBooNE) used to recover the charge distribution in the Z direction

- Use the electronics response functions to get the current and the response of a single electron (below) to get the charge.







Conclusions

- Migdal effect enhances sensitivity of DM searches to lighter mass WIMPs
- Migdal Effect has been observed in radioactive decays in both light and heavy elements, but no observation in nuclear scattering
- We propose first observation of the effect in nuclear scattering using OTPC allowing a full 3D reconstruction of the event's topology which is a key feature of our experiment. Our goal is to capture events with both recoil and electron tracks emerging from the same vertex in a most favourable conditions for the first observation of the effect.
- Construction of the experiment is underway.

More information about MIGDAL experiment

Poster session (https://indico.ific.uv.es/event/6178/contributions/15923/)

Chris McCabe : *Migdal event rates for D-D and D-T generators*

Backup slides

MIGDAL: Migdal In Galactic Dark mAtter expLoration

CERN (GDD) F. Brunbauer, E. Oliveri, L. Ropelewski, L. Scharenberg, R. Veenhof

Coimbra-LIP E. Lopez Asamar, A. Lindote, M. I. Lopes, F. Neves, V. N. Solovov

Helsinki Institute of Physics F. Garcia

Imperial College London H. M. Araujo, J. E. Borg, T. Marley, M. Nakhostin, T. J. Sumner

King's College London C. McCabe

STFC/Rutherford Appleton Laboratory
(ISIS) C. Cazzaniga, S. Lilley, P. Luna Dapica, C. D. Frost, M. Kastriotou, R. Turnley
(PPD) S. Balashov, C. Brew, M. van der Grinten, A. Khazov, P. A. Majewski
(TD) E. Holtom, J. Tarrant

Royal Holloway University of London A. C. Kaboth

University of Birmingham I. Katsioulas, T. Neep, K. Nikolopoulos

University of New Mexico D. Loomba, A. F. Mills

University of Oxford H. Kraus

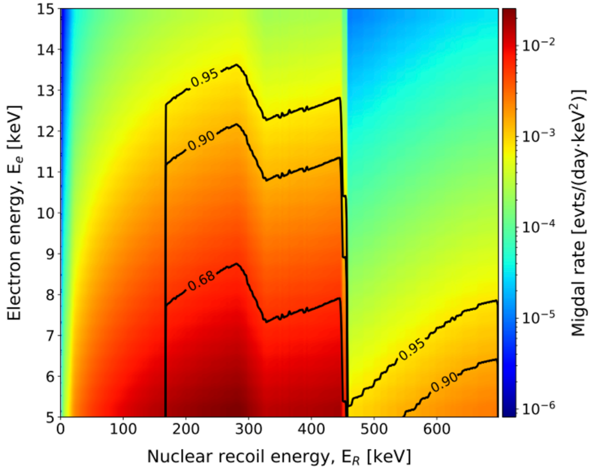
University of Sheffield V. Kudryavtsev

Formed in 2019 with 40 members from 11 institutions

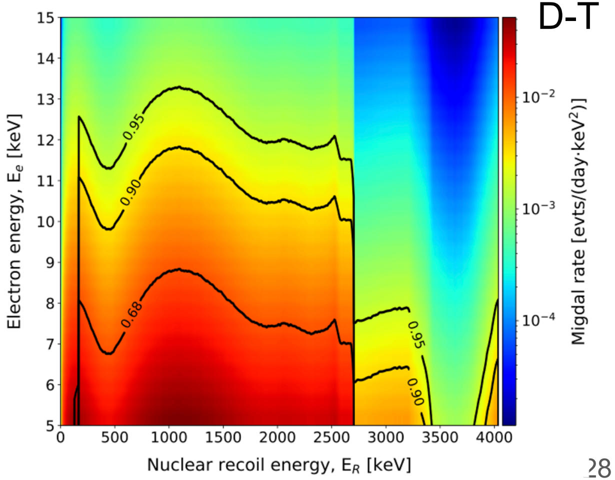
Expected number of Migdal events in CF_4 using DT generator

- The expected number of Migdal events in the detector are calculated as a function of NR energy (E_R) and Migdal e^- energy (E_e) for both D-T and D-D neutron sources.
- Contours are drawn using a track length threshold of 4 mm (130 keV for C, and 170 keV for F) at 68%, 90% and 95% confidence levels.

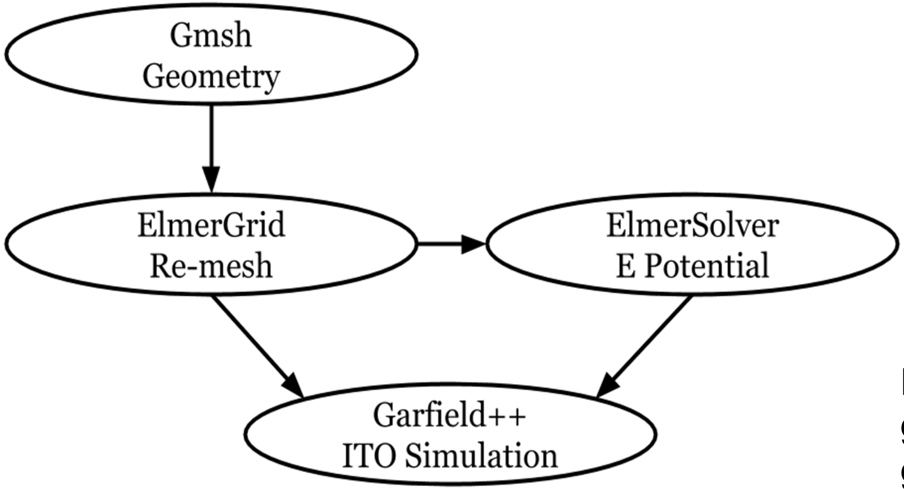
D-D

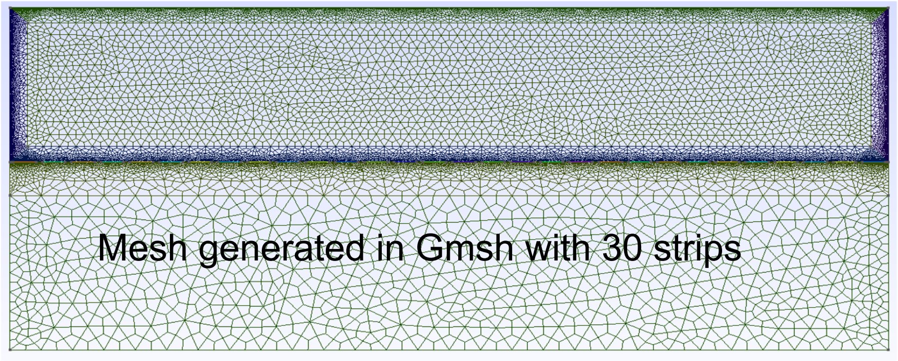


D-T

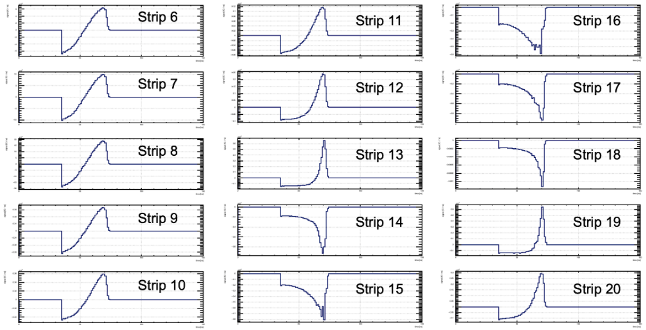


Observation of the Migdal effect with Optical TPC
- 3D track reconstruction -





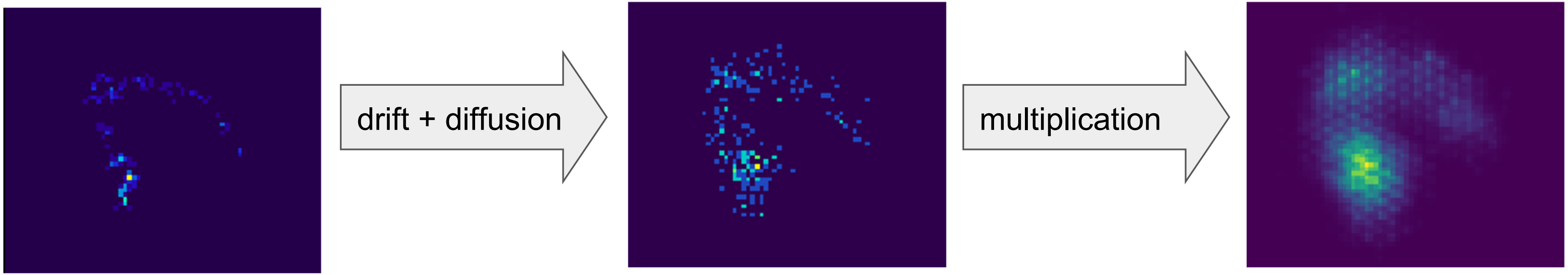
Raw pulses generated with garf ++



- Third coordinate reconstruction with charge readout using high granularity pattern of strips providing timing information

Image deconvolution: Motivation

As spatial distribution of the charge broadens in the process of registration, the features of the original track got blurred in the recorded image:



Looking for a way to recover the original shape of the track, at least to some extent