The Migdal effect for low-mass WIMP search

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Sudden displacement of a nucleus with respect to electrons.

\[ m_{\text{DM}} = 1 \text{ GeV} \]

‘Normal’ nuclear scattering

[Graph showing counts per keV/kg/day vs. nucleus or electron energy in keV with a highlighted observable energy range.]
$m_{DM} = 1$ GeV

‘Normal’ nuclear scattering

+ Migdal effect (ionisation of 1 electron)
What do we already know about the Migdal effect?

ernest migdal

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

[1] A. Migdal Ionizatsiya atomov pri yadernyh reaktsiyakh, ZhETF, 9, 1163-1165 (1939)
[6] X. Fabian et al., Electron Shakeoff following the $\beta^+$ decay of Trapped $^{19}$Ne$^+$ and $^{35}$Ar$^+$ trapped ions, PRA, 97, 023402 (2018)
Migdal effect searches in liquid/gases using neutron scattering

1. Dense medium.
2. NR+EL transitions in close proximity.
3. Signal from enhanced S1 and S2 due to X-rays from L and M shells.
4. Experiment at LLNL with fast neutrons from DT generator.
5. LZ experiment at SURF with fast neutrons from DD generator.

1. High pressure Ar (1 bar) and Xe (5 bar).
2. Looking for two-cluster signals from NR+Migdal electron (cluster A) and characteristic X-ray (cluster B).
3. Experiment at in Tsukuba with 565 keV neutrons from $^7\text{Li}(p, n)^7\text{Be}$ reaction at an irradiation facility at the National Institute of Advanced Industrial Science and Technology (AIST), Japan.
4. Low pressure operation at 66 mbar.
5. Enough mass as a target for fast neutrons from DD/DT neutron generators.
6. NR and electrons tracks with 5 keV threshold long enough for optical detection to provide direction and dE/dx information.
7. Experiment at ISIS/NILE (UK).
Migdal effect searches in liquid/gases using neutron scattering. LZ experiment with DD neutron generator.

Simulations:
1. N shell Migdal is too similar to NR
2. M Shell: Expected 152 events, with +1 keVee
3. L Shell: Expected 6 events, with +5 keVee
4. K shell Migdal is too few

Results:
1. Collected 36k single scatter events E>20 keVnr (after cuts)
2. Main backgrounds: multiple scatters and inelastic scattering together with compton scattering with unresolved position
3. In preliminary high-S2 region analysis, observing 23 events on a background 9.6±0.5(sys). Observed excess consistent with Migdal signal predicted by Ibe and Cox. Profile Likelihood Ratio (PLR) analysis is being finalised.
Migdal effect searches in liquid/gases using neutron scattering. Experiment at ILL with DT neutron generator.

5.7+/-1.2 signals expected
2 events observed
2.1+/0.9 backgrounds expected

~10 times fewer Migdal events estimated by fit than prediction, statistically consistent with 0 signals

1. Jingke Xu, Experimental result on measuring the Migdal effect with neutron-induced nuclear recoils at the keV level in liquid xenon; UCLA Dark Matter 2023 03/31/2023
Migdal effect searches in Ar and Xe using neutron scattering. MIRACLUE experiment with $^7\text{Li}(p, n)^7\text{Be}$ neutron beam.

Detector tests:
1. Xenon TPC worked with neutron beam successfully
2. Energy & topology were measured
3. Analysis for Migdal branching is ongoing
4. Argon TPC: planning neutron test for Jan 2024

K. Nakamura et al. Detection capability of the Migdal effect for argon and xenon nuclei with position-sensitive gaseous detectors

Progress of Theoretical and Experimental Physics, Volume 2021, Issue 1, January 2021, 013C01, https://doi.org/10.1093/ptep/ptaa162
The MIGDAL experiment

Create a dedicated experiment for the *unambiguous* observation of the Migdal effect in nuclear scattering:

- Phase 1: Observe the effect in CF4 in high energy recoils
- Phase 2: Observe the Migdal effect in CF4 + noble gases

We are the only experiment aiming to observe the nuclear and electron recoils emerging from a common vertex

H. Araujo et al., The MIGDAL experiment: Measuring a rare atomic process to aid the search for dark matter.
The MIGDAL experiment

- Low-pressure gas: 50 Torr of CF$_4$
  - Extended particle tracks
  - Avoid gamma interactions
  - Can stably work with fraction of Ar

- TPC Signal amplification
  - 2 x glass-GEMs (Cu + Ni cladded)

- Readout:
  - Optical: Camera + photomultiplier tube
  - Charge: GEMs + 120 ITO anode strips

- High-yield neutron generator
  - D-D: 2.47 MeV ($10^9$ n/s)
  - D-T: 14.7 MeV ($10^{10}$ n/s)
  - Defined beam, “clear” through TPC

- Electron and nuclear recoil tracks
  - Migdal: NR+ER tracks, common vertex
  - NR and ER have very different dE/dx
  - 5 keV electron threshold
  - 5.9 keV X-rays from Fe-55 induce 5.2 keV photoelectrons from F for calibration at threshold.
The MIGDAL optical-TPC

- TPC inside of the central aluminium cube
- Drift gap: 3 cm between woven mesh and cascade of two glass-GEMs ($E_{\text{DRIFT}}=200$ V/mm for minimum electron diffusion)
- Transfer and signal induction gaps: 2 mm
- Low outgassing materials; vacuum before fill $2 \times 10^{-6}$ mbar; signal unchanged several days after fill

Two glass GEMs one Cu- and one Ni-cladded:
- thickness: 550 μm
- OD/pitch: 170/280 μm
- active area: 10x10 cm$^2$
- total gain $\sim 10^5$

ITO strips wire bonded to readout
- 120 strips
- width/pitch: 0.65/0.83 mm

Two field shaping copper wires
Light and charge readout

**ITO anode strips**
Post-GEM ionisation
Readout of (x,z) plane
Pitch: 833 µm
Digitised at 2 ns/sample
*(Drift velocity: 130 µm/ns)*

**qCMOS camera**
*(Hamamatsu ORCA - QUEST)*
Detects GEM scintillation through glass viewport behind ITO anode
Readout of (x,y) plane
Exposure: 8.33 ms/frame
*(continuous)*
Px scale: 39 µm (2×2 binning)
Lens: EHD-25085-C; 25mm f/0.85

**VUV PMT (Hamamatsu R11410)**
Detects primary and secondary (GEM) scintillation
Absolute depth (z) coordinate
Digitised at 2 ns/sample  [Trigger]
The NILE facility at Rutherford Appleton Laboratory

- D-D and D-T fusion generators installed in “shielding bunker”
- Collimators & additional shielding provide clean beam through OTPC
- D-T collimator 1 m, D-D 30 cm
Experiment installation in the NILE bunker

MIGDAL experiment fully assembled at NILE

- Lead shield: 10 cm
- Borated HDPE shield: 20 cm
- Collimator HDPE+ lead: 30 cm long
First Science Run (Summary)

- The First Science run took place from the 17th of July to the 3rd of August.

- Data taken using D-D neutron generator, with a lower NR rate than designed, is recorded continuously during 10 hour long shifts, and includes significant fraction of empty frames.

- Frames taken with 20 ms exposure time. Longer than planned due to problems with camera’s Linux firmware.

- Data taking interspersed with regular calibration runs (\(^{55}\text{Fe}\)) to monitor the gain of the detector.

- Voltage across GEMs increased by a small amount each day to keep constant gain.

- Total gain in GEMs tuned to a threshold required to see fully resolved \(^{55}\text{Fe}\) peak.

- Average spark rate ~ 7/min due to high dynamic range the detector operates at.

- Half of the data is blinded.
Examples of events (Single Nuclear Recoil)

- Track length: 4 mm
- Energy: \( \sim 100 \text{ keV}_{ee} \)
Examples of events (Migdal-like event)

**Single Nuclear Recoil**
Track length: 14.6 mm
Energy: ~ 500 keV$_{\text{ee}}$

and

**Two 5.2 keV photoelectrons**
from F induced by 5.9 keV X-rays from $^{55}$Fe source
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ML object detection algorithm identifies tracks in the image. Overlapping boxes indicate Migdal-like event.
Examples of events (Migdal-like event)

Combined image with the ITO signals shows three separate events by associating the shared axis of the ITO strips and camera (x).

MIGDAL Preliminary Data

Synchronised signals from ITO strips.
Examples of events (Migdal-like event)

Combined image with the ITO signals shows three separate events by associating the shared axis of the ITO strips and camera (x).

Synchronised signals from ITO strips.

Timing information from ITO strips separates all 3 tracks.
1. Fixed communication between DAQ PC and camera - use CoaXPress instead of UBS decreasing exposure time from 20 ms to 8.3 ms - less chance for coincidence events.
2. Fixed missing bonded connection to central ITO strips.
3. Use FPGA to record timing information of every trigger also within 3 ms of DAQ dead time.
4. New GEMs w/o metallisation around mounting holes
5. Use of mask limiting events detected by the ITO strips without being seen by the camera
6. At the later stage of the SSR - use of a new collimator increasing NR rate x3.
Summary

- Several experiments using different detection techniques search for the Migdal effect.
- Effect is investigated in light atoms like C and F as well as in heavier Ar and Xe.
- We have first results from experiments using LXe (LZ and experiment at LLNL).
- Early next year we should hear results from MIRACLUE using high pressure TPC filled with gaseous Xe at high pressure.
- The MIGDAL experiment’s first science run took place with DD neutron source at the NILE facility at RAL. The detector performed well through the weeks of operation with highly ionising NRs.
- Analysis of recorded data underway with 50% of recorded data kept blinded.
- Second Science Run planned for January.