Simulating the Optical Properties of the MIGDAL Experiment OTPC

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ABSTRACT

The optical properties of the Optical Time-Projection Chamber in the MIGDAL experiment are investigated to better understand signals detected and optimise its inner components.
Properties of the equipment are varied such as the reflectivity of the GEM planes, the depth of the event and the efficiency of the photomultiplier tubes.
Significant effects originate from the depth of the source position and the quantum efficiency of the PMTs which should be chosen to optimise the signals generated.

BACKGROUND

THE MIGDAL EFFECT

The Migdal effect describes the excitation or ionisation of an atomic electron due to a sudden change in the state of the nucleus. In nuclear scattering, this change is the sudden velocity acquired by the nucleus when an incident particle transfers some momentum to it.

This effect has been experimentally observed in beta and alpha decays but not in nuclear scattering.

This is an interesting effect for dark matter experiments as it could allow the range of dark matter particle masses to be extended to lighter dark matter candidates.

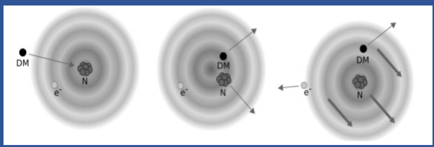


Fig 1: The dark matter particle enters from the left and scatters off of the nucleus of the atom. The nucleus then gains a velocity and leaves the electrons behind briefly. During this time, the electrons can be ionised [1].

THE MIGDAL EXPERIMENT

The MIGDAL experiment aims to confirm the presence of the Migdal effect in nuclear scattering. It uses a neutron generator to scatter neutrons off of the nuclei in low pressure CF4 gas.

The experiment uses an Optical Time-Projection Chamber (OTPC) which detects the initial scintillation light produced at a PMT and allows electrons from the resulting ionisation tracks to drift in the opposite direction, become amplified and produce secondary scintillation light which is detected by a camera. The drift time of these electrons provides the depth information for event reconstruction.

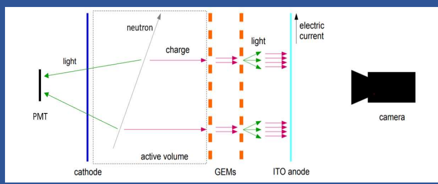


Fig 2: The signal generation of the OTPC showing how signals are detected in both the forward and backwards direction [2].

METHOD

This project focussed on investigating the optical properties of the OTPC and their effect on the quality of the signals generated. Both the PMT and the camera were modelled as PMTs and recorded the number of photons detected for each simulation.

The geometry of the detector (diagram shown in Figure 3) was created in an ANTS2 environment and inner components were included as needed.

Simulations were run by generating 20,000 photons from each specified location in the central area. This forms a 16 cm × 16 cm grid of nodes at 2 mm intervals in the x-y plane. These photons were set of isotropically from each location and the fraction (CF) of these photons detected was plotted as a colour gradient. This percentage can be converted into the energy recorded via the equation

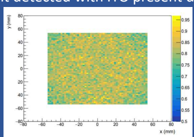
$$E = 1/CF * \#\,\gamma\ recorded * work\ function\ of\ CF4 * e\ to\ \gamma\ ratio$$

This is represented as contour lines in the following graphs.

RESULTS

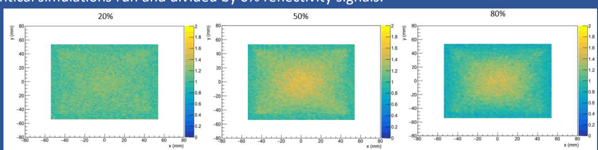
ITO SILHOUETTE

Simulations set at z=41.58 mm and detected at PMT#0.
Light detected with ITO present divided by light detected in empty geometry.



The ITO has a refractive index is higher than its surroundings.
The plastic frame is set as optically opaque.
The collection percentage at the ITO is reduced by 10%-20% and no light generated behind the frame is visible.

The reflectivity of the detector walls increased to 20%, 50% and 80% respectively.
Identical simulations run and divided by 0% reflectivity signals.



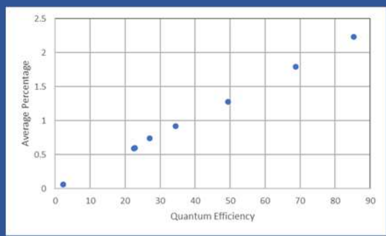
The light detected increases by 20%, 50% and 80% respectively and definition along the diagonals appears most pronounced at 50% reflectivity.

QUANTUM EFFICIENCY OF PMT

Simulations set at z=31.58 mm and detected by PMT #1.
Wavelength-dependence of the PMTs was included for the range 100 nm to 700 nm.

Eight efficiencies chosen for analysis:

Wavelength	Efficiency
165 nm	22.8 %
165 nm	68.7 %
240 nm	27.0 %
240 nm	49.4 %
290 nm	34.4 %
290 nm	85.3 %
630 nm	2.3 %
630 nm	22.5 %



The quantum efficiency of the PMTs has a linear relationship to the signal detection.
The quantum efficiency should be chosen such that the largest values lie within the wavelength range of interest.
In this scenario, energies up to 6 keV recorded.

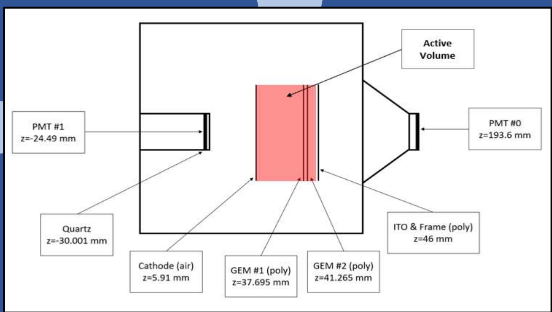
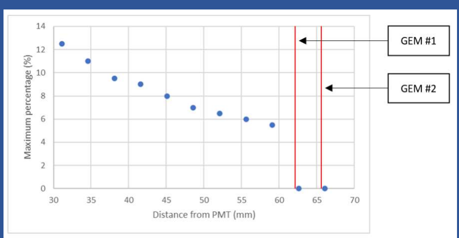


Fig 3: Diagram of the composition of the OTPC including all inner components and their location and materials for use in ANTS2 simulations.

ACTIVE VOLUME SWEEP

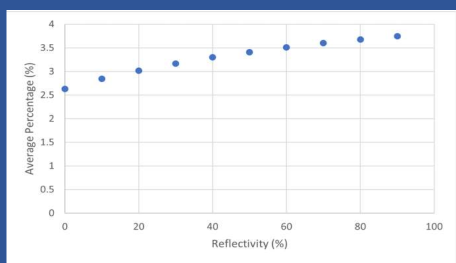
Simulations set at 3.5 mm intervals between z=6.58 mm & z=41.58 mm and detected at PMT#1.
Refractive index of quartz window and opaque quality of GEM planes included.



The percentage recorded falls with distance from PMT as the solid angle subtended by the PMT decreases.
The GEM planes are opaque and block all light.
In this scenario, energies up to 36 keV recorded.

REFLECTIVITY OF GEM PLANE

Simulations set at z=31.58 mm and detected at PMT#1.
Reflectivity of the first GEM plane (closest to PMT#1) is varied from 10% to 90% at 10% intervals.



The reflectivity of the GEM plane has a positive correlation with the collected percentage of light at the PMT.
The maximum average percentage increase is ~1.5%.
This does not significantly increase signal at PMT.
In this scenario, energies up to 13 keV were recorded.

REFERENCES

[1] P. Majewski, 'OTPC for the Observation of the Migdal Effect in Nuclear Scattering', RD51 collaboration meeting and topical workshop on New Horizons in Time Projection Chambers, 2020
[2] E. Asamar, 'The LZ and MIGDAL Experiments: Current Status and Plans', 17th MultiDark workshop, 2021

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