Rare event searches with gaseous detectors

Tom Neep, on behalf of the Birmingham Gaseous Detectors Laboratory (and many others)
Warwick
May 19, 2022
The Standard Model (\& beyond)

- The Standard Model of particle physics is “complete”
- It does an annoyingly good job of describing the data from the LHC (with a few notable exceptions)
- Lots of observations suggest that dark matter exists
  - Galactic rotation curves
  - Cosmic microwave background
  - Small scale structure
  - ‘Bullet’ cluster

![Dark Matter Pie Chart]

![Standard Model Diagram]
• What do we know about dark matter? Not much!

**Dark Sector Candidates, Anomalies, and Search Techniques**

- **QCD Axion**
- **WIMPs**
- **Ultralight Dark Matter**
  - Pre-Inflationary Axion
  - Post-Inflationary Axion
- **Hidden Sector Dark Matter**
  - Hidden Thermal Relics / WIMPless DM
  - Asymmetric DM
  - Freeze-In DM
- **SIMPs / ELDERS**
- **Beryllium-8**
- **Muon \( g-2 \)**
- **Small-Scale Structure**

**Small Experiments:** Coherent Field Searches, Direct Detection, Nuclear and Atomic Physics, Accelerators

**Microlensing**
Dark matter

- Direct dark matter searches have made great strides in excluding WIMP-like dark matter
- Increasing interest in pushing towards lower masses, $\mathcal{O}(100 \text{ MeV})$

Figure 3: Current status of searches for spin-independent elastic WIMP-nucleus scattering assuming the standard parameters for an isothermal WIMP halo: $\langle v \rangle = 0.3 \text{ GeV}/c^3$, $v_0 = 220 \text{ km}/s$, $v_{\text{esc}} = 544 \text{ km}/s$. Results labelled “M” were obtained assuming the Migdal effect \[131\]. Results labelled “Surf” are from experiments not operated underground. The $\langle v \rangle$-floor shown here for a Ge target is a discovery limit defined as the cross section $d$ at which a given experiment has a 90% probability to detect a WIMP with a scattering cross section $d > d_{3 \sigma}$. It is computed using the assumptions and the methodology described in \[151, 153\], however, it has been extended to very low DM mass range by assuming an unrealistic $1\text{ m eV}$ threshold below $0.8 \text{ GeV}/c^2$. Shown are results from CDEX \[155\], CDMSLite \[156\], COSINE-100 \[157\], CRESST \[158, 159\], DAMA/LIBRA \[160\] (contours from \[161\]), DAMIC \[162\], DarkSide-50 \[163, 164\], DEAP-3600 \[144\], EDELWEISS \[165, 166\], LUX \[167, 168\], NEWS-G \[169\], PandaX-II \[170\], SuperCDMS \[171\], XENON100 \[172\] and XENON1T \[21\]–\[175\].

Bubble chambers filled with targets containing $^{19}$F have the highest sensitivity to spin-dependent WIMP-proton couplings. The best limit to date is from PICO-60 using a $52 \text{ kg}$ $^{3}$C$_8$F$_8$ target \[176\]. At lower WIMP mass, between $2 \text{ GeV}/c^2$ and $4 \text{ GeV}/c^2$, the best constraints come from PICASSO (3.0k g \[177\]). CRESST used crystals containing lithium to probe spin-dependent DM-proton interactions down to DM mass of $\langle v \rangle < 800 \text{ MeV}/c^2$ \[178\]. The strongest constraints on spin-dependent WIMP-neutron scattering above $\langle v \rangle > 3 \text{ GeV}/c^2$ are placed by the LXe TPCs with the most sensitive result to-date coming from XENON1T \[41, 179\]. The results from the cryogenic bolometers (Super)CDMS \[180, 181\] and CRESST give the strongest constraints below $\langle v \rangle < 3 \text{ GeV}/c^2$. CDMSLite \[182\] uses the Neganov-Trofimov-Luke effect to constrain spin-dependent WIMP-proton/neutron interactions down to $m = 1.5 \text{ GeV}/c^2$ and CRESST-III \[159\] exploits the presence of the isotope $^{17}$O in the CaWO$_4$ target to constrain spin-dependent WIMP-neutron interactions for DM particle’s mass as low as $160 \text{ MeV}/c^2$.

Exploiting the Migdal effect again significantly enhances the sensitivity of LXe TPCs to low-mass DM with XENON1T providing the most stringent exclusion limits for both, spin-dependent WIMP-proton and WIMP-neutron couplings between $80 \text{ MeV}/c^2$ and $90 \text{ MeV}/c^2$. 

ARXIV: arXiv:2104.07634
The Migdal effect

- Typically we assume that the electron cloud in an atom move instantaneously with a nuclear recoil
- In reality the electrons take a short amount if time to catch up with the recoiling nucleus
- This can cause ionisation and excitation of the atoms, emission of one or more Migdal electrons \( (P \approx O(10^{-6})) \)
- Electronic recoil detection increases the sensitivity of our detectors to light WIMPs
- First described by A. Migdal in 1939 A. Migdal, ZhETF, 9, 1163-1165 (1939), ZhETF, 11, 207-212 (1941)
To explore dark matter masses of $O(100 \text{ MeV})$ we need detectors with a lower threshold.
Exploring lower dark matter masses

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**Option A: Exploit the Migdal effect**

- No need to build a new detector?
- Can reinterpret existing results?
- **Problem:** The Migdal effect has not yet been observed in nuclear scattering!
- **Solution:** Build a detector to observe the Migdal effect in nuclear scattering
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**Option B: Build detectors with light targets**

- If DM is light then a light target is a better match
- Need a low background detector – low material budget
- Need low electronic noise – aim for single electron threshold
- **Solution:** Build a detector which can be filled with a light target
A generic gaseous detector

1. Particle enters the detector and scatters off a nucleus
2. Nucleus ionizes the gas, creating electron–ion pairs
3. In the presence of an electric field, electrons drift towards the anode
4. Electrons avalanche in a region with high E-field magnitude. Electrons given enough energy to ionize more electrons–ion pairs, which in turn can ionize more and so on...
5. Electrons (or ions) induce current on electrodes (Shockley-Ramo)

- Can build large detectors at a reasonable cost
- The gas and pressure can be changed to suit the requirements of the experiment
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The MIGDAL Experiment

- The Migdal In Galactic Dark MAtter Exploration experiment aims to make an unambiguous observation of the Migdal effect in nuclear scattering using an optical time projection chamber
- Similar concept to the diagram on the previous slide
Electron avalanche performed using two GEMs
- GEMs are micropattern gas detectors, in the same family of gaseous detectors as Micromegas
- Very small holes in a dielectric sheet
- Electrons are directed through the holes and avalanche inside of them
- Glass sandwiched with copper (0.55 mm thick glass with 2 μm of copper on either side)
- GEM parameters: 170 μm diameter holes, 280 μm pitch
MIGDAL: Readout

- The experiment is equipped with multiple readouts
- A PMT is used to collect light produced in both the initial ionization and in the avalanche. This gives us information about the absolute z-position of the initial interaction
- An Indium Tin Oxide (ITO) strip anode is used to readout the charge produced. This gives us information about the tracks produce in the x and z (time) directions
- A CMOS camera records the light leaving the GEMS, giving us a picture of the tracks in the x-y plane
- We are involved in simulating all of this, I am the simulation coordinator for the experiment
Example simulated Migdal-like event: CMOS image
• Experiment will be based at RAL
• We will first use a 2.45 MeV DD neutron source and later a 14.1 MeV DT neutron source
• Expect to start data taking very soon. Stay tuned!
Exploring lower dark matter masses

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Spherical Proportional Counters (SPCs)

Overview

- SPCs consist of a grounded metallic shell, which acts as a cathode, a gas volume and a central anode sensor
- The anode is kept at a high voltage and supported by a grounded metallic rod

Advantages

- Low capacitance, independent of cathode radius – low noise, single electron threshold
- High-pressure operation – can reach large target masses
- Optimal volume-to-surface ratio – low background
- Single readout in its simplest form
- Easy to switch target gas
• The signal of an “event” is a voltage pulse, which can be deconvolved to get a current pulse.
• Each pulse contains information that can be used to distinguish different features of observed events, potentially allowing signal/background discrimination.
Pulse shape discrimination

Figure 8. Readout pulses produced by 2.38 keV electrons from an initial radius of 10 cm in a 15 cm radius detector in the gases He:Ne:CH\textsubscript{4} (72.5% : 25.0% : 2.5%) at 1.0 bar (red) and Ne:CH\textsubscript{4} (94% : 6%) at 1.0 bar (blue).

Figure 9. The pulse integral from interactions of 5.9 keV electrons in Ar:CH\textsubscript{4} (98% : 2%) at 300 mbar in a 15 cm in radius detector, (a) using an ideal detector; (b) using a realistic configuration with a correction electrode and a supporting rod.
● The first NEWS-G detector was called SEDINE and operated at LSM for 43 days in Spring 2015
● 60 cm diameter copper SPC filled with Ne+CH4 (0.7%) at 3.1 bar [9.6 kg · days]
● Set world leading limits on “WIMP-like” dark matter with \( m_{\chi^0} < 650 \) MeV
● Limits have since been surpassed
● Main background from decays in the copper sphere

How to improve?
● Larger target mass (bigger detector)
● Lower backgrounds
● Better signal/background discrimination
Larger target mass – bigger detector?

- To increase the target mass we ideally want a larger detector
- Not as simple as it might sound
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- To collect the charge at the edge of the detector efficiently we need a large drift field
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Can increase the drift field by increasing the anode radius
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- But increasing the anode radius reduces the electric field in the avalanche region (lower gain)
- So need to increase the voltage, but this can lead to instabilities
- Ideally we need a way to decouple the fields in the avalanche and drift regions…
The solution is to use a multiple anode sensor, known as ACHINOS sensors.

- The drift field and avalanche fields can be decoupled.
• An additional advantage is that we can perform multi-channel readout, allowing the position of the primary interaction to be determined and help particle identification (distinguish signal from certain backgrounds)

• Plot shows the amplitude asymmetry formed from the rod-side and far-side anodes from simulation
Electroplating

- The largest background in the previous iteration of the analysis was from $^{210}$Pb decays in the copper sphere
- In addition to using 99.99% pure copper, the inner surface of the sphere has been **electroplated**
- A 500 $\mu$m layer of pure copper has been plated on the inner surface of SNOGLOBE
- Rate of copper $\approx 36$ $\mu$m per day
- Expect to reduce background rate by more than a factor of 2 in the ROI
The current NEWS-G SPC is called SNOGLOBE. This will operate at SNOLAB in Canada having previously operated at LSM.

- Several improvements over SEDINE
- 140 cm diameter → Possible thanks to the ACHINOS
- 4N Aurubius Copper (99.99% pure) with 500 µm electroplated copper inner surface
- Two readouts (possible fiducialisation)
SNOGLOBE

- Expect to improve sensitivity by several orders of magnitude and set limits down to 100 MeV
- The detector is now in position at SNOLAB
- Commissioning is underway and data taking to start this year (delayed due to COVID)
ECUME

- Despite the electroplating, we still expect the largest background with SNOGLOBE to come from decays in the copper sphere
- The ECUME project aims to build a fully electroformed detector underground
The Future: ECUME & DarkSPHERE

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DarkSPHERE

- Proposal to build a 3m diameter fully-electroformed detector
- Will operate with He and isobutane
- We hope to build and operate this detector at Boulby Underground Lab.
- An opportunity for world leading dark-matter experiment in the UK!!
• Simulations of a 60 anode (!) ACHINOS for DarkSPHERE
• Will potentially allow some level of tracking
• DarkSPHERE will set world leading spin-dependent dark matter limits
• Interest from UK theory community: arXiv:2110.02985

Backgrounds from neutrons in the cavern may become problematic. Can we measure these in-situ?
Detecting neutrons is difficult

Current neutron detectors have several disadvantages

Helium-3 based proportional counters are efficient for thermal and fast neutrons, but need to be operated at high pressure.

Helium-3 is extremely expensive

**Proposal:** use an SPC filled with N$_2$ to detect neutrons

Nitrogen is non-toxic, non-flammable and cheap

\[
\begin{align*}
^{14}\text{N} + n & \rightarrow ^{14}\text{C} + p + 625 \text{ keV} \\
^{14}\text{N} + n & \rightarrow ^{11}\text{B} + \alpha - 159 \text{ keV}
\end{align*}
\]

We have been measuring neutrons with a nitrogen-filled SPC in Birmingham!
To test the detection of neutrons we use an $^{241}$Am$^9$Be source

Use the 30 cm diameter SPC, filled with N$_2$ and instrumented with a two-channel achinos

A graphite stack is used to thermalise neutrons. We can move the source in/out of the stack to get thermal/fast neutrons.
• Impurities in the gas emitted by filter (Radon) actually quite useful to calibrate the detector!
• Paper very soon!
- We can also produce neutrons at the MC40 cyclotron
- Deuteron beam on a Beryllium target to produce fast neutrons with energies up to 10 MeV
- Can place various moderators in the beam (paraffin, boron doped polyethylene, lead)
- Make comparisons with our simulation framework (preliminary results)!
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- Many experiments are searching for $\nu\beta\beta$ decay

### Requirements for a $\nu\beta\beta$ experiment

1. **Low background** Low rate of signal events requires as small a background as possible
2. **Large isotope mass** Limits on $\nu\beta\beta$ half-life require large isotope masses
3. **Good energy resolution** Essential to discriminate the $\nu\beta\beta$ signal from the $2\nu\beta\beta$ background
• Many experiments are searching for $0\nu\beta\beta$ decay

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### Properties of Spherical Proportional Counters

1. **Low background** a) Spherical shape has the optimal surface-to-volume ratio, b) Very low material budget c) Radial discrimination through pulse analysis
2. **Large isotope mass** Large masses of extremely pure gaseous isotopes can be achieved through high pressure operation
3. **Good energy resolution** ???
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- SPCs good $\nu\beta\beta$ detectors? Conceptual design investigated in detail in [JINST 13 (2018) 01, P01009]
Neutrinoless double beta decay

- Neutrinos have mass and oscillate between flavours! Right-handed neutrinos?
- Majorana proposed that neutral particles can be their own anti-particles
- If this is the case then we can introduce **neutrinoless double-beta decay**
- Such a process would violate lepton number and may help to shed light on the matter–anti-matter asymmetry of the universe
- Measure the energy of two electrons
- If there is $0\nu\beta\beta$ then we expect a peak at the $Q$-value of the process, compared with a continuous spectrum from $2\nu\beta\beta$
- Example below from the GERDA experiment
• **R2D2** (Rare decays with a radial detector) is an R&D project to investigate using a Xenon filled SPC to search for $\nu\beta\beta$

The initial goal of the project is to demonstrate the required energy resolution to search for $\nu\beta\beta$ can be achieved (1% FWHM at $Q_{\beta\beta}$ of 2.458 MeV)
R2D2 spherical TPC: first energy resolution results

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P. Hellmuth\textsuperscript{a} I. Katsioulas\textsuperscript{d} P. Knights\textsuperscript{d,c} I. Giomataris\textsuperscript{e} M. Gros\textsuperscript{a} P. Lautridou\textsuperscript{f}
A. Meregaglia\textsuperscript{a,1} X. F. Navick\textsuperscript{4} T. Neep\textsuperscript{d} K. Nikolopoulos\textsuperscript{d} F. Perrot\textsuperscript{a} F. Piquemal\textsuperscript{a} M. Roche\textsuperscript{a}
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\textsuperscript{d}School of Physics and Astronomy, University of Birmingham, B15 2TT, United Kingdom
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\textsuperscript{f}SUBATECH, IMT-Atlantique, Université de Nantes, CNRS-IN2P3, France

- To investigate whether the desired energy resolution can be achieved a 20 cm radius aluminium SPC has been produced and operated at CENBG in Bordeaux
- The detector was filled with a mix of Argon/CH\textsubscript{4} (98/2\%)
- An\,\alpha\, particle source (\textsuperscript{210}Po) was used, producing\,\alpha\, particles with \(E = 5.3\,\text{MeV}\)
Results (i)

- Measured data are compared with simulation results using JINST 15 (2020) 06, C06013.
- Good agreement
- Pulse properties can be used to select specific events
Resolution measurement

- The energy resolution is measured to be ≈ 1.1% FWHM at 5.3 MeV
- Scaling to the $Q_{\beta\beta}$ of $^{136}$Xe gives a resolution of 1.6%
- $W$-value and Fano factor of Xenon more favourable than Argon
- Tested at two different pressures (track lengths varying from a few to 20 cm). Results independent of track length.
- Promising first results!
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- **Neutron measurements** have been performed here in Birmingham – expect papers on the graphite stack and cyclotron measurements in the coming weeks/months!
- The **R2D2** project is continuing to study the suitability of an SPC for $0\nu\beta\beta$ decay searches. Recently demonstrated adding light readout to an SPC
Back-up
Evidence for Dark matter

- Galactic rotation curves
- Lensing
- Bullet cluster
- $\Lambda$CDM
Figure 4: Sensitivity projections (90% CL) for spin-independent WIMP-nucleon scattering. The neutrino floor is defined as in Fig. 3 and shown for different targets. Shown are projections from ARGO, CRESST, CYGNUS, DAMIC-M, DarkSide-20k, DARWIN, EDELWEISS, LZ, NEWS-G (ECUME), PandaX-4t, SuperCDMS, T-REX, XENONnT along with the envelope of the current results from Fig. 3. Neutrino-induced backgrounds. The ultimately lower background achievable in argon experiments due to the pulse-shape discrimination of ERs allows a better discovery potential for higher WIMP mass, see Fig. 5. The discovery potential at lower mass is better in xenon experiments thanks to their much lower experimental energy threshold. When operated in charge-only mode, the large liquid noble gas TPCs also have a good sensitivity in the low mass region below $\sim 5 \text{GeV}/c^2$, however, the discovery potential is superior for the dedicated low-mass searches using bolometers and crystals thanks to their lower backgrounds and energy thresholds.

It is important to emphasise that the whole spectrum of direct WIMP searches with all its complementary approaches, targets and search channels cannot be put into one common figure. Experiments with targets containing $^{19}$F are needed to optimally probe spin-dependent WIMP-proton couplings. Xenon targets ($^{129}$Xe, $^{131}$Xe) are required to test spin-dependent WIMP-neutron couplings with the highest sensitivity, however, there are a number of isotopes which can also provide excellent results in one or/and the other channel (e.g., $^7$Li, $^{17}$O, $^{23}$Na, $^{27}$Al, $^{29}$Si, $^{73}$Ge, $^{127}$I, $^{183}$W). The search for signatures of inelastic scattering requires a low background in both, NR and ER (before rejection), channels; an additional excellent energy resolution will allow for an optimal characterisation of the process. Interactions of DM particles in the mass range of $\mathcal{O}(1 \times 100) \text{ MeV}/c^2$ are best searched for by detectors with a sensitivity to single electrons, e.g., Si CCDs, Ge bolometers or liquid noble gas TPCs in charge-only mode. Other models introduce different coupling between DM and protons vs. neutrons to explain the apparent tension between DM claims and limits (e.g., [188]): in such a "xenophobic" model, $^{48}$Ca construction.
The SPC landscape

Birmingham Sphere, ⌀30cm
Boulby Sphere, ⌀30cm
R2D2 Sphere, ⌀40cm
SEDINE, ⌀60cm
SNOGLOBE, ⌀140cm
Achinos weighting fields

Current on electrode from Ramo-Shockley theorem

\[
i_n = -q \frac{\vec{E}^n_w \cdot \vec{v}}{V^n_w}
\]

(1)

Direction of \(\vec{v}\) is the same as the electric field of the detector. Focus on top anode, \(\vec{E}\) and \(\vec{E}^\text{far}_w\) are in same direction. \(\vec{E}\) and \(\vec{E}^\text{near}_w\) are in opposite directions \(\therefore\) opposite currents
The setup of the detector studied and the most relevant expected backgrounds for one year of data taking.
• Interesting lessons learnt during the process of producing the “final” comparison seen on the previous slide

• Diffusion and noise have large impacts on the Dt distribution
Monitoring & Calibration

- Detector stability is monitored using a laser system
- Can be used to calibrate the detector
- $^{37}$Ar calibrations are performed at the end of runs
SEDINE analysis

Fig. 9. Top panel: distribution of the rise time. Bottom panel: logarithmic scale events rates. Use of H and He targets will allow us to reach WIMP mass sensitivity down to 0.1 GeV.

Constraints by lead, \( \sigma \) our references to the histograms, the bars, red particles assigned, Q. Arnaud et al. / Astroparticle Physics 97 (2018) 54–62

Among experiments of \( 16 \) to \( 25 \) GeV/c, \( 2 \) hits, \( 10^{3} \) hints, the \( 2 \) mass, \( 10^{5} \) ECLP. Use of H and He targets will allow us to reach WIMP mass sensitivity down to 0.1 GeV.

Use of H and He targets will allow us to reach WIMP mass sensitivity down to 0.1 GeV.

• Studied achinos $\phi$ dependence for **JINST 15 (2020) 11, P11023**
• 3D printed DLC sensor, 11 1mm diameter anodes in 30cm diameter SPC
• Here an $^{55}$Fe source has been moved around the detector (at the same latitude)

• Gain changes versus $\phi$
• Lines up with which anode the source is closest too
• Gain variation is well reproduced by the simulation!
• We can show with simulation this can be corrected by applying different voltages to each side of the achinos
Our simulation framework combines:
- **Geant4**, for simulating the interactions of particles/radiation with matter
- **Garfield++**, for simulating the electron-ion drift and signal calculation (interfaces to Heed, SRIM and Magboltz)
- **ANSYS**, finite-element software, for electric field calculations

Our framework uses these toolkits, along with custom calculations, to produce a complete simulation.

![Image of electric field magnitude](image_url)
Simulation: Initial particle tracking, ionisation and drift

- We use Geant4 to create and track our initial particles we want to study
- Geant4 tracks these through the detector until it produces electrons with $E < 2$ keV
- At this point Garfield++ takes over
- $\delta$-electrons are produced (HEED), and then all the electrons are drifted in the detector using ANSYS and Magboltz
• Close to the anode, where the electric field is strongest, the electrons avalanche, producing electron-ion pairs
• Depending on the properties of the detector, this process can produce 10,000s of electrons
• Tracking each one of these becomes extremely computationally expensive
• Instead we parameterise the gain by numerically integrating the Townsend coefficient (minus attachment) along the path of each primary electron

$$\bar{G} = \exp \left( \int_{\vec{r}} \alpha(\vec{r}) - \eta(\vec{r}) d\vec{r} \right)$$

• Electron multiplication then follows a Polya distribution
• Studied achinos phi dependence in the context of
• 3D printed DLC sensor, 11 1mm diameter anodes in 30cm diameter SPC
• Here an $^{55}$Fe source has been moved around the detector (at the same latitude)

- Gain changes versus $\phi$
- Lines up with which anode the source is closest too
- Gain variation is well reproduced by the simulation!
- Gain is higher when source inline with rod-side anode
We investigated what happens when different voltages are applied to either side of the achinos

Able to flatten out the gain fluctuations to a large extent with a rough tuning

Can expect a fine-tuning can lead to uniform gain in near and far sides of the detector

Could potentially even calibrate each anode individually