WIMPs, KK axions and DRIFT

Neil Spooner (University of Sheffield)

- Dark Matter
- Directional TPC idea
- DRIFT II
- KK axions and TPC
Direction sensitive WIMP detectors

- **WIMP Wind**
- Galactic WIMP Halo
- June 12:00h
- December 0:00h
- $\gamma$
- $v_0=230\text{km/s}$
- $\cos \gamma$
- $WIMP$ astrophysics?
- Determine galactic origin
- Recoil Flux at Boulby @ 0hrs Sidereal
- $WIMP$ recoil
- MC ~30 WIMPs to confirm galactic origin
Determining Halos (galactic co.)

WIMP flux inputs
- assume all S (32GeV) recoils with 100GeV WIMPs.

Standard Maxwellian halo, \( v_0 = 220 \text{km s}^{-1} \).

Triaxial - rather extreme case: \( p = 0.72, q = 0.7 \)

Triaxial halo with \( p = 0.9, q = 0.8 \).

N-body simulations also suggest mild radial orbit bias.
\[
\beta(r) = 1 - \frac{\left\langle v_{\phi}^2 \right\rangle - \left\langle v_{\phi}^2 \right\rangle}{2\left\langle v_r^2 \right\rangle}
\]

Example detector outputs
Low background low pressure TPC

Simulated events
SRIM 40 keV S recoils in 40Torr Cs₂

electron track of similar energy is off scale (sketch)

negative ion drift with CS₂ rediscovered by Jeff Martoff (Temple)
How many WIMPs to see the halo

**Model for realistic (advanced) detectors**

- 40 Torr CS$_2$
- 1 kV cm$^{-1}$ drift field
- 200 μm resolution
- 10 cm drift
- SRIM2003 - recoil scattering and diffusion

**Vectorial Statistics:**

Recoil directions estimated as principal axis ±r of moment analysis of pixel signals.

**Axial Statistics:**

Recoil sense known(unknown): 10-20(100-400) events needed to reject isotropy at 95% confidence in 95% of experiments.

primary limitations: (1) recoil scattering and diffusion
(2) head-tail
DRIFT II (a,b,c,...) - multi-module

**first steps to cheap modules**

- **Aim**
  WIMP sensitivity of $10^{-6}$ pb per module per year

- **Basic Design**

  Modular… $n \times (3-4) \times 1m^3$ fiducial vol, NITPCs
  - Back-to-back drift vols & dual MWPC readout
  - Vertical planes, warp adjust strongback MWPCs
  - **3d track reconstruction (anode, grid and z-drift)** (resolution: $\Delta x = 2mm$, $\Delta y = 0.1mm$, $\Delta z = 0.1mm$)
  - Low noise DAQ (few keV S-recoil threshold)
  - low leak vessel design ($<10^{-5}$T.L.s$^{-1}$).
  - Simple gas system (various pressure & gas mixtures)
DRIFT IIa construction

- vacuum vessel
- MWPC, 1m²
- assembly of field cage
- DAQ
DRIFT IIa installation at Boulby (1.1km depth)
DRIFT II shielded and running

Continuous, stable, shielded operation since Aug 17th 05.

- 6 kg.days of unshielded data from engineering runs with ~3 kg.days partially-shielded.
- 12 kg.days of shielded data so far (~80 days continuous operation at 90% live time).
Long-term running and detector stability

- Cathode Current
- CS2 Weight
- Pressure
- Vessel Temperature

Axions, CERN-1105-Niel Spooner
Track analysis

MWPC wire planes

example track (alpha)

\[ R^2 = \Delta x^2 + \Delta z^2 \]

\[ R^3 = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2} \]

Wire 1

Wire 2

\[ \Delta x \]

Wire 3

Wire 4

alpha region

recoil region

γ region

\[ \text{NIPs} = 32 \text{ keV S recoil} \]

90%
Gammas rejection basics

- Test with 1 ft³ detector at Occidental

Low threshold

High threshold

Gammas

Neutron

Low thresh. High thresh.

Gamma Region

Neutron Region

Low thresh.

High thresh.

Ionization

Ionization
1000 Wires grouped down to 8 Channels

GRID: 12bit 5MHz sampling PCI ADCs.
Internal 64 fold grouping & Amptek pre-amplification - 8 channels per MWPC
X & Y alpha vetos read into GRID DAQ

ANODE: ditto

Slow Control: 120 chan Agilent data acq unit.
DRIFT IIa underground data

Typical neutron calibration event in right detector:

Background alpha crossing central drift-cathode (parts of track detected by both MWPCs).
DRIFT Ila data analysis

- **Raw data**
- **Analysis software**
- **Waveform statistics**
- **SQL database**
  - 55Fe calibration
  - R2 plots
  - Track finding
  - Cuts

**Signal features**:
- Minimum value
- Maximum value
- FWHM
- Width (time)
- Width (samples)
- Integrated area
- Timestamp
- Polarity
- Signal profile index
- Event number
- Polarity
- Voltage weighted time
- Minimum value index
- Maximum value index
- Start time/index
- End time/index
- Baseline offset
- Height to width ratio

**Graphical representation**
- Baseline/zero-line
- Minimum
- Maximum
- Software threshold
- \( \Sigma/N_{ips} \)
Solar Kaluza-Klein axions

- Axions arise from Peccei-Quinn solution to strong CP problem in QCD (see other talks….)

- In theories with $n$ extra dimensions, axions may be able to propagate and acquire so-called Kaluza-Klein excitations

- Such Kaluza-Klein axions produced in the Sun may be trapped into Earth-crossing orbits

- Decay of these trapped Kaluza-Klein axions to pairs of back-back photons may be observable in a suitable detector such as a Time Projection Chamber (TPC) like DRIFT

- Prospects for such a detection are determined by:
  - Axion-photon coupling constant $g_{a\gamma\gamma}$
  - The local axions number density $n_0$
  - Volume of detector ($m^3$)
  - Background gammas (1-10 keV)

KK axion lifetime

Axions couple to two photons:

\[ g_{a\gamma\gamma} = \frac{\alpha_{EM}}{\pi} \frac{C_a}{f_{PQ}} \]

Axion model factor \( \sim 1 \)

Standard electromagnetic coupling

Symmetry breaking energy scale

This implies decay to two photons with mean lifetime:

\[ \tau = \frac{64\pi}{g_{a\gamma\gamma}^2 m_a^3} \]

However, astrophysical constraints imply \( \tau \) too long to observe:

\[ 10^9 GeV \leq f_{PQ} \leq 10^{12} GeV; 10^{30} \leq t \leq 10^{45} \text{ days} \]

But propagation in extra dimensions allows shorter, observable, lifetime

\[ m_a = m_{an} \sim \frac{n}{R} \]
Solar KK axion mass spectrum

Basis for an experimental search:
B. Morgan, N. Spooner et al, D. Hoffmann et al., K. Zioutas...


• Leads to differential decay spectrum:

\[ \frac{dR}{dm_a} = \frac{g_{a\gamma\gamma}^2}{64\pi} n_0 m_a^3 f(m_a) \]

\[ R = (2.5 \times 10^{11} \text{ m}^{-3} \text{ day}^{-1}) \left( \frac{g_{a\gamma\gamma}}{\text{GeV}^{-1}} \right)^2 \left( \frac{n_0}{\text{m}^{-3}} \right) \]

Typical rate \( \sim 1 \text{ m}^{-3} \text{ day}^{-1} \) (~keV events)

Result for trapped axions in orbits around Sun
(local number density depends on \( g_{a\gamma\gamma} \))

\[ g_{a\gamma\gamma} = 9.2 \times 10^{-14} \text{ GeV}^{-1} \quad n_0 = 10^{14} \text{ m}^{-3} \]

Mass spectrum for solar axions trapped in orbits around the sun

Low pressure TPC is ideal

Decay in space so best to have large volume $\sim m^3$

Low pressure allows separation of back to back gammas

1. **Spatial cut**

\[ P(s : m_a) = \frac{s}{\lambda^2(m_a/2)} e^{-s/\lambda(m_a/2)} \]

Spatial separation between photoelectrons from axion decay of mass $m_a$

Photon mean free path in the gas

2. **Energy cut**

\[ |E_1 - E_2| > \sqrt{2}\sigma_p(E) \]

Energy resolution

90% at 1.64

3. **Time cut**

\[ peak \sim \lambda(m_a/2) \]
Signal and \( \gamma \) background MCs

**Signal**
- Electron pairs from KK axion decay photons
- Spatial separation cut
- 90% cut (>3.6 MFP)

**Background**
- \( \Delta z \)
- Electron pairs
- Spatial background cut

\[ \Delta T = (|t_1 - t_2|) + \Delta z / N_{\text{diff}} \]
**γ background prediction** (DRIFT, 160 Torr CS$_2$)

### Issues
- Random gamma coincidences
- Coincident backgrounds:
  - Compton scatters
  - ~2 keV S K-shell x-ray

### CS$_2$ conclusion
- Good resolution on R (low diffusion)
- Good low gamma sensitivity
- Poor ΔT (gas is slow)
- Poor K - pair background

Nevertheless background rates ~0.1 m$^{-3}$ day$^{-1}$ are possible for $m_a$ of 6-20 keV, several orders of magnitude less than for solid state detectors.
Axions, CERN-1105-Neil Spooner

KK axion limit prediction (preliminary)

BASIC LIMIT - Add Pb shielding until vessel background dominates (10 cm for 1 ppb)

\[ g_{a\gamma} \text{GeV}^{-1} \]

\[ n_0 \text{ m}^{-3} \]

[1 m^3 yr, CS\textsubscript{2}, 160 Torr, \( m_a = 6-20 \text{ keV} \), 1 ppbU/Th in vessel]

points consistent with solar x-rays from axions (Di Lella et al.)

POSSIBLE IMPROVEMENT (lots of ideas)

- alternative gases to avoid K- events: (a) P10 - but poor R, (b) CF\textsubscript{4} - but longer MFPs…
- larger volumes, higher pressure, purer materials, better analysis
Is DRIFT sensitive enough to the x-rays?

Energy calibration performed using automated Fe55 exposures.

Noise reduction using Fourier transform & box-car smoothing

Individual Fe55 (5.9keV) events on the grid sum
Axions, CERN-1105-Neil Spooner

But, grouped readout limits spatial sensitivity to projection on the xy plane.

e.g. uncut low threshold data (1000 events)

Preliminary calibration data from $^{55}$Fe

Few keV gammas

Alphas, sparks..
Conclusion - next steps - DRIFT II b, c..

DRIFT Ila running for WIMPs!

Low energy threshold and spatial resolution may allow identification of back to back gammas from KK axions

Needs upgrade:
  - gamma shielding
  - less channel grouping

Meanwhile DRIFT IIb due for U/G installation Feb 2006:
  - triggerless DAQ
  - lower threshold
  - lower-cost

Bulk micromegas provides route to better PSD...