The experimental axion search

Helioscope search, micromegas detectors and decay search

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The axion and direct experimental searches

The CAST experiment

Towards a new generation axion helioscope: IAXO

**Micromegas detectors.** Detection principle, performances, discrimination capabilities, technology development (bulk, microbulk, resistive, piggyback), Underground Rare events, simulation and characterization, high rate applications.

**A large spherical TPC for axion searches.**
A new light boson arising from QCD theory

QCD predicts violation of CP in strong interactions

Bad agreement between theoretical and experimental values for the electric dipole moment of neutron

\[ d_n^{(theory)} \approx 10^{-16} \text{ e \cdot cm} \]
\[ d_n^{(exp.)} < 6.3 \times 10^{-26} \text{ e \cdot cm} \]

\[ \Rightarrow \bar{\theta} < 10^{-9} \text{ e \cdot cm} \]

Why is \( \bar{\theta} \) so small?

Peccei-Quinn introduced the axion field to solve this problem

\[ \mathcal{L}_a = \left( \bar{\theta} - \frac{a(x)}{f_a} \right) \frac{1}{f_a} \frac{g}{8\pi} G^\mu\nu \tilde{G}_{a\mu\nu} \]
The axion properties

- Neutral pseudoscalar
- Practically stable
- Very low mass
- Very low cross-section
- Coupling to photons

The theory predicts one unique parameter (scale factor) to describe the axion.

$$g_{a\gamma} = \frac{\alpha}{2\pi} \left( \frac{E}{N} - \frac{2}{3} \frac{4 + z}{1 + z} \right)^{1+z} \frac{1}{z^{1/2}} \frac{1}{m_{\pi} f_{\pi}} m_a$$

Mass depends on this parameter and it needs to be determined experimentally.

$$m_a = 6 \text{eV} \frac{10^6 \text{GeV}}{f_a}$$

$$\Omega_\alpha \approx \left( \frac{5 \mu \text{eV}}{m_\alpha} \right)^{7/6}$$

If the axion mass is small enough could contribute to the content of Cold Dark Matter of the Universe.
Direct Axion Detection Techniques (I)

Bragg Diffraction

Microwave Cavity Searches


Geomagnetic Axion Conversion

Axions can convert to photons in Earth’s magnetic field

Idea is to observe the Sun through the Earth

Davoudiasl & Huber, hep-ph/0509293
Laser experiments

Vacuum properties

Light Shining Through Wall

Telescope Searches

e.g. Grin et al. 2006 astro-ph/0611502v1

Helioscope Searches

Inoue et al. 2002 astro-ph/0204388v1
The axion search roadmap
The CERN Axion Solar Telescope (CAST) Experiment


CAST is using a prototype superconducting LHC dipole magnet able to track the Sun for about 1.5 hours during Sunrise and Sunset.
Operation at $T=1.8$ K, $I=13,000$A, $B=9$T, $L=9.26$m

Expected signal
X-Ray excess during tracking at 1-10 keV region

CAST sensitivity depends on the detector background
0.3 counts/hour in 14.5 cm$^2$

$g_{a\gamma\gamma} = 10^{-10}$ GeV$^{-1}$
The CAST experiment: Axion mass scanning principle

\[ P_{a\rightarrow\gamma} = \left( \frac{B g_{a\gamma}}{2} \right)^2 \frac{1}{q^2 + \Gamma^2/4} \left[ 1 + e^{-\Gamma L/2} - 2e^{-\Gamma L/2} \cos(qL) \right] \]

\( L = \text{magnet length}, \ \Gamma = \text{absorption coefficient} \)

\[ q = \left| \frac{m_a^2 - m_\gamma^2}{2E} \right| \]

\[ m_\gamma (\text{eV}) = \sqrt{\frac{4\pi\alpha N_e}{m_e}} \approx 28.9 \sqrt{\frac{Z}{A}} \rho \approx \sqrt{0.02 \cdot \frac{P(\text{mbar})}{T(\text{K})}} \]

**Expected Number of counts**

\[ N_\gamma = \int \frac{d\Phi_a}{dE_a} P_{a\gamma} A_{CB} t_{\text{tracking}} dE_a \]

Assuming: \( g_{a\gamma} = 1.0 \times 10^{-10} \ \text{GeV}^{-1} \)

\[ N_\gamma \approx 2 \ \text{events/day} \]
The CAST experiment: Scientific results

CAST Phase I (Vacuum)
- $m_a < 0.02\text{eV}$
- PRL94 (2005) 121301
- JCAP04 (2007) 020

CAST Phase II (4He)
- $P < 13.4\text{mbar}$, 160 steps
- $0.02 < m_a < 0.39\text{eV}$
- Completed (2005-2006)
- JCAP02 (2009) 008

CAST Phase II (3He)
- $P < 120 \text{ mbar}$
- Completed (2007-2011)
- $0.39 < m_a < 0.64 \text{ eV}$
- $0.64 < m_a < 1.15 \text{ eV}$

Latest results up to 1.15 eV submitted for publication
Remarkable improvement of Micromegas detectors inside CAST experiment.

3 Micromegas (Microbulk technology) installed in 3 of the 4 CAST magnet apertures. Operating with Ar + 2% Isobutane at 1.45 bar

Readout 106x106 strips -> 6x6 cm²

Plus mesh temporal signal

Detectors installation in 2008

Sunrise side detector

Sunset side detectors
CAST detectors readout provides *temporal and spatial information* of the events.

The temporal and spatial properties of events are to do an *efficient selection of X-rays*.
6keV events from an $^{55}$Fe source are used for X-ray selection and background discrimination.

**No cuts: Including only 1 xy-cluster events**

**Micromegas: Background rejection capabilities.**

- **Fast pulses**
- **Pulse shape**
- **Pulse amplitude energy [keV]**
- **Strips and mesh energy balance**
Possibility to apply a multivariate analysis with the parameters obtained with the readout.

Pulse shape, risetime, cluster size, number of clusters

X-ray events coming from a X-ray Fe55 source are distributed around an ellipsoid centroid with a given distribution.

Software efficiency can be easily fixed by setting the distance limit.
Micromegas: Background rejection optimization

Good performance of Micromegas detectors during first years of operation at CAST. **Background could be reduced by improving detector technology and quality, shielding and exploiting discrimination capabilities.**

**Detector background depends on**

- **Intrinsic detector radiation**
  Micromegas detectors can be built with low radiative materials (Plexiglass, Kapton, Copper)

- **Shielding from external radiation**
  Protecting the detector with material like Lead, Copper, Polyethylene, Cadmium

**Discrimination capabilities achieved by**

- New Micromegas technology. Detector stability and homogeneity.
- Temporal and spatial event readout
- Statistical offline analysis for optimized discrimination

Our group in Univ. Zaragoza (Spain) prepared further investigations to prove the background reduction limit achievable with these detectors.
A dedicated set-up at Zaragoza for background studies

New acquisition software completely based in C++, ROOT, python and GNUPLOT.

Gas, Ar + 2\% iso, flowing in open loop with flow and pressure controlled.

Shielding reproduces CAST configuration.

Faraday box prepared for automatic calibrations with $^{55}$Fe source.

Slow control: temperature and pressure and detector currents.

Some modifications in electronics. Fundamental modules are the same.

Nitrogen flux = 30 - 50 l/h (for vol < 17 l)
Capacity for more than 2 weeks.
Canfranc Underground Lab (LSC) situated in the Spanish Pyrenees at the deep of 2500 m.w.e

- $10^4$ reduction factor in cosmic muons
- Stable environmental conditions (T, P, humidity)
- Environmental gamma radiation well known.

CAST-like set-up and shielding

Installed underground
Some members of the crew proud of the new heavy gift just installed.

Bricks ready to be mounted.

Crosschecking electronic noise and acquisition tuning

Small cabling passthrough hole

Shielding upgrade to investigate intrinsic detector background
Data taken at 3 different shielding configurations

“Half” closed: 5π/6 20 cm external Pb

CAST-like: No external Pb (but still 4π)

0.5 cm Cu + 2.5 cm Pb + Nitrogen flux to avoid Rn

Complete: 20 cm external Pb
First approach to final background limited only by intrinsic radioactivity (from microbulk, chamber materials, inner shielding):

\[ < 2 \cdot 10^{-7} \text{ counts keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} [2-7 \text{ keV}] \quad (~1 \text{ count/day}) \]

This result proves that background levels >20 times lower that current CAST MM nominal background are possible via shielding improvement.

Data taken at 3 different shielding configurations

CYGNUS June 2011
Towards a new generation axion helioscope

- **Goal**: 1-1.5 orders of magnitude in sensitivity to $g_{a\gamma}$ better than CAST


All bores equipped with x-ray focusing and low bkg detectors
- Fully exploiting innovations of CAST

Each conversion bore (between coils) about 0.5-1 m diameter

New larger toroidal magnet – specifically built for axion physics
Astrophysical hints for ALPs in the high mass end, and future phases of ADMX in the low mass end will explore large part of the QCD axion model region in the next decade.

IAXO prospects in the high mass end, and future phases of ADMX in the low mass end will explore large part of the QCD axion model region in the next decade.

Much larger QCD axion region explored.
Micromegas technologies

In first Micromegas detectors (conventional technology) mesh and read-out strips were two independent entities. **New technologies were developed to keep mesh and strips in a single entity** providing a fixed amplification gap.

**Bulk**
- 30 um inox mesh
- 128 um pillars
- Reacheable energy resolution 18%
- FWHM @ 6 keV
- Spatial uniformity and very robust
- Limit on energy resolution due to thickness of the mesh

**Microbulk**
- 5 um copper mesh
- 30 um mesh holes
- Pillars are replaced by attached Kapton substrate.
- Reacheable energy resolution (<13% FWHM @ 6keV)
- Good behaviour against sparks
Microbulk micromegas fabrication process

Kapton foil (50µm), both sides Cu-coated (5µm)

Construction of readout (strips/pads)

Added a single-side Cu-coated kapton foil (25/5)

Construction of one direction readout lines

Vias construction by etching the kapton

Construction of the second direct readout lines and vias

Photochemical production of mesh holes

Kapton etching and cleaning
Read-out board 4 layers PCB

Laminated photoimageable coverlay

Stainless steel mesh on frame

Laminated photoimageable coverlay

Exposure + development + cure + cut

Easy manufacturing - Large size compatible - Low cost

Robust and electrically testable at the production time

New resistive micromegas technologies

Micromegas started to use resistive coatings to reduce the discharge weakness of Non-resistive Micromegas.

Discharges in general have a negative effect on the detector by
- Increasing the dead time of the detector (field loss during few ms due to charge loss recovery time)
- Damaging the electronics due to the high intensity currents.
- Damaging the detector itself by melting electrodes.

Resistive bulk
An insulating layer is placed on top read-out strips, then high resistive strips are placed on top.

Also for large area applications

Piggyback (ceramic-resistive micromegas)
Micromegas are bulk-ed in a ceramic substrate with a resistive coating. **Read-out independent from detector.**

Signal transmission through capacitive coupling, high ceramic permittivity.
Micromegas in other experiments

COMPASS
40x40 cm² Micromegas

CLAS12G

T2K

Michigan TPC

ILC/TPC

6 keV electrons in He + 5% iC₄H₁₀ 350 mbar

MIMAC
NSW

ATLAS

Small Wheel

Micromegas detector

The New Small Wheel upgrade for the HL-LHC

Performance requirements

- Rate capability: 10 kHz/cm²
- Spatial resolution: 60 μm/track segment
- Angular resolution: 0.3 mrad/segment
- Good double track resolution
- Trigger capability: BCID (angle ≈ 1 mrad)
- Efficiency: ‘at least as good as now’

- Radiation resistance: tbd
- Good ageing properties: tbd

Total area of micromegas detectors required

1200m²

Large area due to multilayer micromegas will be implemented in each sector.

NSW meeting, 06/10/2011
Joerg Weisbach (CERN)
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A resistive prototype detector is exposed to different radiation natures.

Gain control measurements are performed before and after each exposure.

After the ageing both detectors are taken to the H6 CERN-SPS pion beam line.

The goal to accumulate an integrated operation charge equivalent to the one would be obtained at the HL-LHC for 10 years for each type of radiation.
High intensity thermal neutron irradiation had place at C.E.A. Orphee reactor.

Several neutron research lines available.

Neutron flux : $\sim 8 \times 10^8$ n/cm$^2$/sec

Neutron energy : 5 to 10 meV
Neutron irradiation: Mesh current history

Neutron flux at the level of CSC in ATLAS \( \sim 3 \times 10^4 \) neutrons/cm²/s

10 years at HL-LHC \((\Rightarrow x10.10^7 \text{ sec})\) with a security factor: \(x3\)

At the HL-LHC, we will accumulate \(1.5 \times 10^{13}\) n/cm²

At Orphee we have \(\sim 8 \times 10^8\) n/cm²/sec so in 1 hour we have \(8 \times 10^8 \times 3600 \sim 3 \times 10^{12}\) n/cm²/hour which is about 2 HL-LHC years (200 days/year).
The two R17 prototypes were taken to the H6 SPS CERN pion beam to perform a comparative study between both prototypes, irradiated and non-irradiated one.

The performance was evaluated in terms of spatial resolution (SR) and efficiency.

Simplified beam set-up with R17 detectors
Detectors long offset produces systematics due to pion scattering. Resistive detectors were considered for track reconstruction. Non final set-up for intrinsic SR determination.

Residual distribution and alignment of resistive R17 prototypes to reference chambers

**Micromegas**

\[ E = \text{constant} \]
\[ C \approx S > 1 \text{nF} \]

**GEM**

**Cylindrical Proportional Counter**

\[ E = \frac{V}{\ln(b/a)}r \]
\[ L = \text{length and} \]
\[ a = \text{radius of the wire,} \ b = \text{tube radius} \]
\[ C = \frac{2\pi L}{\ln(b/a)} >> 10 \text{ pF} \]

**Spherical Proportional Counter**

\[ E = \frac{1}{r^2} \]
\[ \approx \frac{V}{R_i} \text{ close to the ball} \]
\[ C \approx R_{in} < 1 \text{pF} \]
Spherical TPC advantages

- Simple and cheap
- Large volume
- Single read-out
- Robustness
- Good energy resolution
- Low energy threshold
- Efficient fiducial cut
- High dynamic range

Good capability for particle recognition

Great flexibility (P, gaz)
Allows to play with parameters used for discrimination and background

Long drift times (few hundreds of microseconds).
Fiducial selection by risetime

World record with TPC (C peak @270eV)

Am241 source with polypropylene foil

Detector set-up and calibration

Existing spheres running in ground and underground laboratories

- 2 LEP cavity 130 cm Ø
- 1 low activity 60 cm Ø in operation @ LSM

SEDINE set-up at Modane (LSM) 30 cm sphere
  - Underground
  - Radiopure copper sphere
  - 10-15 cm lead
  - 25 cm poliethilene
  - Purified air (Radon free)

Home made Ar-37 source: irradiating Ca-40 powder with fast neutrons
  - $7 \times 10^6$ neutrons/s

Irradiation time 14 days. Ar-37 emits
  - K(2.6 keV) and L(260 eV) X-rays (35 d)

250 mbar gas
- 8 mm ball

Total rate 40 hz of low energy lines
Detector construction and installation at LSM (France)
Gravitationally trapped massive Axion (like) particles decays

Our sensitivity only 2-prong events contribution

$$T_\odot \ll \tau_a$$

$$\rho_a = 1.18 \times 10^{39} \left( \frac{g_{a\gamma}}{\text{GeV}^{-1}} \right)^2 \left[ \text{m}^{-3} \right]$$

$$\tau_a = 1.35 \times 10^5 \left( \frac{g_{a\gamma}}{\text{GeV}^{-1}} \right)^{-2} \left( \frac{m_a}{\text{eV}} \right)^{-3} \text{s}$$

$$N_\gamma = \tau_a^{-1} \cdot \rho_a \cdot V_{Sph} \cdot T_{exp} \cdot \epsilon_{det}$$

Spherical TPC allows to perform a search for this kind of particles. **Large volume, low energy threshold, good rejection capabilities.**

KK-axions tower of mass states

Expected X-ray distribution due to decay dependency with the mass

(R = 65 cm)
Detecting 2-prong events

Digitisation @ 1 MHz, soft trigger
RC integration removed

Raw pulse
Preamp output

Unconvoluted pulse

\[ i(t) = \frac{dV(t)}{dt} + \omega_c V(t) \]

Pulse parameters definition

Close hist (within 5us) can be identified
Pulse unconvolution is used to identify peak position in time.
Derivative helps to discover profile variations or very close events.

Extremely low electronic noise! 1 electron equivalent energy is observed clearly!
2-prong events observed from a 55Fe source in Argon

Full Spectrum without cuts (Cosmics + Fe55 peak)

Fe55 run at P = 100 mbar Ar + 2%CH4

Enhancement for decay search we only need VOLUME

Very low background rates for doubles events even at ground level

Doubles
Energy within 5%

1 day data
Pure single events spectra

Very low background for 2-prong events

Copper peak

Riseslope depends strongly on the distance to the sensor, due to diffusion.

Enhances for selection of a fiducial volume

Detector construction and installation at LSM on September 2012

Background discrimination LSM 500 mbar Ar+2%CH4
Great flexibility in gas mixture and pressure

Too close events (< 5us)

Drift time difference between 2 gammas

Double det.
At low E
Requires
Low P

Pressure changes are equivalent to switch OFF/ON the signal!!

E = 4-6 keV

E = 0-2 keV

E = 2-4 keV

Optimum pressure including diffusion
Sensitivity prospects to KK-axions ($R=6.5\,\text{m}$)

Doubles efficiency @1bar

A tentative long data run scanning
At 4 different pressures

30 days each pressure 6.5 m

Play with pressure to get a smoother energy scan

Our sensitivity only doubles contribution

5keV hint reachable
Axion Roadmap

![Diagram of axion mass and coupling parameters](image)

- **LSW (ALPS-I)**
- **Helioscopes (CAST)**
- **TeV Transparency**
- **ALPS-II**
- **REAPR**
- **IAXO**
- **Solar \( \nu \)**
- **HB**
- **EBL**
- **X-Rays**

**Axes:**
- Log Coupling [GeV^{-1}]
- Log Mass [eV]
BACKUP
A dedicated Supernova detector

Simple and cost effective - Life time >> 1 century

Through neutrino-nucleus coherent elastic scattering


<table>
<thead>
<tr>
<th></th>
<th>He</th>
<th>Ne</th>
<th>Ar</th>
<th>Kr</th>
<th>Xe</th>
<th>Xe (with Nuc. F.F)</th>
</tr>
</thead>
<tbody>
<tr>
<td># Number of events (no quenching, zero threshold)</td>
<td>.16</td>
<td>3.95</td>
<td>19.1</td>
<td>76.8</td>
<td>235</td>
<td>179</td>
</tr>
<tr>
<td># Number of events (after quenching, $E_{th}=0.25$ keV)</td>
<td>0.08</td>
<td>1.5</td>
<td>6.7</td>
<td>23.8</td>
<td>68.1</td>
<td>51.8</td>
</tr>
</tbody>
</table>

Sensitivity for galactic explosion

For $p=10$ Atm, $R=2$ m, $D=10$ kpc, $U_{\nu}=0.5 \times 10^{53}$ ergs

Idea: A worldwide network of several (tenths or hundreds) of such dedicated Supernova detectors

robust, low cost, simple (one channel)

To be managed by an international scientific consortium and operated by students

Destruction of massive star initiated by the Fe core collapse

- $10^{53}$ ergs of energy released
- 99% carried by neutrinos
- A few happen every century in our Galaxy, but the last one observed was over 300 years ago
Dark matter search through very low energy threshold < 100 eV

- Bkg ~ O(1) cpd/kg/keV >10 keV, ~ too many
- ULEGe bkg @ KS ~ CRESST-1 @ GS
- Intensive studies on sub-keV background

CoGeNT 2010
BUT, DAMA and COGENT claim rejected?

Light Dark Matter candidates

- Light scalars or fermions (Fayet, Boehm&Fayet)
- Kaluza-Klein Axion like Particle
- Electron-Interacting dark matter
- Secluded WIMP dark matter (Arkani-Hamed, Pospelov, Ritz, Voloshin)

Our sensitivity with H target

Needs sub-keV energy threshold
Micromegas detectors for the new small wheel

J. Galan

Multilayer description

- Each detector comprises eight active layers, arranged in two multilayers.
- The basic detector unit is an assembly of four layers that form a stiff multilayer.
- The individual layers should be arranged in two doublets in which the Micromegas are mounted back-to-back.
- The flat surfaces of all layers should be parallel to within 40–60 µm and the strips in all layers must be parallel with the same precision.
Some experiments using Bulk Micromegas

ATLAS-SLHC

Very-large

T2K

CLAS12G

ILC/TPC

Michigan TPC

HCAL
ATLAS large chambers

1 x 1 m² micromegas

Industrialization is going on Through CIREA, ELTOS, Triangle Labs (US)

1 x 1 m² readout board composed of 2 boards of 0.5 x 1 m²
2048 strips of 1.06 m length with a pitch of 0.45 mm

Drift electrode and mesh panel (top) and detail showing the O-ring as gas seal
ILC TPC project - Large International collaboration


ILC TPC with Micromegas, L = 4.6 m, D = 3.4 m

Momentum resolution=5x10^{-5}

ILC TPC prototype with Micromegas

Event in DESY test beam

Ion feed back supression

No ExB effect

~ 40 μm average!!
Pad size 2x6 mm

TPC requirements
- gain < 1500
- Ion suppression
- Large surface
- Good uniformity
MIMAC-He3 MIcro-tpc Matrix of Chambers of He3
WIMP directional TPC, Micromegas read-out,
Grenoble – Saclay, Cadarache collaboration

C. Grignon et al., JINST 4 (2009) P11003
Quenching factor measurement

Direct QF evaluation
D. Santos et al., [arXiv:0810.1137]

Recoil from 144 keV neutrons
Micromegas:μTPC chamber
1.49 keV electron
1.5 keV ion

.proton 8 keV, He + 5% iC₄H₁₀, 350 mbar

Recall from 144 keV neutrons

40 keV ¹⁹F, 70% CF₄ + 30% CHF₃, 55 mbar

QF at various pressures in He-4

6 keV electrons in He + 5% iC₄H₁₀ 350 mbar
Beam tests took place at the end of October 2012. During two weeks R17 detectors took data. Three different zones were irradiated. And different settings were taken at each of these beam exposed regions.

**Spatial resolution history for the different runs taken during this period.**
Rejection power

Irradiate gas through 200μm Al window
P = 100 mb, Ar-CH₄ (2%)

Rise time cut

Efficiency of the cut in rt =>~ 70% signal (Cd peak)
Severe background reduction
Energy resolution ~ 6 % and 9 % for Cu and Cd

No-Cuts
Entries 234881
Mean x 3161
Mean y 0.01722
RMS x 1728
RMS y 0.032101

rt < 0.016
Ntot=54400 ev
Cd: 8150 events, f=9.1 Hz

rt < 0.015
Ntot=31657 ev
Cd: 7873 events, f=8.8 Hz

rt < 0.014
Ntot=20835 ev
Cd: 5639 events, f=5.3 Hz

Cu ~ 8 keV
Cd ~ 22 keV

If rt ~ 0.0155 ms => R = 65 cm
0.014 ms => ~70% of signal
Ultra low energy threshold observed
arXiv:1010.4132 [physics.ins-det], 2010