WIMPS and LIPSS

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Hampton University
for the LIPSS collaboration
CASA seminar
Feb 2, 2006
outline

- PVLAS results and implications
  - overview only
- previous experimental studies
  - how did all previous searches miss it?
- LIPSS (light pseudoscalar particle search)
  - plans and history
- summary
PVLAS results

based upon experimental idea of L. Maiani, R. Petronzio, and E. Zavattini, PLB 175, 359 (1986)
Dichroism
rotation of polarization plane

Maiani et al., Phy. Lett. B175 (1986); www.ts.infn.it/experiments/pvlas

\[ \varepsilon = -\left( \frac{B_{\text{ext}}L}{4M} \right)^2 \sin \left[ \frac{kL}{2} \left( 1 - \sqrt{1 - \left( \frac{k}{K_m} \right)^2} \right) \right]^2 \frac{N}{\left[ \frac{LK_m}{4k} \right]^2} \]
Dichroism
rotation of polarization plane

ellipticity
dispersion; photon-axion

Maiani et al., Phy. Lett. B175 (1986); www.ts.infn.it/experiments/pvlas

\[
\psi = \left( \frac{B_{\text{ext}}^2 k L}{4 M^2 K_m^2} \right) \left\{ \sin \left[ kL \left( 1 - \sqrt{1 - \left( \frac{k}{K_m} \right)^2} \right) \right] \right\} 1 - \frac{L K_m^2}{2k} \]

- \textbf{M: inverse coupling}
- \textbf{K}_m: inverse compton wavelength
- \textbf{k}: light wavenumber
- \textbf{L}: magnetic field region length
- \textbf{N}: number of traversals
ellipticity
dispersion: photon-axion

PVLAS setup

6 T; 1 meter long dipole magnet
1064 nm; 0.1 W laser
60 km path length in magnet
using 6 meters long optical cavity
cryostat rotation 0.3 Hz
PVLAS results

zavattini et al; see www.ts.infn.it/experiments/pvlas

- B: 5 T
- L: 1 m
- $\omega$: 1.2 eV (1.064 $\mu$)
- OC: 6.3 m
- N: 44000
PVLAS example data
www.ts.infn.it/experiments/pvlas

Gas calibration spectrum

Amplitude spectrum demodulated at the carrier frequency (506 Hz) of the ellipticity modulator.

The expected birefringence signal appears at twice the magnet rotation frequency (0.6 Hz in this case).

Sensitivity

\[ \psi' = 6 \cdot 10^{-3} \quad \frac{1}{\sqrt{Hz}}; \]
\[ \Delta n' = 2 \cdot 10^{-18} \quad \frac{1}{\sqrt{Hz}}; \]

Measurement time 130 s

“signal” peak

RUN 648, 20 mbar di Neon
B = 4.6 T, F = 55 000

Freq. (uniti di freq. rotazione del magnete)
PVLAS results may be explained by a region . . .

\[ 1.7 \times 10^{-6} < g < 1.0 \times 10^{-5} \text{ GeV}^{-1} \]
\[ 0.7 < m < 1.7 \text{ meV} \]

PVLAS effect is $10^4$ stronger than QED (Euler-Heisenbergg) prediction!
interpretation

light pseudoscalar particle
weakly interacting
(weakly interacting massive particle)
pseudoscalar coupling

- pseudoscalar particle coupling to photons

\[
L_{\phi\gamma\gamma} = -\frac{1}{4M} \varphi F_{\mu\nu} \tilde{F}^{\mu\nu} = \frac{g\phi}{4} \vec{E} \cdot \vec{B}
\]

- in present case, use laser light and magnetic field
- light polarization in direction of magnetic field
- PVLAS claims to see effect in both dichroism and ellipticity (using same apparatus).
- we want to test this result in a completely independent way
Axion interpretation?

A. Ringwald; hep-ph/0511184
K. Zioutas et.al., PRL 94, 121301 (2005)
**possibilities . . .**

L. Rosenberg SLAC Summer Institute 2004

**Peccei and Quinn:**
**CP conserved through a hidden symmetry**

This CP violation should, e.g., give a large neutron electric dipole moment ($T + CPT = C \bar{P}$); none is unobserved.
(9 orders-of-magnitude discrepancy.)

This leads to the “Strong CP Problem”: Where did QCD CP violation go?

1977: Peccei and Quinn: Posit a hidden broken $U(1)$ symmetry ⇒

1) A new Goldstone boson (the axion);
2) Remnant axion VEV nulls QCD CP violation.

Peccei, Quin (1977); S. Weinberg (1978); F. Wilczek (1978)
matter/energy budget of universe

- Stars and galaxies are only ~0.5%
- Neutrinos are ~0.3–10%
- Rest of ordinary matter (electrons and protons) are ~5%
- Dark Matter ~30%
- Dark Energy ~65%
- Anti-Matter 0%

axion a dark matter candidate
search strategies to date

- **two broad classes of axion searches**
  - detect relic (big-bang leftover), or solar, or stellar axions
  - produce and then detect axions in terrestrial expt
    - more difficult, in general, since there are two factors of small couplings
    - LIPSS uses this strategy
    - BFRT collaboration also used this strategy
relic axions

microwave cavities
relic axions

- Axions created moments after the big bang.
- Thermalized over time.
- Mass range must be consistent with astrophysical observables.
microwave cavity technique

Condition for resonant conversion:
\[ h\nu = m_a c^2 \]

Local axion number density \( \sim 10^{13} \text{/cc} \)

system output:
- axion signal, width \( \theta(10^{-6}\nu_0) \)
- cavity thermal
- electronics

\( a \)
- nearby galactic halo axion
- high field solenoidal magnet
- cryogenic high Q microwave cavity
- ultra-low noise detector
- external magnetic field
- cavity electric field
microwave cavity search: example

Sikivie (1983); Ansel’m (1985); van Bibber et al (1987)
microwave cavity search: example
microwave cavities

\[ P_a = \left( \frac{\alpha g \gamma}{\pi f_a} \right)^2 V B_0^2 \rho_a C \frac{1}{m_a} \text{Min}(Q_L, Q_a) \]

- \( V \): cavity volume
- \( m \) (f): mass (coupling)
- \( B \): magnetic field
- \( R \): galactic halo axion density on Earth
- \( C \): mode dependent constant (0.6)
- \( Q_L \): cavity’s loaded quality factor
- \( Q_a \): galactic halo axion quality factor (\(10^6\))

\[ \text{SNR} = \frac{P_a}{P_N} \sqrt{Bt} = \frac{P_a}{k_B T_S} \sqrt{\frac{t}{B}} \]

- \( P_N \): average thermal noise power
- \( T_S \): cavity temperature plus noise ‘temperature’
data taking – microwave cavities

Cavity is tuned in roughly 1-2 kHz steps
(Cavity BW approximately 10 kHz)
microwave cavity experiments find no evidence for relic axions in parameter space indicated.
solar and stellar axions

helioscope search

supernova explosions
CAST – axions from the sun

CERN Axion Solar Telescope
Axions from the sun...
...become x-rays inside an LHC dipole magnet
CAST experiment

- decommissioned LHC test magnet
  - $L = 10 \text{ m} ; \ B = 9 \text{ T}$
- moving platform
  - up to 50 days/year of alignment
- 4 magnet bores, for x-ray detection
  - solar temperature $\rightarrow$ keV axions $\rightarrow$ keV x-rays
- 3 x ray detectors
- x ray focussing system to increase S/N ratio
CAST technology

Grazing-incidence x-ray optics

Micromegas x-ray camera
CAST finds no evidence to date for solar axions in parameter space indicated.
astrophysical bounds
L. Rosenberg, SLAC Summer Institute 2004

Example: neutrinos from SN1987A

Ellis and Olive, 1987; Raffelt and Seckel, 1988; Turner, 1988, etc

Supernova in the LMC. Neutrinos are trapped and diffuse out over timescales of around 10 seconds.

Kamiokande and IMB together recorded 19 neutrinos from SN1987A.

Aneaxon of mass between $10^{-3}$ and 2 eV would take so much energy out that the length of the explosion would be observably forshortened.

Overall summary: Astrophysics (stellar evolution and SN1987A), cosmology, and laboratory experiments leave the invisible CDM axion window $10^{-6} < m_a < 10^{-3}$ eV (with large uncertainties)
CAST finds no evidence to date for solar axions in parameter space indicated.

SN1987A does not rule out PVLAS result.
cryogenic dark matter search in Soudan underground laboratory

new limits in large mass range; no evidence for WIMPs
production and detection

accelerator/laser experiments
SLAC Experiment E137

sensitive to massive (> eV) axions; none seen

$f_{PQ}$ must be considerably greater than the weak scale
Photon regeneration
(Phys. Rev. D47 3707 (1993 BFRT collaboration)
BFRT results: regeneration expt

no ps signal seen

FIG. 18. Integrated charge spectrum. The pedestal is at channel 63 and the single photoelectron peak [see inset in (a)] is fitted by a truncated Gaussian centered at channel 108, with standard deviation of 34 channels. The sensitivity is 0.25 pC/channel. (a) Dark current spectrum including the electronic noise. (b) Subtracted spectrum when light was admitted from the first magnet; used for calibration. (c) Subtracted spectrum when no light was allowed into the second magnet.
searches to date: summary

- The combination of accelerator searches, astrophysical, and cosmological arguments leaves open a search window.

\[ 10^{-6} < m_a < 10^{-3} \text{ eV} \]

- Massive axion discovery still solves the strong CP problem, but not the dark matter problem.

Search for light axions (< eV)
searches to date: summary

- The combination of accelerator searches, astrophysical, and cosmological arguments leaves open a search window.
  \[ 10^{-6} < m_a < 10^{-3} \text{ eV} \]

- Massive axion discovery still solves the strong CP problem, but not the dark matter problem.

Search for light axions (< eV)

Very light axions forbidden: else too much dark matter

\[ \Leftrightarrow \text{Dark matter range: “axion window”} \]

Heavy axions forbidden: else new pion-like particle
searches to date: theoretical issues

- neutron and electron edm conflict?
- no conflict with atomic contribution ($E^2$).
- higher order (nonlinear) qed effect?
- noncommutative field theory?
- . . .
possibilities at JLAB

Light PseudoScalar Particle Search (LIPSS)
possibilities at JLAB FEL

- polarization plane rotation, ellipticity
  - reproduce PVLAS with different apparatus

- regeneration
  - FEL photons regeneration
  - Primakoff photons regeneration

- photon collisions
  - wide angle axion production at wiggler center
  - polarization plane rotation
  - four wave mixing in vacuum
    - $2 \rightarrow 2$ or $3 \rightarrow 1$

- microwave cavity
  - primordial axions
  - solar production and lab regeneration (a la CAST)
‘light shining through a wall’

- Couple polarized laser light with magnetic field
- Sikivie (1983); Ansel’m (1985); Van Bibber et al (1987)

\[ P_{\gamma \rightarrow \phi} \approx \frac{1}{4} \left( g BL \right)^2 \left\{ \frac{\sin \left( \frac{m_\phi^2 L}{4 \omega} \right)}{m_\phi^2 L} \right\}^2 \]

\( P \) – photon (or photon-ps) conversion probability
JLAB FEL setup I: regeneration experiment

Superconducting rf linac

Beam dump

IR wiggler

UV wiggler

Injector

2 T; 1 m (?)

Detector

Light shield

"parasitic"

$\phi$'s produced at JLAB FEL
LIPSS plans
back-of-the-envelope

\[ P = g^2 B^2 L^2 / 4 \]
- \( g \) = coupling constant (1/M)
- \( B \) = magnetic field
- \( L \) = magnet length

\[ Y = n P_1 P_2 \varepsilon (\Delta \Omega / \Omega) (N_r + 2) / 2 \]
- \( n \) = photon flux (#/s)
- \( P_1 \) (\( P_2 \)) = production (regeneration) probability
- \( \varepsilon \) = detection efficiency
- \( \Delta \Omega / \Omega \) = solid angle
- \( N_r \) = number of reflections

yield (#/s)
JLAB facility spectroscopic range

FEL proof of principle:

THz proof of principle:
experimental requirements

- B-field parallel to photon polarization
- photon-axion coherence
- large magnetic field
- shield detector from field; vacuum vessel

\[ m_a^2 < \frac{4\pi\omega}{L} \]
rate estimate, as example . . .

\[ P = \frac{g^2 B^2 L^2}{4} \]
\[ = 10^{-11} \]

\[ N = 1.0 \text{ mJ/pulse } \times 75 \text{MHz} \]
\[ = 6 \times 10^{23} \gamma' \text{s/s} \]

\[ Y \sim n \cdot P^2 \cdot \frac{\Delta \Omega}{\Omega} \cdot \varepsilon \]
\[ \geq 1 \text{ Hz} \]

axion-photon conversion probability, \( P \)

J LAB FEL photon rate, \( n \)

photon regeneration rate estimate, \( Y \)

2 T; 1 m magnet

\( \varepsilon \sim 0.5; \ \frac{\Delta \Omega}{\Omega} \sim 0.5 \)
rates (using current FEL)

<table>
<thead>
<tr>
<th>$B_r$ (Tesla)</th>
<th>$L_r$ (meters)</th>
<th>$g$ (eV$^{-1}$)</th>
<th>rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>1.0</td>
<td>$10^{-15}$</td>
<td>0.005</td>
</tr>
<tr>
<td>1.0</td>
<td>1.0</td>
<td>$5 \times 10^{-15}$</td>
<td>3.0</td>
</tr>
<tr>
<td>1.5</td>
<td>0.8</td>
<td>$10^{-15}$</td>
<td>0.01</td>
</tr>
<tr>
<td>1.5</td>
<td>0.8</td>
<td>$5 \times 10^{-15}$</td>
<td>4.2</td>
</tr>
</tbody>
</table>

uses: dipole magnet at end of straight section: 1.0 m long and 0.31 Tesla

100 kW (1 eV) FEL laser light

q.e. ~ 0.3; detector accep ~ 0.9
experimental issues

single photon counting in IR

axion-photon coherence
Hamamatsu
R5509 PMT

dark current > nA

* Spectral response characteristics when used with the dedicated cooler
Rockwell Scientific Hawaii 1RG – for example

<table>
<thead>
<tr>
<th>FPA Parameter</th>
<th>Rockwell FPAs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector technology</td>
<td>MBE HgCdTe or Si PIN</td>
</tr>
<tr>
<td>Detector input circuit</td>
<td>SFD</td>
</tr>
<tr>
<td>Readout mode</td>
<td>Ripple</td>
</tr>
<tr>
<td>Pixel readout rate</td>
<td>100 kHz to 5 MHz (continuously adjustable)</td>
</tr>
<tr>
<td>Total pixels</td>
<td>1024 x 1024</td>
</tr>
<tr>
<td>Pixel Pitch</td>
<td>18 µm</td>
</tr>
<tr>
<td>Fill factor</td>
<td>≥ 98%</td>
</tr>
<tr>
<td>Output ports</td>
<td>Signal: 1, 4, 32 selectable Guide Window and Reference</td>
</tr>
<tr>
<td>Spectral range</td>
<td>0.3 - 5.3 µm</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>≥ 30K</td>
</tr>
<tr>
<td>Quantum Efficiency (array mean)</td>
<td>≥ 65%</td>
</tr>
<tr>
<td>Charge storage capacity</td>
<td>≥ 100,000 e-</td>
</tr>
<tr>
<td>Pixel Operability</td>
<td>≥ 95%</td>
</tr>
<tr>
<td>Dark Current (array mean)</td>
<td>≤ 0.1 e-/sec (77K, 2.5 µm)</td>
</tr>
<tr>
<td>Read noise (array mean)</td>
<td>≤ 15 e- CDS @ 100 kHz</td>
</tr>
<tr>
<td>Power Dissipation</td>
<td>≤ 4 mW @ 100 kHz</td>
</tr>
</tbody>
</table>

dark current and read noise
quantum efficiency
spectral range
begin with this? (on hand)
SBIG ST-237A

<table>
<thead>
<tr>
<th>Camera</th>
<th>Pixel Array</th>
<th>Number of Pixels</th>
<th>Pixel Size</th>
<th>CCD Size mm</th>
<th>CCD Area mm²</th>
<th>Diag FOV 11&quot; Fastar (544mm FL)</th>
<th>Dark Current at 0 C.</th>
<th>Read Noise</th>
<th>Full Well Capacity</th>
<th>Peak QE</th>
<th>Compute r Interface</th>
<th>Full Frame Transfer</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST-402ME</td>
<td>765 x 510</td>
<td>390,000</td>
<td>9u</td>
<td>4.6 x 6.0</td>
<td>32</td>
<td>52 arcmin</td>
<td>1e⁻/p/s</td>
<td>17e⁻</td>
<td>100,000 e⁻</td>
<td>83%</td>
<td>USB 2.0</td>
<td>0.8 sec</td>
</tr>
<tr>
<td>ST-237A</td>
<td>657 x 495</td>
<td>325,000</td>
<td>7.4u</td>
<td>3.7 x 4.9</td>
<td>18</td>
<td>38 arcmin</td>
<td>5e⁻/p/s</td>
<td>15e⁻</td>
<td>20,000e⁻</td>
<td>75%</td>
<td>Parallel</td>
<td>15 sec</td>
</tr>
</tbody>
</table>

CCD Area mm²:
- 32 for ST-402ME
- 18 for ST-237A

Full Frame Transfer:
- 0.8 sec for ST-402ME
- 15 sec for ST-237A

Camera types:
- ST-402ME
- ST-237A

Pixel Array:
- 765 x 510 for ST-402ME
- 657 x 495 for ST-237A

Number of Pixels:
- 390,000 for ST-402ME
- 325,000 for ST-237A

Pixel Size:
- 9u for ST-402ME
- 7.4u for ST-237A

CCD Size mm:
- 4.6 x 6.0 for ST-402ME
- 3.7 x 4.9 for ST-237A

Diag FOV 11" Fastar (544mm FL):
- 52 arcmin for ST-402ME
- 38 arcmin for ST-237A

Dark Current at 0 C.:
- 1e⁻/p/s for ST-402ME
- 5e⁻/p/s for ST-237A

Read Noise:
- 17e⁻ for ST-402ME
- 15e⁻ for ST-237A

Full Well Capacity:
- 100,000 e⁻ for ST-402ME
- 20,000e⁻ for ST-237A

Peak QE:
- 83% for ST-402ME
- 75% for ST-237A

Computer Interface:
- USB 2.0 for ST-402ME
- Parallel for ST-237A

Full Frame Transfer Time:
- 0.8 sec for ST-402ME
- 15 sec for ST-237A
'light shining through a wall'

www.desy.de/~ringwald

couple polarized laser light with magnetic field

Sikivia (1983); Ansel’m (1985); Van Bibber et al (1987)

$P_{\gamma \rightarrow \phi} \approx \frac{1}{4} (gBL)^2 \left\{ \sin \left( \frac{m_\phi^2 L}{4\omega} \right) \right\}^2$

photon-ps conversion probability

$\{\} \sim 1$

$m_\phi^2 < 4\omega/L$
coherence

PVLAS

BFRT

see web site: www.desy.de/~ringwald

\[ g \text{ [GeV}^{-1}] \]

\[ m_\phi \text{ [eV]} \]
ps-photon coherence - LIPSS

$\omega = 1.2 \text{ eV (1064 } \mu \text{)}$
(same as PVLAS)

$P_{\gamma \to \phi} \approx \frac{1}{4} (gBL)^2 \left\{ \sin \left( \frac{m^2 \phi L}{4 \omega} \right) \right\}^2$

vertical - axis
PVLAS and BFRT: photon-axion coherence

plots from K. McFarlane

\[ m_a^2 < \frac{2\pi \omega}{L} \]

magnet length a limitation in BFRT
PVLAS and BFRT: photon-axion coherence

\( m_a^2 < 4\pi\omega / L \)

magnet length a limitation in BFRT

Plots from K. McFarlane

\( L_{\text{Ma}} / 4 \)

2πω = 1.6 µ; 1.06 µ
QM uncertainty relation

- $\Delta n \Delta \phi > 1$

- $n$ number of quanta detected
- $\phi$ phase of detected radiation

Limit on the measurement precision of the number of quanta $n$ in a wave, and the phase of the radiation $\phi$. 
ideas . . .

- use focussing lens at end of regeneration magnet
  - focus on small pixel area $\rightarrow$ better S/N
- use new rf structure in upstairs lab with two powerful magnets
  - purchase 2 ea $\sim 0.5$ m long, $\sim 2$ T magnets
- use B field of electron beam
  - can get $\sim 100$ T close to electron beam
  - probably too small an effect
# 1

ideash

focussing
lense

pixel array

S/N ~ 1
per pixel
GW magnets

gap: 7.9 cm
magnetic length: 0.42 m
design field integral: 5.92 K Gauss.
current 223.24 A

have 4 extra magnets and their stands in Magnet Test and 2 mounted to stands in the FEL UV Line.

a rarely used power supply for the 2G dump spectrometer is available in the FEL for quick response at slightly lower max current. 220 A maximum.

max field at 0.8 Tesla → 1.5 Tesla with shims
the GWs are 0.6 or so meters long
with current setup, IR light . . .
UV FEL – the way to go!!

- visible and UV light → use phototube
  - fast (can time relative to rf structure of beam)
  - reduce noise
  - good quantum efficiency
  - experience
- can use longer magnets
  - axion-photon coherence
  - probability ∼ L²
- more space on vault floor
photon regeneration from pseudoscalars at x-ray lasers
Rabadan, Ringwald, Sigurdson  hep-ph/0511103

JLAB in ~1 hour with UV FEL
axion interpretation?

A. Ringwald; hep-ph/0511184
K. Zioutas et.al., PRL 94, 121301 (2005)
initial ‘engineering’ run

- 100 kW IR FEL
  - 1.06 \( \mu \) and 1.64 \( \mu \) IR light

- 2 GW magnets for regeneration
  - 1.5 T, 1.0 meter long, acceptance ~ 0.8

- SBIG Astronomical Instruments ST-237A CCD camera
  - ~10\% q.e., low dark current (cps), on hand

begin within next couple of months (?)
how we got to this point

A. Afanasev alerted okb > 2 years ago of importance of measurement

okb made initial approaches to FEL people (Boyce, Shinn, etc), axion experts (Rosenberg); very low level

initial meetings began at Hampton ~ year ago; VFWM discussed; HU laser experiment discussed.

PVLAS result: Afanasev again emphasized importance of measurement. K. McFarlane and other HU particle experimentalists joined discussions

initial meeting of interested Hampton and JLAB scientists (Williams, Boyce, etc); more serious now

series of meetings at JLAB; talks at TAWG and JLAB
initial meetings participants

- A. Afanasev – particle/nuclear theorist
- G. Biallas – FEL experimentalist
- J. Boyce – FEL experimentalist
- O.K. Baker – particle/nuclear experimentalist
- H. Brown – graduate student
- S. Ma – graduate student
- K. McFarlane – particle experimentalist
- J.T. Seo – optics experimentalist
- T. Shin – particle experimentalist
- S. Shukui – FEL experimentalist
- V. Vassilakopoulos – particle experimentalist
- G. Williams – optics experimentalist
- Q. Yiang – optics experimentalist
summary

- axion search not just a shot in the dark now!!
  - PVLAS result can be tested; new data point from LIPSS
- can perform regeneration experiment to test PVLAS result at JLAB FEL
  - can reach interesting region of parameter space with IR FEL
  - can perform definitive experiment with UV FEL
- this is particle physics at the FEL
  - constraints on a new mass scale in particle physics
    - PeV scale!!