Gamma to milli-eV particle search

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Dark Matter

- What is the dark matter of the universe?
Dark Matter

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![Graph showing WIMP-type Candidates](image)

L. Roszkowski

1/30/2008
Dark Matter

• What is the dark matter of the universe?
Outline

• Intro to Axions and Axion-like particles
• Physics motivation for our experiment
  – milli-eV mass scale
  – PVLAS anomaly
• “Light shining through a wall”
  – Past Experiments
  – GammeV
  – Other current experiments
• Results (NEW!)
• Phase II: “Particles in a Jar”
  – Chameleons
• Conclusions
Axions

- Postulated in the late 1970s as a consequence of not observing CP violation in the strong interaction.

\[ L_{CP} = -\frac{\alpha_s}{8\pi} (\Theta - \text{arg det } M_q) \text{Tr} \tilde{G}_{\mu\nu} G^{\mu\nu} \]

- The measurement of the electric dipole of the neutron implies \( \Theta < \sim 10^{-10} \). \( \Rightarrow \) Strong CP Problem of QCD
  - This is very much on the same order of an issue with the Standard Model as the hierarchy problem that motivates supersymmetry.
    - “Axions are just as viable a candidate for dark matter as sparticles” \( \rightarrow \) Bjorken
    - “If not axions, please tell me how to solve the Strong-CP problem” \( \rightarrow \) Wilczek
    - “Axions may be intrinsic to the structure of string theory” \( \rightarrow \) Witten

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Axions

- Peccei-Quinn (1977) and Wilczek (1978) and Weinberg (1978) provided a solution: $\Theta$ represents a dynamical pseudoscalar field, $a=\phi$, with a potential that conserves CP.

\[ \Theta = \frac{a(x)}{f_a} \]

- The Peccei-Quinn mechanism implies a new symmetry that gets spontaneously broken and the axion emerges as a pseudo Nambu-Goldstone boson with small mass.

- Mass and couplings related to the pion

\[ m_a = m_\pi \frac{f_\pi}{f_a} = \frac{0.6 \text{ meV}}{f_a/10^{10} \text{ GeV}} \]
Axions

- Axions couple to photons

\[ L_{\text{int}} = -\frac{1}{4} \frac{\phi}{M} F_{\mu\nu} \tilde{F}^{\mu\nu} = \frac{\phi}{M} (\vec{E} \cdot \vec{B}) \]

- An axion like particle (ALP) is a more general particle that can arise from either a pseudoscalar or scalar field, \( \phi \), and no longer has the connection to the pion.
Axion parameters are constrained by cosmological and experimental measurements

- Stars don’t burn out, SN1987A events+energy are OK, and axions aren’t all the mass of the universe.
- Low mass limits set by microwave cavities and higher mass axions are excluded by solar telescopes.
**GammameV**

**ADMX Experiment**

- **Axion Dark Matter Experiment**
  - Tunable microwave cavity in B field looking for dark matter axions converting into a detectable photons.

**High Q cavity**

**SQUID upgrade for receiver**
ADMX Results

- Scan narrow frequency bands. World's quietest spectral receiver.
- Observations consistent with known radio sources or statistics.

- Upgrades should allow sensitivity into the QCD axion / dark matter candidate region of interest.
CAST Experiment

- CERN Axion Solar Telescope

Point LHC dipole toward the sun. Detect possible X-rays from axion reconversion.

CAST
CAST Results

• 2004 results hep-ex/0411033 and new results with small gas pressures hep-ex/0702006 to probe QCD axion.

\[
g_{\gamma\gamma} \text{(95\% C.L.)} < 1.16 \times 10^{-10} \text{ GeV}^{-1}
\]
GammeV Motivation

• In the context of searching for axions, GammeV is looking for an axion-like particle with a mass in the milli-eV region.

• In particular, GammeV exploits the photon couplings and looks for the oscillation of photons into milli-eV particles and then back into photons (with a strong coupling that would otherwise be excluded by the CAST experiment).

• The motivation for GammeV to search in the milli-eV region follows ...
Gam\textsubscript{meV} \textbf{milli-eV Mass Scale}

- milli-eV (10\textsuperscript{-3}) eV mass scale arises in various areas in modern particle physics.
  - Dark Energy density
    - $\Lambda^4 = 7 \times 10^{-30}$ g/cm\textsuperscript{3} $\sim (2 \times 10^{-3}$ eV)$^4$
  - Neutrinos
    - $(\Delta m_{21})^2 = (9 \times 10^{-3}$ eV)$^2$
    - $(\Delta m_{32})^2 = (50 \times 10^{-3}$ eV)$^2$
  - See-saw with the TeV scale:
    - meV $\sim$ TeV$^2$/M\textsubscript{planck}
  - Dark Matter Candidates
    - Certain SUSY sparticles (low mass gravitino)
    - Axions and axion-like particles

Energy frontier
Neutrinos
Astrophysics
all in one!
PVLAS Experiment

- Designed to study the vacuum by optical means: birefringence (generated ellipticity) and dichroism (rotated polarization)
PVLAS Experiment

- Rotating SC magnet ($\frac{1}{2}$ Hz)
- Modulators (500 Hz)
- $\frac{1}{4}$ wave plate to switch between ellipticity and rotation
- Optical cavity to amplify path length in B field
- Expect signals in 2nd harmonic only when $B_{ext}$ field is aligned with either $E$ or $B$ of the $\gamma$
- Cross-checks including with birefringent gasses
Signal at 2\textsuperscript{nd} harmonic

Ellipticity $\Psi$ due to birefringence

$$\Psi = \pi N \frac{L}{\lambda} \Delta n \sin(2\theta)$$

Note: N\textsubscript{2} has opposite phase from Ne. For N\textsubscript{2}, the fast axis is along the B field, and vice versa for Ne.

Signal amplitude (rad/pass) vs phase w.r.t. the B field, for various gas pressure settings

PVLAS Calibration
GammeV

PVLAS Rotation Results


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PVLAS Ellipticity Results

Amplitude

1st harmonic

2nd harmonic

Cotton-Mouton effect vs gas pressure

Amplitude is non-zero for 2nd harmonic

Non-zero amplitude is also seen at 1064nm

Conferences only
A new axion-like particle with mass at 1.2 meV and $g \sim 2 \times 10^{-6}$ is consistent with rotation and ellipticity measurements.
Critique of PVLAS interpretation

Postives for a new particle interpretation
- Effect seen in both ellipticity and rotation at 532 and 1064nm
- Scalar interpretation points to a small region in M vs m
- Cotton Mouton effect is observed as expected
- No rotation effect with no B field
- Copious theoretical ideas to evade astrophysical and other bounds

Concerns for a new particle interpretation
- Systematics from rotation magnet (eddy currents) understood?
- Extra 1st harmonic signal not explained
- Some cross checks done w/large signals

GammeV motivation is to test the axion-like particle interpretation of the PVLAS anomaly in a direct manner
Critique of PVLAS interpretation

**Postives for a new particle interpretation**
- Effect seen in both ellipticity and rotation at 532 and 1064nm
- Scalar interpretation points to a small region in $M$ vs $m$
- Cotton Mouton effect is observed as expected
- No rotation effect with no B field
- Copious theoretical ideas to evade astrophysical and other bounds

**Concerns for a new particle interpretation**
- Systematics from rotation magnet (eddy currents) understood?
- Extra 1st harmonic signal not explained
- Some cross checks are done w/large signals
- New data does not observe the effect and concludes there is likely an instrumental artifact (hep-ex/0706.3419) [after we started]

**GammeV motivation is to test the axion-like particle interpretation of the PVLAS anomaly in a direct manner**
Light Shining Through a Wall Experiment

Assuming 5T magnet, the PVLAS “signal”, and 532nm laser light

\[ \mathcal{L}_{\text{int}} = -\frac{1}{4} \frac{\phi}{M} F_{\mu\nu} F^{\mu\nu} = \frac{\phi}{M} (\vec{E} \cdot \vec{E} - \vec{B} \cdot \vec{B}) \]

\[ \mathcal{L}_{\text{int}} = -\frac{1}{4} \frac{\phi}{M} \tilde{F}_{\mu\nu} \tilde{F}^{\mu\nu} = \frac{\phi}{M} (\vec{E} \cdot \vec{B}) \]

\[ P_{\text{regen}} = \frac{16 B_1^2 B_2^2 \omega^4}{M^4 m_\phi^8} \sin^2 \left( \frac{m_\phi^2 L_1}{4\omega} \right) \cdot \sin^2 \left( \frac{m_\phi^2 L_2}{4\omega} \right) \]

\[ P_{\text{regen}}^{\text{GammeV}} = (3.9 \times 10^{-21}) \times \frac{(B_1/5 \text{ T})^2(B_2/5 \text{ T})^2(\omega/2.33 \text{ eV})^4}{(M/4 \times 10^5 \text{ GeV})^4(m_\phi/1.2 \times 10^{-3} \text{ eV})^8} \]

\[ \times \sin^2 \left( \frac{\pi}{2} \frac{(m_\phi/1.2 \times 10^{-3} \text{ eV})^2(L_1/2.0 \text{ m})}{(\omega/2.33 \text{ eV})} \right) \sin^2 \left( \frac{\pi}{2} \frac{(m_\phi/1.2 \times 10^{-3} \text{ eV})^2(L_2/2.0 \text{ m})}{(\omega/2.33 \text{ eV})} \right) \]
**BFRT Experiment**

- Brookhaven, Fermilab, Rochester, Trieste (1992)

BFRT is not sensitive in the PVLAS region of interest.

\[
\frac{16B_1^2 B_2^2 \omega^4}{M^4 m_\phi^8} \sin^2 \left( \frac{m_\phi^2 L_1}{4\omega} \right) \cdot \sin^2 \left( \frac{m_\phi^2 L_2}{4\omega} \right)
\]
GammeV Collaboration

GammeV

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Batavia, IL 60510

D. Gustafson
University of Michigan
Ann Arbor, MI 48109

Ten person team including a summer student, 3 postdocs, 2 accelerator / laser experts, 4 experimentalists (nearly everyone had a day job) PLUS technical support at FNAL

Nov 2006 : Initial discussion and design (Aaron Chou, WW leaders)
Apr 2007  : Review and approval from Fermilab ($30K budget!)
May 2007  : Acquire and machine parts
Jun 2007  : Assemble parts, test electronics and PMT calibration
Jul 2007  : First data but magnet and laser problems
Aug 2007  : Start data taking in earnest
Sep 2007  : Complete data taking and analysis
Jan 2008  : PRL Accepted (results reported here)
GammeV Proposal

Search for evidence of a milli-eV particle in a light shining through a brick wall experiment to unambiguously test the PVLAS interpretation of an axion-like (pseudo-)scalar.

The "wall" is a welded steel cap on a steel tube in addition to a reflective mirror.

Existing laser in Acc. Div. nearly identical with a similar spare available.

High-QE, low noise, fast PMT module (purchased).
Laser box

3.2W laser
10ns wide
pulses@20Hz

Laser box is safety interlocked, mounted on cement blocks, holds optics, and interfaces to vacuum inside the magnet.

Video image of reflected laser spot is monitored during data taking.

Optics allows for the alignment laser and Nd:YAG to be aligned using ~3m path in the box so the low power laser can be steered through the apparatus.
**Tevatron Magnet**

- Our magnet: TC1206 one of the best spare Tevatron dipole magnets. It was selected because it was previously run at high current.

- Operating current was 5040A to have 5T over the entire 6m length. Measured with NMR probes.

- Terrific support from the magnet test facility that gave us space and infrastructure on their test stand.
The “Wall” and plumbing

The plunger can be adjusted by 2 meters so that the wall can either be placed in the center of the magnet or at a position 1m from the end of the magnet. This unique feature allows us to be sensitive to other masses.
Single photon detector

- Hamamatsu H7422P-40 PMT
- GaAsP photocathode, QE=40%
- Dark Count rate ~ 100 Hz with built-in thermoelectric cooler

We studied the response of the PMT using a single photon LED flasher system. There is a clear separation between noise dominated by the power supply and the single photon peak. We flash the LED during data taking.

Discriminator inefficiency (0.6+/-0.1)%
Data acquisition

- **QuarkNet timing cards**
  - Built by Fermilab for Education Outreach (High School cosmic ray exp’ts.)
  - Interfaces to computer via USB (Visual Basic software for our DAQ)

- Four inputs, phase locked to a GPS 1pps using a 100MHz clock that is divided by eight for 1.25ns timing.

- Boards also send firing commands to the laser and LED pulser system

- Digital oscilloscope recorded PMT signals for LED photons and for rare coincidences.

Time the laser pulses (20Hz) and time the PMT pulses (120Hz). Look for time correlated single photons. All pulses are ~10ns wide.

<table>
<thead>
<tr>
<th></th>
<th>Ch0</th>
<th>Ch1</th>
<th>Ch2</th>
<th>Ch3</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMT Quark Net</td>
<td>PMT pulse</td>
<td>LED pulse</td>
<td>Scope trigger</td>
<td>Isochronous CLK</td>
</tr>
<tr>
<td>Laser Quark Net</td>
<td>Laser Photodiode</td>
<td>Laser Splash</td>
<td>Laser Synch pulse</td>
<td>Isochronous CLK</td>
</tr>
</tbody>
</table>
Expected Sensitivity

- **Black** = BFRT 3 sigma upper bound
- **Pink** = PVLAS 3 sigma signal region
- **Grey** = FNAL 3 sigma exclusion with 5 hours running at each beam dump position
  - **Blue** = center of magnet
  - **Red** = 0.8m from end
- **By changing the baseline, we cover the entire PVLAS signal region**

Sensitivity via O. Helene, 1983

April Review
### The competition

<table>
<thead>
<tr>
<th>name</th>
<th>place</th>
<th>magnet (field length)</th>
<th>laser wavelength power</th>
<th>$P_{\text{PVLAS}}$</th>
<th>photon flux at detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALPS</td>
<td>DESY</td>
<td>5 T 4.21 m</td>
<td>1064 nm 200 W cw</td>
<td>$= 10^{-19}$</td>
<td>10/s</td>
</tr>
<tr>
<td>BMV</td>
<td>LULI</td>
<td>11 T 0.25 m</td>
<td>1053 nm 500 W 4 pulses/day</td>
<td>$= 10^{-21}$</td>
<td>10/pulse</td>
</tr>
<tr>
<td>LIPSS</td>
<td>Jefferson Laboratory</td>
<td>1.7 T 1.0 m</td>
<td>900 nm 10 kW cw</td>
<td>$= 10^{-23.5}$</td>
<td>0.1/s</td>
</tr>
<tr>
<td>OSQAR (preliminary phase)</td>
<td>CERN</td>
<td>9.5 T 1.0 m 9.5 T 3.3 m</td>
<td>540 nm 1 kW cw</td>
<td>$= 10^{-20}$</td>
<td>10/s</td>
</tr>
<tr>
<td>PVLAS (regeneration)</td>
<td>INFN Legnaro</td>
<td>5 T 1 m 2.2 T 0.5 m</td>
<td>1064 nm 0.8 W cw Npass=5 x $10^5$</td>
<td>$= 10^{-23}$</td>
<td>10/s</td>
</tr>
</tbody>
</table>

- World-wide effort to check the PVLAS signal (including PVLAS).
- Many approaches. Ours is straight-forward and not expensive.
- We have tried to maximize signal to noise not just signal.
The competition

- **OSQAR**: null result for PVLAS scalar/pseudoscalar, but no formal limits set and they use a residual gas (not vacuum).
- **LIPSS**: begin to cover PVLAS region of interest for scalar particle interpretation but low B field.
- **BMV**: Use 14 pulses and cover PVLAS region of interest for pseudoscalar case.
- **ALPS**: Phase 0 results show some sensitivity.
“Leaky mirror” data involves sending the laser directly into our PMT after attenuation so that we get about 1 photon per 100 pulses.
- Two mirrors leak ~10⁻⁶ through
- 10 micron pin hole captures ~10⁻⁶
- Neutral density filters give ~10⁻⁷

Look at the PMT pulse closest to a laser pulse and plot the time difference.
- Poisson distribution
- Nearly flat over short times <<ms

Real photons show up!
GammeV Results

- Use the “Leaky Mirror” data to verify both the absolute timing and the sensitivity to polarization.
- The isochronous pulse to both QuarkNet boards can be used to remove a 10ns jitter.
GammeV Results

• Take data in four configurations
  - Scalar (with $\frac{1}{2}$-wave plate) with the plunger in the center and at 1m
  - Pseudoscalar also with the plunger in the center and 1m positions

• In each configuration, acquire about 20 hours of magnet time or about 1.5M laser pulses at 20Hz.
  - Monitor the power of the laser using a power meter that absorbs the laser light reflected back into the laser box using NIST traceable calibration to +/-3%

• Total efficiency (25 +/- 3)%
  - PMT detection efficiencies from factory measurements QE x CE
    39% x 70% = 27%
  - Measured attenuation in BK7 windows and lens: 92%

• Background in a 10ns wide search region is estimated by counting the events in a 10,000ns wide window around all the laser pulses and dividing by 1000.
## GammeV Results

<table>
<thead>
<tr>
<th>Spin</th>
<th>Position</th>
<th># Laser pulse</th>
<th># photon / pulse</th>
<th>Expected Background</th>
<th>Signal Candidates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scalar</td>
<td>Center</td>
<td>1.34 M</td>
<td>0.41e18</td>
<td>1.56±0.04</td>
<td>1</td>
</tr>
<tr>
<td>Scalar</td>
<td>1 m</td>
<td>1.47M</td>
<td>0.38e18</td>
<td>1.67±0.04</td>
<td>0</td>
</tr>
<tr>
<td>Pseudo</td>
<td>Center</td>
<td>1.43M</td>
<td>0.41e18</td>
<td>1.59±0.04</td>
<td>1</td>
</tr>
<tr>
<td>Pseudo</td>
<td>1m</td>
<td>1.47M</td>
<td>0.42e18</td>
<td>1.50±0.04</td>
<td>2</td>
</tr>
</tbody>
</table>

![GammeV Preliminary](image)

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GammeV Results

- Results are derived. We show $3\sigma$ exclusion regions and completely rule out the PVLAS axion-like particle interpretation by more than $5\sigma$.

Double spike because we were 10cm away from the center
• **GammeV** results are used to set improved limits on massive new paraphotons that arise from a new U(1) symmetry.
Phase II: GammeV

- “A particle in a jar”: search for chameleons
  - Add terms in the Lagrangian with a coupling to the stress-energy tensor and a position dependent potential.

\[ L_{\text{int}} = -V(\phi) + \exp\left(\frac{\phi}{M_D}\right) g_{\mu\nu} T^{\mu\nu} - \frac{1}{4} \frac{\phi}{M} F_{\mu\nu} F^{\mu\nu} \]

- That is, the interaction depends on the environment of the particle.
- This is one way to reconcile astrophysical limits such as the sun radiating all of its energy away in axions.

- Shine laser in B field (no wall), build up chameleons between our optical windows (100% reflection when encountering matter), turn off laser, turn on PMT, look for an exponentially decaying afterglow as chameleons convert back into photons. Turn the magnet off and back on to halt and start this afterglow process.
Conclusion

• At FNAL, a small group of us had fun this past summer. There were days I went into work thinking today might be the day that a new revolutionary particle might appear.

• We achieved the goal of excluding a region of interest for an axion-like particle with a high confidence level.

• Axions are a real possible dark matter candidate. My opinion is that more effort should go into looking for them.

• Finally, just like there are theories that are “Not Yet Thought Of”, so there are also opportunities for such experiments. Maybe something like a chameleon or something even stranger will be the next New Physics.