Particle Interpretations of the PVLAS Data

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Plan:

1. Vacuum Magnetic Dichroism and Birefringence
   Polarized light propagation through a magnetic field: global data

2. Possible Explanations
   Production of new weakly interacting light particles (WILPs)?

3. Crucial Laboratory Tests
   Light or dark-current through-a-wall experiments, ...

4. Problems of Particle Interpretations
   Astrophysical, cosmological, and other constraints

5. WILPs in Models with Light Extra-U(1)s
   Light mini-charged particles from gauge kinetic mixing, ...

6. Summary
1. Vacuum Magnetic Dichroism and Birefringence

- Send linearly polarized laser beam through transverse magnetic field ⇒ measure changes in polarization state:
  - rotation (dichroism)
  - ellipticity (birefringence)

[Brandi et al. ‘01]
1. Vacuum Magnetic Dichroism and Birefringence

- Send linearly polarized laser beam through transverse magnetic field ⇒ measure changes in polarization state:
  - rotation (dichroism)
  - ellipticity (birefringence)

BFRT experiment: [Cameron et al. ‘93]
(Brookhaven, Fermilab, Rochester, Trieste)

\[ B \sim 2 \text{ T}, \ell = 8.8 \text{ m}, \omega = 2.4 \text{ eV}, N_{\text{pass}} = 34 - 254 \]

PVLAS experiment: [Zavattini et al. ‘06]

\[ B = 5 \text{ T}, \ell = 1 \text{ m}, \omega = 1.2 \text{ eV}, N_{\text{pass}} = 44000 \]

Q&A experiment: [Chen, Mei, Ni ‘06]

\[ B = 2.3 \text{ T}, \ell = 1 \text{ m}, \omega = 1.2 \text{ eV}, N_{\text{pass}} = 18700 \]
# 1. Vacuum Magnetic Dichroism and Birefringence

- Send linearly polarized laser beam through transverse magnetic field ⇒ measure changes in polarization state:
  - rotation (dichroism)
  - ellipticity (birefringence)
- No signal in BFRT

<table>
<thead>
<tr>
<th>BFRT experiment</th>
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<tbody>
<tr>
<td><strong>Rotation</strong></td>
</tr>
<tr>
<td>( (L = 8.8 \text{ m}, \lambda = 514.5 \text{ nm}, \theta = \frac{\pi}{4}) )</td>
</tr>
<tr>
<td>( N_{\text{pass}} )</td>
</tr>
<tr>
<td>254</td>
</tr>
<tr>
<td>34</td>
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</tbody>
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| **Ellipticity**                  |
| \( (L = 8.8 \text{ m}, \lambda = 514.5 \text{ nm}, \theta = \frac{\pi}{4}) \) |
| \( N_{\text{pass}} \) | \( |\psi| \) [nrad] | \( \psi_{\text{noise}} \) [nrad] |
| 578                             | 40.0                              | 11.0                     |
| 34                              | 1.60                              | 0.44                     |

| **Regen.** \( (L = 4.4 \text{ m}, \langle \lambda \rangle = 500 \text{ nm}, N_{\text{pass}} = 200) \) |
| \( \theta \) [rad] | rate [Hz] |
| 0                  | \(-0.012 \pm 0.009\) |
| \( \frac{\pi}{2} \) | \(0.013 \pm 0.007\) |

[Cameron et al ’93]
1. Vacuum Magnetic Dichroism and Birefringence

- Send linearly polarized laser beam through transverse magnetic field ⇒ measure changes in polarization state:
  - rotation (dichroism)
  - ellipticity (birefringence)
- No signal in BFRT; signal in PVLAS

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<td><strong>Rotation</strong> $(L = 1 \text{ m}, N_{\text{pass}} = 44000, \theta = \frac{\pi}{4})$</td>
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<td>$\lambda$ [nm]</td>
</tr>
<tr>
<td>1064</td>
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<tr>
<td>532</td>
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| **Ellipticity** $(L = 1 \text{ m}, N_{\text{pass}} = 44000, \theta = \frac{\pi}{4})$ |
| $\lambda$ [nm] | $\psi$ [$10^{-12}$ rad/pass] |
| 1064 | $-3.4 \pm 0.3$ (preliminary) |
| 532 | $-6.0 \pm 0.6$ (preliminary) |

[PRL ’06; IDM ’06]
1. Vacuum Magnetic Dichroism and Birefringence

- Send linearly polarized laser beam through transverse magnetic field \( \Rightarrow \) measure changes in polarization state:
  - rotation (dichroism)
  - ellipticity (birefringence)

- No signal in BFRT; signal in PVLAS; no signal in Q&A

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[Q&A coll. '06]
2. Possible Explanations

- Viable explanation in terms of real and virtual production of
  - light neutral spin-zero boson (Axion-Like Particle (ALP)),

\[
\left(\frac{g}{4}\right) \phi^(-) F_{\mu\nu} \tilde{F}^{\mu\nu} \left(\phi^+ F_{\mu\nu} F^{\mu\nu}\right)\]

Effects of Nearly Massless, Spin Zero Particles on Light Propagation in a Magnetic Field

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A. Ringwald (DESY)
2. Possible Explanations

- Viable explanation in terms of real and virtual production of
  - light neutral spin-zero boson (Axion-Like Particle (ALP))
  - light MiniCharged Particle (MCP)
    - anti-particle pair,

\[ \partial_\mu \rightarrow \partial_\mu - i e A_\mu \]

Polarized Light Propagating in a Magnetic Field as a Probe for Millicharged Fermions [Gies, Jaeckel, AR '06]

In analogy to theoretically well-studied \( e^+ e^- \) real and virtual production

[...; Toll '52; Adler '71; Tsai, Erber '74, '75; ...]
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If interpreted in terms of ALP:

[Ahlers, Gies, Jaeckel, AR ’06]
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\[
(\frac{g}{4}) \phi^{(-)} F_{\mu\nu} \tilde{F}^{\mu\nu} \quad (\phi^{(+)} F_{\mu\nu} F^{\mu\nu})
\]

- light MiniCharged fermion (MCF)– anti-fermion pair

Check by upcoming
- polarization experiments
- photon regeneration experiments

If interpreted in terms of ALP:

[Ahlers, Gies, Jaeckel, AR '06]

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2. Possible Explanations

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\[ \partial_\mu \rightarrow \partial_\mu - i\epsilon e A_\mu \]

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- Explanation in terms of real and virtual production of Second Photon (SP) in fusion model of photon: [de Broglie '32]
  - Photon: \( S = 1 \) bound state of spin 1/2 particle-antiparticle pair
  - SP: \( S = 0 \) bound state

Parameters: Mass splitting \( \Delta \) and magnetic moment \( \beta \mu_B \) of particle

If interpreted in terms of SP:

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A. Ringwald (DESY)
3. Crucial Laboratory Tests

- Laser polarization experiments at higher magnetic fields

BMV (Toulouse): 11 T pulsed magnet
3. Crucial Laboratory Tests

- Laser polarization experiments at higher magnetic fields
- Light shining through a wall

“Light shining through a wall”

\[ \gamma \rightarrow \phi \rightarrow \phi \rightarrow \gamma \]  
[\text{Sikivie '83; Ansel'm '85; Van Bibber et al. '87}]

| Name      | Laboratory | Magnets          | \( P_{\gamma\phi\gamma | g\text{PVLAS}} \) |
|-----------|------------|------------------|------------------------------------------------|
| ALPS      | DESY/D     | \( B_1 = B_2 = 5 \text{ T} \) \<br>\( \ell_1 = \ell_2 = 4.21 \text{ m} \) | \( \sim 10^{-19} \) |
| BMV       | LULI/F     | \( B_1 = B_2 = 11 \text{ T} \) \<br>\( \ell_1 = \ell_2 = 0.25 \text{ m} \) | \( \sim 10^{-21} \) |
| LIPSS     | Jlab/USA   | \( B_1 = B_2 = 1.7 \text{ T} \) \<br>\( \ell_1 = \ell_2 = 1 \text{ m} \) | \( \sim 10^{-23.5} \) |
| OSQAR     | CERN/CH    | \( B_1 = B_2 = 11 \text{ T} \) \<br>\( \ell_1 = \ell_2 = 7 \text{ m} \) | \( \sim 10^{-17} \) |
| PVLAS     | Legnaro/I  | \( B_1 = 5 \text{ T} \) \<br>\( \ell_1 = 1 \text{ m} \) \<br>\( B_2 = 2.2 \text{ T} \) \<br>\( \ell_2 = 0.5 \text{ m} \) | \( \sim 10^{-23} \) |

[AR '06]
3. Crucial Laboratory Tests

- Laser polarization experiments at higher magnetic fields
- Light shining through a wall

**Axion-Like Particle Search:**

[DESY, Laser Zentrum Hannover, Sternwarte Bergedorf]

\[ B = 5 \ T, \ell = 4.2 \text{ m}, \langle P \rangle = 0.2 \text{ kW}, \omega = 1.2 \text{ eV}, N_r = 0 \]

\[ \dot{N}_0 \sim 1 \times 10^{21} / \text{s} \]

Test of ALP interpretation of PVLAS in summer 2007

Venice, March 2007
3. Crucial Laboratory Tests

- Laser polarization experiments at higher magnetic fields
- Light shining through a wall
- Dark current through a wall

[Diagram showing experimental setup]

[Gies, Jaeckel, AR ’06]
3. Crucial Laboratory Tests

- Laser polarization experiments at higher magnetic fields
- Light shining through a wall
- Dark current through a wall

Cryogenic Current Comparator:
[DESY, GSI, Universität Jena]
3. Crucial Laboratory Tests

- Laser polarization experiments at higher magnetic fields
- Light shining through a wall
- Dark current through a wall

TESLA accelerator cavity | CCC:

![Graph showing data](image)

[![Graph showing data](image)](image)

[Gies,Jaeckel,AR unpubl.]
3. Crucial Laboratory Tests

- Laser polarization experiments at higher magnetic fields
- Light shining through a wall
- Dark current through a wall
- Invisible Orthopositronium decay

"Search for Invisible Orthopositronium Decay" [Dobroliubov, Ignatiev '89]

\[
\text{BR}(\text{OP } \rightarrow \epsilon^+ \epsilon^-) \simeq \frac{3\pi \epsilon^2}{4\alpha (\pi^2 - 9)} \simeq 371 \epsilon^2
\]

[Dobroliubov, Ignatiev '89]

\[
\text{BR}(\text{OP } \rightarrow \text{inv.}) < 2.8 \times 10^{-6}
\]

[Badertscher et al. '06]: \( \text{BR}(\text{OP } \rightarrow \text{inv.}) < 4.2 \times 10^{-7} \)

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3. Crucial Laboratory Tests

- Laser polarization experiments at higher magnetic fields
- Light shining through a wall
- Dark current through a wall
- Invisible Orthopositronium decay
- Searches for excess $e^-$ from elastic $e^\pm e^-$ scattering in detector near nuclear reactor
- Nuclear power reactors with $P > 2 \text{ GW}$ emit more than $10^{20} \gamma / s$
- These $\gamma$s may convert within reactor into $e^+ e^-$ pairs
- A small fraction of these particles could lead to an observable excess of electrons from $e^\pm e^-$ scattering in a detector
- Recent results from theTEXONO experiment set up at the Kuo-Sheng Nuclear Power Station (2.8 GW) in Taiwan probing for $\mu \nu_e$ by searching for an excess of events from $\nu e^-$ magnetic scattering

\[ \Rightarrow \text{Bound on fractional electric charge,} \]

\[ \epsilon \lesssim 10^{-5}, \text{ for } m_\epsilon \lesssim 1 \text{ keV} \]

- May be improved in near future with massive liquid argon detector

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4. Problems of Particle Interpretations

- Energy loss of stars:
  - **ALPs**: Primakoff $\gamma Z \rightarrow \phi Z$
  - MCPs: plasmon decay
  - SP: no problem

- **ALP**$^0$:
  - Non-Newtonian force,
    \[
    V(r) = \frac{G m_1 m_2}{r} + \frac{y^2}{4\pi n_1 n_2 r e^{-m_\phi r}} \text{ from Yukawa coupling}
    \]
    \[
    L_{\phi pp} = y_\phi \Psi_p \bar{\Psi}_p
    \]
    \[
    y_\phi \simeq \frac{3}{2} \alpha \pi (g_m p) \log \Lambda_{m_p}
    \]

**HB stars**

**Galactic dark matter**

**Way out**: $g|_{\text{star}} \ll g|_{\text{vacuum}}$

- Even more sub-eV particles and fields, e.g.
  - **U(1)** bosons mixing with photon
  - scalar field with low scale phase transition

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A. Ringwald (DESY)
4. Problems of Particle Interpretations

- Energy loss of stars:
  - ALPs: Primakoff $\gamma Z \rightarrow \phi Z$
  - MCPs: plasmon decay $\gamma^* \rightarrow \epsilon^+ \epsilon^-$

Way out: $\epsilon_{\text{plasma}} \ll \epsilon_{\text{vacuum}}$

$\Rightarrow$ Even more sub-eV particles and fields,
  e.g. U(1) bosons mixing with photon

[Davidson, Hannestad, Raffelt '00]

[Masso, Redondo '06]

[Abel et al. '06; Foot, Kobakhidze '07]
4. Problems of Particle Interpretations

- Energy loss of stars:
  - **ALPs**: Primakoff $\gamma Z \rightarrow \phi Z$
  - **MCPs**: plasmon decay $\gamma^* \rightarrow e^+ e^-$
  - **SPs**: no problem

- **ALP 0^+**: Non-Newtonian force,

$$V(r) = G \frac{m_1 m_2}{r} + \frac{y^2 n_1 n_2}{4\pi r} e^{-m_\phi r}$$

from Yukawa coupling

$$\mathcal{L}_{\phi pp} = y \phi \bar{\Psi}_p \Psi_p$$

$$y \simeq \frac{3 \alpha}{2\pi} (g m_p) \log \frac{\Lambda}{m_p}$$

- From torsion-balance experiment:

$$g < 4 \times 10^{-17} \text{ GeV}^{-1},$$

for $m_\phi = 1 \text{ meV}; \Lambda \gg m_p$

-Way out: ALP 0^+ couples only to additional light U(1) bosons mixing with photon

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Venice, March 2007
5. WILPs in Models with Light Extra-U(1)s

- Consider extension of SM with additional “hidden sector” U(1)’s \( \Rightarrow \) in general gauge kinetic mixing with “visible” U(1), e.g.

\[
\mathcal{L} = -\frac{1}{4} F^T \mathcal{K}_F F + \frac{1}{2} A^T \mathcal{M}_A^2 A + e_j A,
\]

with special mixing

\[
\mathcal{K}_F = \begin{pmatrix}
1 & \chi & \chi \\
\chi & 1 & 0 \\
\chi & 0 & 1
\end{pmatrix}
\]

Mixing may arise from integrating out heavy particles:

- e.g. threshold effect from two species of fermions, \((e_a, e_b)\) and \((e_a, -e_b)\), with masses \(m\) and \(m'\):

\[
\chi \approx \frac{e_a e_b}{6\pi^2} \log \left( \frac{m'}{m} \right)
\]

\[\begin{align*}
\cdots & A^\mu_a & A^\mu_b \\
\cdots
\end{align*}\]
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with special mixing

\[ \mathcal{K}_F = \begin{pmatrix} 1 & \chi & \chi \\ \chi & 1 & 0 \\ \chi & 0 & 1 \end{pmatrix} \]

Mixing may arise from integrating out heavy particles:

e.g. closed string exchange between visible sector D-branes and hidden sector anti-D-branes,

\[ \chi \sim g_a g_b \left( \frac{2^{(8-p)/2}}{\alpha_p M_s} \right)^{\frac{2(5-p)}{6-p}} \left( \frac{R}{r} \right)^{\frac{d-p+3}{6-p}} \]

[Abel, Jaeckel, Khoze, AR ‘06]
5. WILPs in Models with Light Extra-U(1)s

- Consider extension of SM with additional “hidden sector” U(1)’s \(\Rightarrow\) in general gauge kinetic mixing with “visible” U(1), e.g.

\[
\mathcal{L} = -\frac{1}{4} F^T K_F F + \frac{1}{2} A^T M_A^2 A + e j A,
\]

with special mixing and mass pattern

\[
K_F = \begin{pmatrix} 1 & \chi & \chi \\ \chi & 1 & 0 \\ \chi & 0 & 1 \end{pmatrix}, \quad M_A^2 = \begin{pmatrix} m_\gamma^2 & 0 & 0 \\ 0 & \mu^2 & 0 \\ 0 & 0 & 0 \end{pmatrix}
\]

- Hidden sector CP, with special charge assignment \((0, e, -e)\), acquires visible mini-charge

\[
e \simeq \begin{cases} -\chi & \text{for } m_\gamma = 0 \\ (\mu^2/\omega_d^2) \chi & \text{for } m_\gamma = \omega_d \gg \mu \end{cases}
\]

\(\Rightarrow\) Viable MCP explanation of PVLAS \((m_\gamma = 0)\)

for \(\chi \sim 10^{-6}, \quad m_\varepsilon \lesssim 0.1 \text{ eV}\);
5. WILPs in Models with Light Extra-U(1)s

- Consider extension of SM with additional “hidden sector” U(1)’s ⇒ in general gauge kinetic mixing with “visible” U(1), e.g.

\[ \mathcal{L} = -\frac{1}{4} F^T K_F F + \frac{1}{2} A^T M_A^2 A + ejA, \]

with special mixing and mass pattern

\[ K_F = \begin{pmatrix} 1 & \chi & \chi \\ \chi & 1 & 0 \\ \chi & 0 & 1 \end{pmatrix} \]

- Hidden sector CP, with special charge assignment \((0, e, -e)\), acquires visible mini-charge

\[ \epsilon \equiv \begin{cases} -\chi & \text{for } m_\gamma = 0 \\ (\mu^2/\omega_p^2) \chi & \text{for } m_\gamma = \omega_p \gg \mu \end{cases} \]

⇒ Viable MCP explanation of PVLAS \((m_\gamma = 0)\)

for \(\chi \sim 10^{-6}, m_\epsilon \lesssim 0.1 \text{ eV}\); in accordance with the life time of stars \((m_\gamma = \omega_p \sim \text{keV})\), if \(\mu \lesssim 0.1 \text{ eV}\) \[\text{[Abel et al. '06]}\]
5. WILPs in Models with Light Extra-U(1)s

- Consider extension of SM with additional “hidden sector” U(1)’s ⇒ in general gauge kinetic mixing with “visible” U(1), e.g.

\[ \mathcal{L} = -\frac{1}{4} F^T \mathcal{K}_F F + \frac{1}{2} A^T \mathcal{M}^2_A A + e j A, \]

with special mixing and mass pattern

\[ \mathcal{K}_F = \begin{pmatrix} 1 & \chi & \chi \\ \chi & 1 & 0 \\ \chi & 0 & 1 \end{pmatrix}, \]

- Hidden sector CP, with special charge assignment \((0, e, -e)\), acquires visible mini-charge

\[ \epsilon \simeq \begin{cases} -\chi & \text{for } m_\gamma = 0 \\ (\mu^2/\omega_p^2) \chi & \text{for } m_\gamma = \omega_p \gg \mu \end{cases} \]

⇒ Viable MCP explanation of PVLAS \((m_\gamma = 0)\) for \(\chi \sim 10^{-6}\), \(m_\epsilon \lesssim 0.1\) eV; in accordance with the life time of stars \((m_\gamma = \omega_p \sim \text{keV})\), if \(\mu \lesssim 0.1\) eV \[\text{[Abel et al. '06]}\]

⇒ Extend minimal model by hidden sector scalar, \(m_\phi \sim \text{meV}\), coupled to hidden sector CPs ⇒ Viable ALP explanation \[\text{[Masso,Redondo '06]}\]

- Coupling to two photons can be arranged to be in PVLAS range,

\[ g \sim \frac{\alpha}{2\pi} \frac{y_f}{m_f} \sim 2 \times 10^{-6} \text{ GeV}^{-1} \left( \frac{\chi}{10^{-6}} \right)^2 \left( \frac{y_f \text{ eV}}{m_f} \right) \]

- Yukawa coupling to proton,

\[ y \sim \frac{\alpha}{\pi} \frac{\chi^2 \mu}{m_f}, \]

suppressed by factor \(\mu/m_p\) compared to case without kinetic mixing ⇒ no problem with non-Newtonian forces, if \(\mu \lesssim \text{meV}\)

A. Ringwald (DESY)

Venice, March 2007
6. Summary

- The evidence for a vacuum magnetic dichroism and birefringence by PVLAS has triggered a lot of theoretical and experimental activities:
  - Particle interpretations alternative to ALP interpretation: e.g. MCP
  - Models, which evade strong astrophysical and cosmological bounds on such particles, have been found. Require typically even more WILPs than just the ones introduced for the solution of the PVLAS puzzle
  - Decisive laboratory based tests of particle interpretation of PVLAS anomaly in very near future. More generally, experiments will dig into previously unconstrained parameter space of above mentioned models

- Experiments exploiting low energy photons may give information about fundamental particle physics complementary to the one obtained at high energy colliders