Attacking Hidden Forces with Intense Photon- and Electron-Beams

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3rd International Workshop on High Energy Physics in the LHC Era
January 4-8, 2010, Valparaiso, Chile
Outline:

1. Case for Light Particles Beyond the Standard Model
   1.1 Axions and Axion-Like Particles
   1.2 Hidden-Sector Abelian Gauge Bosons

2. New Experiments at the High-Intensity Frontier
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3. Conclusions
1. Case for Light Particles Beyond the Standard Model

1.1 Axions and Axion-Like Particles

- **Strong CP problem:** Due to non-Abelian nature of QCD, additional CP-violating term in the Lagrangian,

\[ \mathcal{L}_{\text{CP-viol.}} = \frac{\alpha_s}{4\pi} \theta \text{tr} \ G_{\mu\nu} \tilde{G}^{\mu\nu} \]

- Upper bound on electric dipole moment of neutron ⇒

\[ |\bar{\theta}| \equiv |\theta + \text{arg det } M| \lesssim 10^{-10} \]

- **Unnaturally small!**
• **Peccei-Quinn solution to the strong CP problem:**

- Introduce axion field $a$ as dynamical $\theta$ parameter, which enjoys shift symmetry, $a \to a + \text{const.}$, broken only by anomalous terms

$\Rightarrow$ Low-energy effective Lagrangian:

$$\mathcal{L}_a = \frac{1}{2} \partial_\mu a \partial^\mu a + \mathcal{L}_a^{\text{int}} \left[ \frac{\partial_\mu a}{f_a} ; \psi \right] + \frac{\alpha_s}{4\pi f_a} a \, \text{tr} \, G^{\mu\nu} \tilde{G}_{\mu\nu} + \frac{s\alpha}{8\pi f_a} a \, F^{\mu\nu} \tilde{F}_{\mu\nu} + \ldots$$

- $\theta$-term in $\mathcal{L}_{\text{SM}} + \mathcal{L}_a$ can be eliminated by exploiting the shift symmetry, $a \to a - \theta f_a$

- Topological charge density $\propto \langle \text{tr} \, G^{\mu\nu} \tilde{G}_{\mu\nu} \rangle \neq 0$ provides nontrivial potential for axion field; minimized at $\langle a \rangle = 0 \Rightarrow$ axion is pseudo-Nambu-Goldstone boson with mass

$$m_a = \frac{m_\pi f_\pi}{f_a} \sqrt{m_u m_d} \approx 0.6 \text{ meV} \times \left( \frac{10^{10} \text{ GeV}}{f_a} \right)$$

[S.Weinberg '78; Wilczek '78]
– Attacking Hidden Forces –

– For large $f_a$: axion is ultralight and invisible

[J.E. Kim ‘79; Shifman et al. ‘80; Dine et al. ‘81;...]

– Phenomenologically very important: axion couples to photons,

\[
\gamma \gamma \gamma \gamma \gamma \gamma = -\frac{1}{4} g a F_{\mu \nu} \tilde{F}^{\mu \nu} = g a \vec{E} \cdot \vec{B},
\]

with

\[
g = \frac{\alpha}{2\pi f_a} \left( \frac{2}{3} \frac{m_u + 4m_d}{m_u + m_d} - s \right) \sim 10^{-13} \text{ GeV}^{-1} \left( \frac{10^{10} \text{ GeV}}{f_a} \right)
\]

[Bardeen, Tye ’78; Kaplan ’85; Srednicki ’85]

A. Ringwald (DESY) Valparaiso, January 2010
• Observational and experimental exclusion limits on $f_a$:

- Solid lower bound, $f_a \gtrsim 10^9$ GeV
- Overclosure constraint generically $f_a \lesssim 10^{12}$ GeV, but can be postponed to GUT scale, for fine-tuned initial conditions
• **Axions in string theory:**

Axions and axion-like fields with global anomalous PQ symmetries generic in string compactifications: KK zero modes of form fields \[ \text{[Witten '87; ...; Conlon '06, Svrcek, Witten '06; Arvanitaki et al. '09; ...]} \]

Typically, for axions,

\[
10^9 \text{ GeV} \lesssim f_a \sim M_s \lesssim 10^{16} \text{ GeV} \\
10^{-2} \text{ eV} \gtrsim m_a \sim \frac{m_\pi f_\pi}{M_s} \gtrsim 10^{-9} \text{ eV}
\]

and, for axion-like particles,

\[
f_\phi \sim f_a, \quad 0 \leq m_\phi \sim \frac{\Lambda^2}{M_s} \lesssim m_a
\]

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• **Indirect hints for axions and axion-like particles?**
  
  - **Non-standard energy loss in white dwarfs** recently pointed out, compatible with the existence of axions with an axion-electron coupling, $g_{ea} \sim 10^{-13}$, suggesting an axion decay constant [Isern et al. ’08],

  \[ f_a \sim g_{ea} m_e = 4 \times 10^9 \text{ GeV} \Rightarrow g_{\gamma a} \sim \alpha / f_a \sim 10^{-11} \text{ GeV}^{-1} \]

  - **Anomalous transparency of the universe in gamma rays** inferred from observation of distant astrophysical sources in TeV gamma rays, despite expected strong absorption due to $e^+e^-$ pair production. May be explained by conversion of $\gamma$s into axion-like particles $\phi$ in the magnetic fields around the gamma ray sources. These ALPS travel then unimpeded until they reach our galaxy and reconvert into photons in the galactic magnetic fields [Hochmuth,Sigl ’07;Hooper,Serpico ’07]. Alternatively, the conversion/reconversion could take place in the intergalactic magnetic fields [De Angelis,Mansutti,Roncadelli ’07;…;Mirizzi ’09]. Additional hint: characteristic scatter observed in AGN luminosity relation [Burrage,Davis,Shaw ’09]. Need

  \[ g_{\gamma \phi} \sim 10^{-12} \div 10^{-11} \text{ GeV}^{-1}; \quad m_{\phi} \ll 10^{-12} \text{ GeV} \]

  \[ \Rightarrow \text{ Aim for next-generation direct search experiments (see later)} \]
1.2 Hidden-Sector Abelian Gauge Bosons

- Extensions of standard model based on supergravity or superstrings rely on "hidden sector" of particles which are very weakly coupled to the "visible sector" standard model particles; cf. "gravity mediation" of SUSY breaking ($\Leftrightarrow$ condensation of non-Abelian hidden gaugino)

- Sector "hidden" $\Leftrightarrow$ mediators heavy and/or very weakly coupled

- Possible light hidden particles: hidden sector U(1) gauge bosons ("hidden photons" $\gamma'$) and hidden sector particles charged under the hidden U(1) ($\Rightarrow$ "mini-charged particles" (MCPs))
• Hidden U(1) gauge factors generic feature of string compactifications

- both in heterotic compactifications, e.g. [Lebedev, Ramos-Sanchez ‘09]

\[ E_8 \times E_8 \rightarrow G_{SM} \times [SU(6) \times U(1)] \]

- as well as in type II orientifold compactifications with D-branes
* KK zero modes of form fields
* Massless excitations of space-time filling D-branes

- Hidden U(1) gauge bosons ("photons") may be light, $m_{\gamma'} \ll \text{TeV}$
• Dominant interaction with $U(1)_Y$ or $U(1)_{em}$ via kinetic mixing \cite{Holdom'85}

$$\mathcal{L} \supset -\frac{1}{4} F_{\mu\nu}^{(vis)} F^{\mu\nu}_{(vis)} - \frac{1}{4} F_{\mu\nu}^{(hid)} F^{\mu\nu}_{(hid)} + \frac{\chi}{2} F_{\mu\nu}^{(vis)} F^{(hid)\mu\nu} + m_{\gamma'}^2 A_\mu^{(hid)} A^{(hid)\mu}$$

$\chi \ll 1$ generated at loop level via messenger exchange $\Rightarrow$ $U(1)$ hidden

– Kinetic mixing in compactification of heterotic string:

$$10^{-17} \lesssim \chi \simeq \frac{e^2}{16\pi^2} C \frac{\Delta m}{M_P} \lesssim 10^{-5},$$

for $C \gtrsim 10$; $10^5 \text{ GeV} \lesssim \Delta m \lesssim 10^{17} \text{ GeV}$
Kinetic mixing between D-brane localized U(1)s in type II compactifications: \cite{Lüst, Stieberger '03; Abel, Schofield '04; Berg, Haack, Körs '05; ...; Goodsell et al. '09}

\[
10^{-12} \lesssim \chi \sim \frac{e e h}{16 \pi^2} \sim 2\pi g_s \left( \frac{4\pi M_s^2}{g_s^2 M_P^2} \right)^{q/12} \lesssim 10^{-3},
\]

for \( q = 0, 4 \); \( 10^3 \text{ GeV} \lesssim M_s \lesssim 10^{17} \text{ GeV} \)
• Current constraints on hidden U(1)s:

[Bartlett,..'88; Kumar,..'06; Ahlers,..'07; Jaeckel,..'07; Redondo,..'08; Postma,Redondo ‘08; Bjorken,Essig,Schuster,Toro'09;…]
- Attacking Hidden Forces –

• Bottom-up motivated hidden U(1) parameter ranges:

[Jaeckel, Redondo, AR ‘08; Arkani-Hamed, .. ‘08; Ibarra, AR, Weniger ‘08; ...]
• **meV scale hidden photon** results in hidden CMB; may explain $N_{\nu}^{\text{eff}} > 3$, as favored from some analyses of CMB + large scale structure if Ly-$\alpha$ data is included; can be checked in light-shining-through-wall experiments [Jaeckel, Redondo, AR '08]

• Region $(\chi, m_{\gamma'}) \sim (10^{-4}, \text{GeV})$ favored by **Unified Dark Matter** scenario: unified description of PAMELA excess and annual modulation signal seen by direct DM search experiment DAMA ... Hidden sector dark matter; hidden U(1) mediates **Dark Force** [Arkani-Hamed et al. '08;...]; can be checked in new fixed-target experiments

• Larger mixing and mass above $Z$ favored by scenario where PAMELA excess explained by annihilation of hidden sector Dirac fermions close to $\gamma'$ resonance [Feldman, Liu, Nath '08]; can be checked at LHC ⇒ Pran Nath's 2nd talk
• Experimental opportunities for hidden U(1)s:

[Goodsell, Jaeckel, Redondo, AR '09]
2. New Experiments at the High-Intensity Frontier

⇒ see also talk by Andrei Afanasev

2.1 Photon Regeneration Experiments

- **Helioscope searches** for axions, axion-like particles and hidden photons

[Sikivie ‘83;...;Redondo ‘08;...]

![Diagram showing photon regeneration experiments involving magnetic fields, oscillations, and detectors.]
Limits on photon coupling $g$ of axions and axion-like particles:

[CAST Collaboration '09]

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• **CAST** limits on kinetic mixing $\chi$ of hidden photons:

[Redondo '08]
- **SHIPS** *(Solar Hidden Photon Search)* at Hamburger Sternwarte:

  - Big helioscope will be mounted on 1 m telescope:
- **SHIPS** (Solar Hidden Photon Search) at Hamburger Sternwarte:

- Expected sensitivity:

![Graph showing the expected sensitivity of SHIPS](image-url)
- Attacking Hidden Forces -

- Laser-light shining through a wall:  
  [Okun '82; Anselm '85; van Bibber et al. '87]
- Attacking Hidden Forces -

- Laser-light shining through a wall:

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Laser</th>
<th>$&lt;P&gt;$</th>
<th>Magnets</th>
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</thead>
<tbody>
<tr>
<td>ALPS (DESY)</td>
<td>532 nm; FP</td>
<td>30-1200 W</td>
<td>$B_1 = B_2 = 5 , T$</td>
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<td></td>
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<td></td>
<td>$\ell_1 = \ell_2 = 4.21 , m$</td>
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<tr>
<td>BFRT (Brookhaven)</td>
<td>$\sim 500$ nm; DL</td>
<td>100 W</td>
<td>$B_1 = B_2 = 3.7 , T$</td>
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<td></td>
<td>$\ell_1 = \ell_2 = 4.4 , m$</td>
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<tr>
<td>BMV (LULI)</td>
<td>1064 nm; LULI</td>
<td>$8 \times 10^{21} , \gamma$/pulse</td>
<td>$B_1 = B_2 = 11 , T$</td>
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<td>$\ell_1 = \ell_2 = 0.25 , m$</td>
</tr>
<tr>
<td>GammeV (Fermilab)</td>
<td>532 nm;</td>
<td>3.2 W</td>
<td>$B_1 = B_2 = 5 , T$</td>
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</tr>
<tr>
<td>LIPSS (JLab)</td>
<td>900 nm; FEL</td>
<td>300 − 900 W</td>
<td>$B_1 = B_2 = 1.7 , T$</td>
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<td>$\ell_1 = \ell_2 = 1 , m$</td>
</tr>
<tr>
<td>OSQAR (CERN)</td>
<td>1064 nm; FP</td>
<td>$&gt; 1 , kW$</td>
<td>$B_1 = B_2 = 9.5 , T$</td>
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• **ALPS** *(Any-Light Particle Search):* [AEI, DESY, Hamburger Sternwarte, Laser Zentrum Hannover]
**ALPS:**

- primary beam: enhanced LIGO laser (1064 nm, 35 W cw)

⇒ frequency doubled to 532 nm

⇒ $\sim 100$ fold power build up through resonant optical cavity (Fabry-Perot), $\sim 10 \mu m$ focus

⇒ CCD camera: expect regenerated photons in signal region of a few pixel
• Preliminary limits from **ALPS** run in 10/2009:
• Possible upgrades of ALPS:

Second Fabry-Perot cavity: [Hoogeveen, Ziegenhagen ‘91; Sikivie, Tanner, van Bibber ‘07]
• Possible upgrades of ALPS:

⇒ Astrophysics barrier can be broken! Interesting parameter range in view of white dwarf energy loss and universe’s transparency for TeV gamma rays anomaly can be tested!

[A. Lindner ‘09]

A. Ringwald (DESY)  Valparaiso, January 2010
2.2 Dark Forces Attack with New Fixed-Target Experiments

- High intensity frontier to search for MeV ÷ GeV-scale \(\gamma'\):
  - low-energy \(e^+e^-\) collider
    
    \[
    \sigma \sim \frac{\alpha^2 \chi^2}{s}
    \]
    
    \(\mathcal{O}\) (few) \(ab^{-1}\) per decade
    
    \[
    \sigma \sim \frac{\alpha^3 Z^2 \chi^2}{m^2_{\gamma'}}
    \]
    
  - fixed-target experiments
    
    \(\mathcal{O}\) (few) \(ab^{-1}\) per day
    
    \[
    \Rightarrow \text{Beam dump and fixed-target experiments especially sensitive!}
    \]

[Reece,Wang '09; Bjorken,Essig,Schuster,Toro '09; Batell,Pospelov,Ritz '09]
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A. Ringwald (DESY)
⇒ **Opportunities at DESY, ELSA, JLab, MAMI?**

- Production cross-section and decay length of $\gamma'$,

$$
\sigma_{\gamma'} \sim 100 \text{ pb} \left( \frac{\chi}{10^{-4}} \right)^2 \left( \frac{100 \text{ MeV}}{m_{\gamma'}} \right)^2
$$

$$
\ell_d = \gamma c \tau \sim 1 \text{ mm} \left( \frac{\gamma}{10} \right) \left( \frac{\chi}{10^{-4}} \right)^{-2} \left( \frac{100 \text{ MeV}}{m_{\gamma'}} \right)
$$

- Vary over many orders of magnitude in interesting parameter range

⇒ Multiple experimental approaches, with different strategies for fighting backgrounds

- $\ell_d \gg \text{cm}$: beam dump; low background
- $\ell_d \sim \text{cm}$: vertex; limited by instrumental bkg
- $\ell_d \ll \text{cm}$: bump hunt; fight bkg with high intensity, resolution
• Past beam dumps:
  [Bjorken, Essig, Schuster, Toro ’09]
  - SLAC E137:
    30 C, 20 GeV, 200 m, 200 m
  - SLAC E141:
    .3 mC, 9 GeV, 10 cm, 35 m
  - Fermilab E774:
    .8 nC, 275 GeV, 30 cm, 7 m
• **Past beam dumps:**
  
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• **New beam dump suggested:**
  
  [Bjorken, Essig, Schuster, Toro ’09]

  – Low power W beam dump
    .3 C, 200 MeV, 20 cm, 50 cm
    .1 C, 6 GeV, 3.9 m, 7 m
• New experiment at DESY?
  
  - DarkDESY at DESY II
    
    [Andreas, Bechtle, Ehrlichmann, Garutti, Gregor, Lindner, Meyners, Redondo, AR]
    
    $\sim 10 \text{ nA with } 0.45 - 7 \text{ GeV}$
• New experiment at DESY?

  – DarkDESY at DESY II

  [Andreas, Bechtle, Ehrlichmann, Garutti, Gregor, Lindner, Meyners, Redondo, AR]

  * ~ 10 nA with 0.45 - 7 GeV
  * first estimates of beam dump sensitivity
  * detector (spare parts of HERA experiments) will be installed this month
  * if background handable, full proposal in spring; experiment could be done in 2010
• **Complementary region** can be probed by thin target bump hunt experiment: need very high integrated luminosity and high resolution (trident) spectrometer

[Bjorken, Essig, Schuster, Toro '09]

⇒ **New experiment at JLab?**

− **Fixed-target experiment in CEBAF Hall A**

[Hall A Collaboration]

* 80 $\mu$A at 2 ÷ 4 GeV
* proposed for period after CEBAF upgrade, but could also be done earlier: only target needed

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3. Conclusions

• A low-energy, high intensity frontier is forming worldwide:
  
  Searching for physics beyond the standard model with intense photon and electron beams

• These laboratory experiments have considerable discovery potential for light particles beyond the standard model, for which there is a strong physics case both from theoretical as well as from phenomenological considerations:
  
  – axions
  – axion-like particles
  – hidden-sector U(1) gauge bosons

• Huge range of masses and couplings to be explored ⇒ Need to attack the dark forces with various “weapons”, ranging from lasers to the LHC!