Search for Dark Neutrino via Vacuum Magnetic Birefringence Experiment

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Including Dark Matter as New Physics

Dark Matter Search

DM:
• $\psi \times 1$
• $\mathcal{P}$ with $B'_{\mu}$

Including $P$ Interaction

V-A interaction
Need to Calculate Effective Lagrangian
→ Vacuum Birefringence Experiment

**QED Case**


**Heisenberg-Euler Lagrangian:**

\[
\mathcal{L} = -\frac{1}{8\pi^2} \int_0^\infty dss^{-3} \exp(-m^2s) \times \left[ \frac{\text{Re } \cosh s}{\text{Im } \cosh s} - 1 - \frac{2}{3} (es)^2 \mathcal{F} \right]
\]

\[
= \frac{1}{2} (E^2 - H^2) + \frac{2\alpha^2 (\hbar/mc)^3}{45 mc^2} \times [(E^2 - H^2)^2 + 7(E \cdot H)^2] + \cdots
\]

\[
\mathcal{L}_{\text{eff}} = -\frac{1}{4} F_{\mu\nu}^2 + \quad + \quad \cdots
\]

- constant background electromagnetic field \( F_{\mu\nu} \)
- electron 1-loop diagrams

\[
X = \sqrt{2(\mathcal{F} + i\mathcal{G})}, \quad \mathcal{F} = \frac{1}{4} F_{\mu\nu} F^{\mu\nu} = \frac{1}{2} \left( \vec{H}^2 - \vec{E}^2 \right), \quad \mathcal{G} = \frac{1}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} = \vec{E} \cdot \vec{H}
\]

\[
\tilde{F}_{\mu\nu} = \frac{1}{2} \epsilon_{\mu\nu\lambda\rho} F^{\lambda\rho}
\]

from J. Schwinger, Phys. Rev. **82**, 664 (1951)
Dark Sector Case (1/3)

\[ \mathcal{F} = \frac{1}{4} F_{\mu\nu} F^{\mu\nu} = \frac{1}{2} \left( B^2 - \bar{E}^2 \right) \]

\[ \mathcal{G} = \frac{1}{4} F_{\mu\nu} \bar{F}^{\mu\nu} = \bar{E} \cdot \bar{B} \]

\[ \mathcal{L}_{\text{eff}} = E_y \ll m_{\text{DM}} \]

\[ \mathcal{L}_{\text{eff}} = -\mathcal{F} + a\mathcal{F}^2 + b\mathcal{G}^2 + ic\mathcal{F}\mathcal{G} \]

We calculated here including coefficients a, b, c

\[ \sim \frac{g^4}{m^4} \]

+ ... ignore higher dimensional terms
Dark Sector Case (2/3)

\[ \tilde{A}^\mu = A^\mu_{SM} + \chi B'^\mu \quad \chi \ll 1 \]

- photon in our theory (massless)
- ordinary photon in SM
- extra U(1) gauge boson

\[ \mathcal{L} = \bar{\psi}_\text{DM} \gamma^\mu (i \partial_\mu - (g_V + g_A \gamma_5) B'_\mu) - m_{DM} \psi_\text{DM} \]
Dark Sector Case (3/3)

• Effective Lagrangian of Fourth Order

\[ \mathcal{L}_{\text{eff}} = -\mathcal{F} + \chi^4 (a\mathcal{F}^2 + b\mathcal{G}^2 + ic\mathcal{F}\mathcal{G}) \]

\[ \mathcal{F} = \frac{1}{4} F_{\mu\nu} F^{\mu\nu} = \frac{1}{2} \left( \vec{B}^2 - \vec{E}^2 \right) \]
\[ \mathcal{G} = \frac{1}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} = \vec{E} \cdot \vec{B} \]

\[ a = \frac{1}{(4\pi)^2 m^4} \left( \frac{8}{45} g_V^4 - \frac{4}{5} g_V^2 g_A^2 - \frac{1}{45} g_A^4 \right) \]
\[ b = \frac{1}{(4\pi)^2 m^4} \left( \frac{14}{45} g_V^4 + \frac{34}{15} g_V^2 g_A^2 + \frac{97}{90} g_A^4 \right) \]
\[ c = \frac{1}{(4\pi)^2 m^4} \left( \frac{4}{3} g_V^3 g_A + \frac{28}{9} g_V g_A^3 \right) \]

\( c = 0 \) when \( g_A \) or \( g_V \) is 0

We followed a method developed by Schwinger

J. Schwinger, Phys. Rev. 82, 664 (1951)
Vacuum Magnetic Birefringence Experiment (1/5)


- OVAL (Observing Vacuum with Laser) experiment

**Conventional**

\[ \varepsilon(-45^\circ) \]

\[ \varepsilon_f = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ -1 \\ 0 \end{pmatrix} \]

**Tabletop experiment**


- BMV experiment


- PVLAS experiment

To see QED 1-loop effect (not yet observed)
refringence:
changing phase velocity of the light

birefringence:
changing phase velocity of 2 light polarizations in different ways

refractive index: $n$
phase velocity: $v$

\[ n = \frac{1}{v} \]
To detect birefringence, we observe a difference of polarization state.

1) Ellipticity

- initial polarization
- birefringence
- final polarization

2) Direction of the long axis of an ellipse

- initial polarization
- birefringence
- final polarization

ex) dark sector in our model with $P$

ex) QED

Vacuum Magnetic Birefringence Experiment (3/5)
Vacuum Magnetic Birefringence Experiment (4/5)

To detect $P$ interaction, we propose a new method

\[ \varepsilon(-45^\circ) \]

\[ \varepsilon_f = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ -1 \\ 0 \end{pmatrix} \]

QED:

- refractions are occurred for parallel (from magnetic field) or perpendicular polarization modes in different ways
- Polarization with 45 degrees includes both modes.
- We detect -45 degrees to see reflections

\[ \Delta \]

- No QED background

- refractions are occurred for parallel or perpendicular polarization modes in different ways
- Polarization with parallel includes both modes.
- We detect perpendicular to see reflections
Vacuum Magnetic Birefringence Experiment (5/5)

To detect $P$ interaction, we propose a new method

Conventional

$\mathbf{\epsilon}_f = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ -1 \\ 0 \end{pmatrix}$

$\mathbf{\epsilon}_i = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 1 \\ 0 \end{pmatrix}$

Fabry-Perot resonator

$\mathbf{\epsilon} \rightarrow -\mathbf{\epsilon}$

$P$ is reduced if only 2 mirrors

Ours

$\mathbf{\epsilon}_f = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}$

$\mathbf{\epsilon}_i = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}$

Ring Fabry-Perot resonator

$\mathbf{\epsilon} \rightarrow \mathbf{\epsilon}$

$P$ is reduced if only 2 mirrors
Dark neutrino

\[ \mathcal{L} = \bar{\psi}_{\text{DM}} [\gamma^\mu (i \partial_\mu - (g_V + g_A \gamma_5) B'_\mu) - m_{\text{DM}}] \psi_{\text{DM}} \]

We assume \( g_A = - g_V (= |e|) \) to obtain the experimental constraint

\[ \nabla - A \text{ current: Dark neutrino} \]

We examine the case, having both the electron and the lightest DS neutrino. For the DS search, QED forms the background to the DS signal.

\[ a = a_{\text{QED}} + \chi^4 a_{\text{DS}\nu'}, \quad b = b_{\text{QED}} + \chi^4 b_{\text{DS}\nu'}, \quad \text{and} \quad c = \chi^4 c_{\text{DS}\nu'} \]
Allowed region

\[ 10^{-6} \leq \chi \leq 10^{-3} \]
\[ m_{\tilde{B}'} \geq 1 \text{ GeV} \]


At VMB experiment, the sensitivity does not depend on dark photon mass.
Conventional, QED/Dark neutrino

\[ k_1 = \frac{\text{ellipticity} \lambda}{\pi |B|^2 L} \]

- QED
- Dark neutrino

Experimental Limit

- Experimental Limit

laser energy: 1 - 4 eV

\[ n_\parallel - n_\perp = \frac{2}{15} \left( \frac{\alpha^2}{m_e^4} \right) B^2 = 4 \times 10^{-24} (B[T])^2 \]

\[ \Psi = \pi (n_\parallel - n_\perp) \frac{L}{\lambda} \]

\( \uparrow \) Exclude region

~100!
New set up, dark neutrino only

No QED background

Experimental Limit

$\kappa_2 = \frac{(\text{polarization rotation}) \lambda}{\pi |B|^2 L}$

$k_2$ with $m_{\nu_e} = 10$ eV

$k_2$ with $m_{\nu_e} = 100$ eV

$k_2$ with $m_{\nu_e} = 1000$ eV

Exclude region

allowed

dark neutrino
Summary

1. We considered Parity violated dark sector model, and derived generalized Heisenberg-Euler formula

2. Our focus lay on light-by-light scattering effective Lagrangian of fourth order and gave a result:

\[
\mathcal{L}_{\text{eff}} = -\mathcal{F} + a\mathcal{F}^2 + b\mathcal{G}^2 + ic\mathcal{F}\mathcal{G}
\]

\[
\mathcal{F} = \frac{1}{4} F_{\mu\nu} F^{\mu\nu} = \frac{1}{2} \left( \mathcal{B}^2 - \mathcal{E}^2 \right) \quad \mathcal{G} = \frac{1}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} = \mathcal{E} \cdot \mathcal{B}
\]

\[
a = \frac{1}{(4\pi)^2 m^4} \left( \frac{8}{45} g_V^4 - \frac{4}{5} g_V^2 g_A^2 - \frac{1}{45} g_A^4 \right)
\]

\[
b = \frac{1}{(4\pi)^2 m^4} \left( \frac{14}{45} g_V^4 + \frac{34}{15} g_V^2 g_A^2 + \frac{97}{90} g_A^4 \right)
\]

\[
c = \frac{1}{(4\pi)^2 m^4} \left( \frac{4}{3} g_V g_A + \frac{28}{9} g_V g_A^3 \right)
\]

3. We focused on Vacuum Magnetic Birefringence Experiment to probe the dark sector and proposed new polarization state and the ring resonator in stead of the usual Fabry-Perot resonator to measure the Parity violated term
Backup
We consider a dark matter model where a dark matter candidate couples to photons via an extra U(1) mediator and assume that this dark matter candidate is a fermion and can couple to the mediator with parity violation. We derived a low energy effective Lagrangian including a parity violated term for light-by-light scattering by integrating out the dark matter fermion. Our focus lies on Vacuum Magnetic Birefringence Experiment to probe the dark sector. We propose the ring resonator (3-4 mirrors) with an appropriate polarization state of light in stead of a usual Fabry-Perot resonator (2 mirrors) with a conventional polarization state of light to measure the Parity violated term. We assume that a dark neutrino is a dark matter, i.e. V-A current, and give constraints on model parameters from a current experimental limit. PTEP 2017 no. 12, 123B03 (2017) (arXiv: 1707.03308 [hep-ph]), arXiv:1707.03609 [hep-ph]
Dark Matter Model (1/3)

SM + $U'(1)_Y + 1$ Complex Scalar

\[ \mathcal{L}_S = \left| \left( i \partial_\mu - g_1 Y_s B_\mu - g'_1 Y'_s B'_\mu \right) S(x) \right|^2 \]

spontaneously broken

\[ \langle S' \rangle = v_s / \sqrt{2} \]

\[ \mathcal{L}_{\text{mixing}} = \frac{1}{2} m_{B'}^2 \left( \varepsilon^2 B_\mu B^\mu + 2 \varepsilon B_\mu B'_\mu + B'_\mu B'^\mu \right) \]

\[ m_{B'} = g'_1 Y'_s v_s \quad \varepsilon \equiv \frac{g_1 Y_s}{g'_1 Y'_s} \]
$m_{B'} = g'_1 Y'_s \nu_s$

**Dark Matter Model (2/3)**

$L_{\text{mixing}} = \frac{1}{2} m_{B'}^2 \left( \varepsilon^2 B_\mu B^\mu + 2\varepsilon B_\mu B'^\mu + B'_\mu B'^\mu \right)$

mass diagonalization

$(m_A)^2 = 0$, $(m_{\tilde{Z}})^2 = \frac{1}{4} v^2 \left( g_1^2 + g_2^2 \right) + \varepsilon^2 \frac{g_1^2}{g_1^2 + g_2^2 - \alpha'} (m_{B'})^2$, and

$(m_{\tilde{B}'})^2 = (m_{B'})^2 \left( 1 + \varepsilon^2 \frac{g_2^2 - \alpha'}{g_1^2 + g_2^2 - \alpha'} \right)$.

$\tilde{A}_\mu = \frac{g_1 A_\mu^3 + g_2 B_\mu}{\sqrt{g_1^2 + g_2^2}} - \varepsilon \frac{g_2}{\sqrt{g_1^2 + g_2^2}} B'_\mu$

We assume $\varepsilon \ll 1$
Dark Matter Model (3/3) 

\[ \tilde{A}_\mu = \frac{g_1 A^3_\mu + g_2 B_\mu}{\sqrt{g_1^2 + g_2^2}} - \varepsilon \frac{g_2}{\sqrt{g_1^2 + g_2^2}} B'_\mu \]

\[ \mathcal{L}'_{\text{eff}} = \chi^4 \left\{ a \mathcal{F}^2 + b \mathcal{G}^2 + ic \mathcal{F} \mathcal{G} \right\} \]

\[ S_\psi(m) = \int d^4x \, \overline{\psi}_{DM} \left[ \gamma^\mu \left( i \partial_\mu - (g_V + g_A \gamma_5) B'_\mu \right) - m \right] \psi_{DM} \]
2 conditions

\[ \frac{h\nu_{\text{laser}}}{1 \text{ eV}} \ll mc^2 \]

\[ \frac{\hbar x e |B|}{10 \text{ Tesla}, (1 \text{ Tesla} \sim 200 \text{ eV}^2)} \ll m^2 c^2 \]
Vacuum Magnetic Birefringence Experiment: laser beam energy

beam energy 1.16 eV @OVAL experiment

For 2 mirrors system: 1 ~ 4 eV

laser energy itself:

m eV ~ 10 k eV are available

thanks to X-ray Free Electron Laser