Oscillations to hidden photon in reactor and accelerator experiments

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XXth International Seminar on High Energy Physics
QUARKS-2018

Roschino, Valdai, Russia
Talk is **based on** and **aimed at stimulating**

- D.G., A.Makarov, I.Timiryasov, arXiv:1411.4007
- ... TEXONO, DANSS,...
- NA64, invisible and visible modes
- SHiP $\nu_\tau$-detector..., when it is fixed
- DUNE Near Detector..., when it is fixed
- exps at Fermilab ?, T2K ?, ...
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Motivation for New Physics at 1 GeV

Widely accepted statements: phenomenology

- Standard Model nicely explains almost all results of particle physics experiments
- We definitely need New particle Physics
  - neutrino oscillations (Nobel Prize 2015)
  - baryon asymmetry
  - dark matter
  - inflation-like stage in the early Universe
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- New Heavy particle contribution to the Higgs boson mass lifts it up but miraculously $m_h \sim E_{EW}$
Guesswork: a logically possible option

- All the new particles are at (below) $E_{EW}$ then quantum contributions to $m_h \sim E_{EW}$ are safe
- Why so far no evidences for such light New Particles ?
- They are only feebly coupled to the Standard Model
  - they are SM gauge singlets (not a GUT)
  - new Yukawa-type couplings ?
  - portal-like couplings ?
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Disclaimer and the main task

- There are no general theoretical motivation for the New Particles to be of (sub)GeV mass but for the feebly coupled light particle best place to show up is the intensity frontier.
- Moreover, there are many concrete BSM theories which suggest such theoretical motivations.
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Three Portals to the hidden World

Renormalizable interaction including SM field and new (hypothetical) fields singlets with respect to the SM gauge group

Attractive feature: couplings are insensitive to energy in c.m.f., hence low energy experiments (intensity frontier) are favorable

- **Scalar portal**: SM Higgs doublet $H$ and hidden scalar $S$
  
  \[ \mathcal{L}_{\text{scalar portal}} = -\beta H^\dagger HS^\dagger S \]

- **Spinor portal**: SM lepton doublet $L$, Higgs conjugate field $\tilde{H} = \varepsilon H^*$ and hidden fermion $N$ sterile neutrino !!
  
  \[ \mathcal{L}_{\text{spinor portal}} = -y \bar{L} \tilde{H} N \]

- **Vector portal**: SM gauge field of $U(1)_Y$ and gauge hidden field of abelian group $U(1)'$
  
  \[ \mathcal{L}_{\text{vector portal}} = -\frac{\varepsilon}{2} B_{\mu \nu}^{U(1)_Y} B_{\mu \nu}^{U(1)'} \]
Massive vectors (paraphotons)

Vector portal to a secluded sector:
one more $U(1)'$ gauge group [spontaneously broken] in secluded sector

$$\mathcal{L}_{\text{DM+mediator}} = \bar{\psi} \left( i \gamma^\mu \partial_\mu - e' \gamma^\mu A'_\mu - m_\psi \right) \psi - \frac{1}{4} A'_{\mu \nu} A'^{\mu \nu} + \frac{m^2_\gamma}{2} A'_\mu A'^\mu + \epsilon A'_\mu \partial_\nu B^\mu_\nu$$

when $m_\psi > m_\gamma' \sim 1 \text{ GeV}$

- limit from BBN:
  $$\tau_V < 1 \text{ s}, \quad \Rightarrow \epsilon^2 \left( \frac{m_\gamma'}{1 \text{ GeV}} \right) \gtrsim 10^{-21}$$

- light for $(g-2)$
- light for Pamela, Fermi, etc

Production by virtual photon $\sigma \propto \epsilon^2$

Decay through virtual photon, $\Gamma \propto \epsilon^2$

$V \to e^+ e^-, \mu^+ \mu^-$, etc

Illustration with concrete examples

Vector portal: hidden photon

Dmitry Gorbunov (INR)
Massive vectors: decays are under control

Decay into SM via mixing with photon

into leptons

$$\Gamma_{A'}^{l^+ l^-} = \frac{1}{3} \alpha_{\text{QED}} m_{A'} e^2 \sqrt{1 - \frac{4 m_l^2}{m_{A'}^2}} \left(1 + \frac{2 m_l^2}{m_{A'}^2}\right),$$

into hadrons

$$\Gamma_{A'}^{\text{hadrons}} = \frac{1}{3} \alpha_{\text{QED}} m_{A'} e^2 \cdot R(m_{A'}),$$

where

$$R(\sqrt{s}) = \frac{\sigma(e^+ e^- \rightarrow \text{hadrons})}{\sigma(e^+ e^- \rightarrow \mu^+ \mu^-)}$$

and

$$\Gamma_{A'}^{\text{tot}} = \Gamma_{A'}^{e^+ e^-} + \Gamma_{A'}^{\mu^+ \mu^-} + \Gamma_{A'}^{\text{hadrons}}$$

Dmitry Gorbunov (INR)
Massive vectors: production by protons

- decays of \( \pi^0, \eta^0 \) and \( \rho^\pm, \rho^0, \omega \)

\[
\text{Br}_{\pi^0 \rightarrow A' \gamma} \approx 2 \varepsilon^2 \left( 1 - \frac{m_{A'}^2}{m_{\pi^0}^2} \right)^3 \text{Br}_{\pi^0 \rightarrow \gamma \gamma}
\]

- proton bremsstrahlung
  concervatively corrected by the Dirac (electric) form factor of proton

\[
F_1 = \frac{1}{\left( 1 + \frac{q^2}{m_D^2} \right)^2} \rightarrow \frac{1}{m_{A'}^4}
\]

with Dirac mass squared \( m_D^2 = 12/r_D^2 \)
and the Dirac radius \( r_D \approx 0.8 \text{ fm} \)

- quark bremsstrahlung
High Intensity frontier: photon sources

- modern proton beams: JPARC, Fermilab, CERN SPS presently operating or under construction
  $10^{20} \sim 10^{21}$ PoT per year
  T2K, DUNE, SHiP, ...​

- Nuclear power plants, thermal power $ThP \sim GW$
  measurements of photon spectrum
  $(E_\gamma > 200\text{ keV})$ from FRJ-1 reactor core

$$\frac{dN_\gamma}{dE_\gamma} \approx 0.6 \times 10^{21} \times \frac{ThP}{GW} \times e^{-\frac{E_\gamma}{0.91\text{ MeV}}} ,$$

TEXONO, NEOS, DANSS, ...​
Actually all neutrino oscillation experiments

light shining through the wall

reactor: $\gamma \rightarrow \gamma'$
detector: $\gamma' + e^- \rightarrow e^- \text{ mimics } \bar{\nu} + e^- \rightarrow e^-$

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Actually all neutrino oscillation experiments

light shining through the wall

**reactor**: \(\gamma \rightarrow \gamma'\)
**detector**: \(\gamma' + e^- \rightarrow e^-\) mimics \(\bar{\nu} + e^- \rightarrow e^-\)
Results based on Compton scattering

$$\frac{\lambda}{10^{14} \text{ cm}} = 2\pi \frac{10^{18} \text{ eV}}{m_{A'}}$$

10 astronomical units !!
Something is wrong. . .

How do we describe very light particles which mix to each other? . . .

say, neutrino. . . ?

. . . but oscillations, of course!
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say, neutrino...?

...but oscillations, of course!
Description

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu}^2 - \frac{1}{4} X_{\mu\nu}^2 - \frac{\epsilon}{2} X_{\mu\nu} F^{\mu\nu} + \frac{m_X^2}{2} X_{\mu}^2 - e A_{\mu} j_{e\mu}^\mu$$

One can make kinetic term diagonal by

$$X_{\mu} \rightarrow X_{\mu} + \epsilon A_{\mu}$$

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu}^2 - \frac{1}{4} X_{\mu\nu}^2 + \frac{m_X^2}{2} (X_{\mu} + \epsilon A_{\mu})^2 - e A_{\mu} j_{e\mu}^\mu + \mathcal{O}(\epsilon^2)$$

keeping $X_{\mu}$ sterile with respect to $U(1)_{em}$

and similar to the neutrino having mixing in the mass matrix
Production of a mixed state

vacuum oscillations: \[ P(A \rightarrow X) = (2\varepsilon)^2 \sin^2 \left( \frac{m_X^2 L}{4E} \right) \]
Mass-state separation: coherence loss in vacuum

Photons come from decaying fission fragments \( \tau = 10^{-12} - 10^{-11} \text{ s} \)

Initial width: \( \sigma \sim 1/\tau \sim 0.03 - 0.3 \text{ cm} \)

Shorter than oscillation length

\[
L_{\text{osc}} \approx 2.5 \text{ cm} \times \frac{E_{\gamma}}{1 \text{ MeV}} \left( \frac{10 \text{ eV}}{m_{\chi}} \right)^2
\]

\( I_{\text{coh}} \sim 6 \times 10^{8-9} \text{ cm} \times \left( \frac{E_{\gamma}}{1 \text{ MeV}} \right)^2 \left( \frac{10 \text{ eV}}{m_{\chi}^2} \right)^2 \)

Always exceeds \( L_{\text{osc}} \)
Hidden photons from reactor: matter effect

- Photons 'get mass' in matter

  in water \( m_\gamma \sim 20 \text{ eV} \)

  hence \( m_X^2 \rightarrow \Delta m^2 \equiv \sqrt{(m_X^2 - m_\gamma^2)^2 + 4\varepsilon^2 m_X^4} \)

  always exceed \( m_\gamma \sim 20 \text{ eV} \) (except resonance \( m_X = m_\gamma \))

- Photons rescatter and 'get absorbed' in matter

  in water for \( E = 1 - 10 \text{ MeV} \) we have \( 1/\Gamma \sim 10 \text{ cm} \)

- The net result at distances \( \gg 1/\Gamma \)

  \[
P = \varepsilon^2 \times \frac{m_X^4}{(\Delta m^2)^2 + E_\gamma^2 \Gamma^2}
\]
Illustration with concrete examples

Vector portal: hidden photon

Oscillations at various situations

In the source (reactor core) of size \( \gg 1/\Gamma \)

\[
P = \varepsilon^2 \times \frac{m_X^4}{(\Delta m^2)^2 + E_\gamma^2 \Gamma^2} = \frac{(\varepsilon m_X^2)^2}{(m_X^2 - m_\gamma^2)^2 + E_\gamma^2 \Gamma^2}
\]

low absorption \( E_\gamma \Gamma \approx 2 \times \left( \frac{E_\gamma}{1 \text{ MeV}} \right) \left( \frac{10 \text{ cm}}{1/\Gamma} \right) \text{ eV}^2 \ll m_\gamma^2 \sim (20 \text{ eV})^2 \)

- \( m_X \gg m_\gamma \implies P = \varepsilon^2 \)
- \( m_X \ll m_\gamma \implies P = \varepsilon^2 \times \left( \frac{m_X}{m_\gamma} \right)^4 \)
- resonance \( m_X \approx 10 \text{ eV} \implies P = 10^5 \varepsilon^2 \)

In the detector (e.g. prompt \( e^- \)) of size \( \gg 1/\Gamma \)

\[
P = \varepsilon^2 \times \frac{m_X^4}{(\Delta m^2)^2} = \frac{(\varepsilon m_X^2)^2}{(m_X^2 - m_\gamma^2)^2}
\]
Limits from TEXONO: \( N_S \propto \varepsilon^2 \times \varepsilon^2 \)
Resonance region... $m_X = m_\gamma$

both reactor core and detector are highly inhomogeneous

Requires a good knowledge of the source internal structure

Can be done by the Neutrino Collaborations
Accelerator experiments: NA64, invisible mode, $\propto \varepsilon^2$

Illustration with concrete examples

Vector portal: hidden photon

Oscillations to hidden photon

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31.05.2018, QUARKS-2018
Accelerator experiments: NA64, invisible mode, $\propto \varepsilon^2$

- 'missed' secondary photons of $E_\gamma \sim 50 - 100 \text{ GeV}$
  
  \[ L_{\text{osc}} \approx 25 \text{ cm} \times \frac{E_\gamma}{100 \text{ GeV}} \frac{(1 \text{ keV})^2}{m_X^2} \]

- lead dump: $m_\gamma \approx 60 \text{ eV}$ $1/\Gamma = 1 \text{ cm}$

- high absorption

\[ E_\gamma \Gamma \approx \left( \frac{E_\gamma}{100 \text{ GeV}} \right) \left( \frac{1 \text{ cm}}{1/\Gamma} \right) (1 \text{ keV})^2 \gg m_\gamma^2 \approx (60 \text{ eV})^2 \]

Consequently

- $m_X \gg 1 \text{ keV} \implies P = \varepsilon^2$
- $m_X \ll 1 \text{ keV} \implies P = \varepsilon^2 \times (m_X/1 \text{ keV})^4$
- no resonance at $m_X = m_\gamma$
NA64 sensitivity to invisible vectors

\[
\begin{align*}
\varepsilon &\quad 10^{-2} \quad 10^{-1} \quad 10^{0} \quad 10^{1} \\
M_A'[\text{GeV}] &\quad 10^{-6} \quad 10^{-5} \quad 10^{-4} \quad 10^{-3} \quad 10^{-2} \quad 10^{-1} \quad 10^{0} \quad 10^{1}
\end{align*}
\]

- \((g-2)\mu\)
- \((g-2)e\)
- E787, E949
- BaBar

NA64: EOT=4\times10^{10}
NA64: EOT=4\times10^{11}
NA64: EOT=4\times10^{12}
Exploiting resonance region with NA64

Other material? No way...

\[ m_\gamma^2 \propto n, \quad \Gamma \propto n \]

need lower energies \( E \sim 1 \text{ GeV} \)
Developing projects: SHiP, . . . DUNE?

**SHiP**: protons of $E = 400$ GeV on target (W-Mo) produce pions:

$$E_\gamma \lesssim 10 \text{ GeV}$$

look for a hit in the $\nu_\tau$-detector,

- non-resonance case: high absorption

$$L_{osc} \approx 5 \text{ cm} \times \frac{E_\gamma}{10 \text{ GeV}} \frac{(700 \text{ eV})^2}{m_X^2}$$

$$E_\gamma \Gamma \approx \left(\frac{E_\gamma}{10 \text{ GeV}}\right) \left(\frac{0.5 \text{ cm}}{1/\Gamma}\right) (700 \text{ eV})^2 \gg m_\gamma^2 \sim (100 \text{ eV})^2$$

critical mass is $m_X = 700$ eV

- resonance case: take soft neutral pions, $E_\pi \sim 0.5$ GeV

$$E_\gamma \Gamma \approx \left(\frac{E_\gamma}{250 \text{ MeV}}\right) \left(\frac{0.5 \text{ cm}}{1/\Gamma}\right) (100 \text{ eV})^2 \sim m_\gamma^2 \sim (100 \text{ eV})^2$$
Summary

- Oscillations generically suppress production of light hidden photons

\[ P = \varepsilon^2 \rightarrow P = \varepsilon^2 \times \left( \frac{m_X}{m_{\text{crit}}} \right)^4 \]

where

\[ m_{\text{crit}} = MAX[m_\gamma, E_\gamma \Gamma] \]

so the sensitivity to light vectors is lost

- One can check for resonance amplification, when . . .

\[ m_X^2 = m_\gamma^2 \gtrsim E_\gamma \Gamma \]

- Extra bonus: secondary photons . . .
Backup slides