Superradiant Searches for Dark Photons in Two Stage Atomic Transitions

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Dark photons

\[ \mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + m^2 A'_\mu A'^\mu - \left( A_\mu + \chi A'_\mu \right) J_{EM}^\mu \]

U(1) vectors mixed with the SM photon appear in many SM extensions

**SUSY breaking sectors**

Dienes Kolda March-Russell 1998

**String compactifications**

Goodsell Jaeckel Redondo Ringwald 2008

**Dark sectors**

Pospelov 2008
Arkani-Hamed Finkbeiner Slatyer Weiner 2008
Ackerman Buckley Carroll Kamionkowski 2008
Light Shining Through Walls

Searches for dark photons currently use cavities to detect the dark photons coming through the wall, (ALPS II).
Stellar emission with longitudinal mode

Stellar emission bounds currently leading for $\sim \text{meV}^+$. 

An, Pospelov, Pradler 1302.3884
Raffelt 1996
Light Shining Through Walls

ALPS II focusing on axion detection.
Superradiance describes the collective (de-)excitation of atoms that emit or absorb photons coherently.

\[
\Delta k \Delta x \sim 1 \\
V \sim \frac{1}{k_1^3} \quad \text{coherence volume momentum limited}
\]

\[
\Gamma = nV \Gamma_0 \quad \text{No SR}
\]

\[
\Gamma_{tot} = n^2 V^2 \Gamma_0 \quad \text{SR}
\]

Analogy to Spin-Independent Direct Detection: sum over emitters versus sum over nucleons in amplitude, squared.

\[
\sigma \propto N^2 \sigma_n
\]
Macro Superradiance

Classic superradiance is limited by the frequency of the photon emitted. Macro superradiance minimizes the momenta of emitters with back-to-back two photon emission.

\[
V_{mac} \sim \frac{1}{|\vec{k}_1 + \vec{k}_2|^3} 
\]

\[
\Gamma_{tot} = n^2 V_{mac}^2 \Gamma_0 
\]
Macro Superradiance

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\[ \Delta \vec{k} = \vec{k}_1 + \vec{k}_2 = \]

\[ V_{mac} \sim \frac{1}{|\vec{k}_1 + \vec{k}_2|^3} \]

macro coherence volume

\[ \Gamma_{tot} = n^2 V_{mac}^2 \Gamma_0 \]

macro SR

\[ \Gamma_{sp} = \int \frac{d^3k_1}{(2\pi)^3} \frac{d^3k_2}{(2\pi)^3} \int d^3r \sum_{a=1}^{N} a_{eg} \frac{4}{4\omega_1\omega_2} \sqrt{\frac{V^2}{2}} e^{-i(\vec{k}_1 + \vec{k}_2 - \vec{k}_{eg}^a)(\vec{r} - \vec{r}_a)} \left[ 2\pi \delta(\omega_{eg} - \omega_1 - \omega_2) \right]^2 \]

Macro-coherent when phase difference minimized, \( |\vec{k}_{eg}^a| \ll |\vec{r} - \vec{r}_a| \).
Macro Coherence in Parahydrogen

$\text{pH}_2$’s first vibrational excitation state electric dipole (E1) transition parity forbidden, leading transition is two photon (E1xE1).
Macro Coherence in Parahydrogen

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This \(~0.5\) eV vibrational mode is the lowest lying state, along with easily attainable 10 ns decoherence times, this makes \( \text{pH}_2 \) a good medium for macro coherence.

| pH\(_2\) Reference | Density (cm\(^{-3}\)) | Temperature (K) | Decoherence Time (ns) |
|--------------------|-------------------------|-----------------|------------------------|
| 57                 | \(10^{19} - 10^{20}\)  | 80-500          | \(~10\)                |
| 42                 | \(5.6 \times 10^{19}\) | 78              | \(~8\) (est)           |
| 37                 | \(10^{19} - 5 \times 10^{20}\) | 78              | \(~10\) (est)           |
| 58                 | \(2.6 \times 10^{22}\) | 4.2             | \(\gtrsim 140\)       |
Macro Coherence in Parahydrogen

\( r_1 \) is the \(|e>,|g>\) Bloch vector where \( r_1 = 1 \) defines fully coherent/in-phase atoms. Our simulations assumed 10 ns decoherence times, and varied laser detuning \( \delta \).
Macro Coherence in Parahydrogen

$r_1$ is the $|e>,|g>$ Bloch vector where $r_1 = 1$ defines fully coherent/in-phase atoms. Our simulations assumed 10 ns decoherence times, and varied laser detuning $\delta$.

- Commercially available lasers have the pulse power necessary to excite $\sim$mg of parahydrogen to full coherence.
- Current record is $r_1 \sim 0.068$.

Motohiko et al. 2015

Superradiant Parahydrogen Target

| Sample Length $L = 30$ cm |
| pH$_2$ Density $n = 10^{21}$ cm$^{-3}$ |
| Pump Laser Freq. $\omega_1 = 0.26$ eV |
| Pump Laser Power $\approx 10^9$ W mm$^{-2}$ |

Bhoonah, JB, Song 2019
Macro Coherence at Queen’s University

One technical challenge is generating enough 10 ns laser pulse power—looking into new methods for simplifying 1064 -> 4806 nm conversion.
Modified search for dark photons:
Use a macro-coherent sample of parahydrogen as a target for a light-shining-through-wall laser.

1. Excite hydrogen to coherent state with back-to-back lasers.
2. Run cavity-amplified light-through-wall laser at same frequency.
3. Look for deexcitation of pH$_2$ during 10 ns coherence window.
4. Calibrate coherence / response of pH$_2$ with cavity laser off.
The transitions for multi-photon emission, in the Standard Model and with a dark photon.

\[ H_I = -d \cdot (\tilde{E}_1 + \tilde{E}_2 + \chi \tilde{E}') \]

electric dipole term from \( E' \)

\begin{align*}
(a) & \; |e\rangle \rightarrow |g\rangle + \gamma + \gamma \\
(b) & \; |e\rangle \rightarrow |g\rangle + \gamma + \gamma
\end{align*}

The gain over traditional light-shining-through-wall regeneration cavity is that the dark photon field acts as a trigger laser for two photon emission.

\[ \Gamma = \frac{1}{8\pi} |a_{eg}|^2 |\rho_{ge}|^2 N^2 \omega_1^3 |E'|^2 \]
Maxwell’s equations with the E1xE1 transition Hamiltonian are integrated over the experimental volume to determine the power emitted in photons from the sample, start from \( r_1 = 1 \).

\[
\begin{align*}
(\partial_t - \partial_z)E_1 &= \frac{i\omega n}{2} \left[ \left( \frac{a_{ee} + a_{gg}}{2} + \frac{a_{ee} - a_{gg}r_3}{2} \right)E_1 + a_{eg}(r_1 - ir_2)(E_2^* + \chi \eta E'^*) \right], \\
(\partial_t + \partial_z)E_2 &= \frac{i\omega n}{2} \left[ \left( \frac{a_{ee} + a_{gg}}{2} + \frac{a_{ee} - a_{gg}r_3}{2} \right)(E_2 + \chi \eta E') + a_{eg}(r_1 - ir_2)E_1^* \right], \\
(\partial_t + \partial_z)E' &= \frac{i\omega n}{2} \left[ \left( \frac{a_{ee} + a_{gg}}{2} + \frac{a_{ee} - a_{gg}r_3}{2} \right)(2\chi^2 \eta E' + \chi E_2) + a_{eg}(r_1 - ir_2)\chi \eta E_1^* \right]
\end{align*}
\]
Using a cavity laser comparable to ALPS I, and a pH$_2$ macro coherence setup similar to a lower power test run [Hiraki et al. 2018], ~10 signal photons for $N_{\text{rep}} = 1000$, $m_A' = 0.1$ meV, $\chi = 10^{-9}$. 

| Dark Photon Generating Cavity | Superradiant Parahydrogen Target |
|-------------------------------|----------------------------------|
| Cavity Length $l = 50$ cm     | Sample Length $L = 30$ cm        |
| Cavity Reflections $N_{\text{pass}} = 2 \times 10^4$ | pH$_2$ Density $n = 10^{21}$ cm$^{-3}$ |
| Cavity Laser Freq. $\omega' = 0.26$ eV | Pump Laser Freq. $\omega_1 = 0.26$ eV |
| Cavity Laser Power $P_L = 1$ W mm$^{-2}$ | Pump Laser Power $\approx 10^9$ W mm$^{-2}$ |
|                                | pH$_2$ Sample Area $A = 1$ cm$^2$ |
Signal photons scale the mixing parameter (until every atom is de-excited.)

\[ N_s \propto P_L N_{\text{rep}} \chi^4 (N_{\text{pass}} + 1) \sin^2 \left( \frac{m_A^2}{4\omega} l \right) \]

| Dark Photon Generating Cavity | Superradiant Parahydrogen Target |
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| Cavity Reflections \( N_{\text{pass}} = 2 \times 10^4 \) | \( \text{pH}_2 \) Density \( n = 10^{21} \text{ cm}^{-3} \) |
| Cavity Laser Freq. \( \omega' = 0.26 \text{ eV} \) | Pump Laser Freq. \( \omega_1 = 0.26 \text{ eV} \) |
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| \( \_ \_ \_ \) | \( \text{pH}_2 \) Sample Area \( A = 1 \text{ cm}^2 \) |
There is improved reach as the number density of $\text{pH}_2$ increases.
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\[ (\omega_{eg}/2 - k_{A'})L < 1 \]
The extremely nonlinear sensitivity scaling with n (also L, t) can be understood quantitatively and qualitatively. Condense field equations, drop z, r_2, fix r_1:

\[ (\partial_t - \partial_z) E_1 = \frac{k_{\text{m}}}{2} \left( a_{\text{ee}} + a_{\text{gg}} + a_{\text{eg}} r_1 \right) E_1 + a_{\text{eg}} (r_1 - r_2) (E_2 + \chi_{\text{eg}} E_1) \]

\[ (\partial_t + \partial_z) E_2 = \frac{k_{\text{m}}}{2} \left( a_{\text{ee}} + a_{\text{gg}} + a_{\text{eg}} r_1 \right) (E_2 + \chi_{\text{eg}} E_1) + a_{\text{eg}} (r_1 - r_2) E_1 \]

\[ (\partial_t + \partial_z) E_3 = \frac{k_{\text{m}}}{2} \left( a_{\text{ee}} + a_{\text{gg}} + a_{\text{eg}} r_1 \right) (2\chi_{\text{eg}} E_2 + \chi E_3) + a_{\text{eg}} (r_1 - r_2) \chi_{\text{eg}} E_1 \]

\[ (\partial_t^2 - \partial_z^2) E_1 - n^2 \Omega_r^2 E_1 = 0 \]

\[ E_1 \propto e^{n \Omega_r t} \]

\[ \Omega_r \propto \omega a_{\text{eg}} r_1 \]

\[ \text{->Exponential dependence on n, t, r_1} \]

and qualitatively.
The extremely nonlinear sensitivity scaling with $n$ (also $L$, $t$) can be understood quantitatively and qualitatively.

Condense field equations, drop $z$, $r_2$, fix $r_1$

$$
(\partial_t - \partial_z) E_1 = \frac{\kappa \omega m}{2} \left[ \frac{d_{xx} + d_{yy}}{2} + a_{zz} - \frac{d_{zz} + d_{yy}}{2} \right] E_1 + a_{zz}(r_1 - \tilde{r}_2)(E_2 + \chi \eta E^\omega) \\
(\partial_t + \partial_z) E_2 = \frac{\kappa \omega m}{2} \left[ \frac{d_{xx} + d_{yy}}{2} + a_{zz} - \frac{d_{zz} + d_{yy}}{2} \right] E_2 + a_{zz}(r_1 - \tilde{r}_2) E_1^2 \\
(\partial_t + \partial_z) E_2' = \frac{\kappa \omega m}{2} \left[ \frac{d_{xx} + d_{yy}}{2} + a_{zz} - \frac{d_{zz} + d_{yy}}{2} \right] (2 \kappa \eta E^\omega + \chi E_0) + a_{zz}(r_1 - \tilde{r}_2) \chi \eta E_0^2
$$

$$
(\partial_t^2 - \partial_z^2) E_1 - n^2 \Omega_r^2 E_1 = 0
$$

$$
E_1 \propto e^{n \Omega_r t}
$$

$$
\Omega_r \propto \omega a_{eg} r_1
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->Exponential dependence on $n$, $t$, $r_1$

and qualitatively
The extremely nonlinear sensitivity scaling with n (also L, t) can be understood quantitatively and qualitatively.

Condense field equations, drop z, r_2, fix r_1

\[
(\partial_t - \partial_z)E_1 = \kappa u n \left[ \frac{\alpha_x + \alpha_y}{2} + \frac{\alpha_x - \alpha_y}{2} r_1 \right] E_1 + a_0(r_1 - ir_2)(E_2 + \chi \eta E_2),
\]

\[
(\partial_t + \partial_z)E_2 = \kappa u n \left[ \frac{\alpha_x + \alpha_y}{2} + \alpha_x - \alpha_y r_2 \right] (E_1 + \chi \eta E_1) + a_0(r_1 - ir_2)E_2,
\]

\[
(\partial_t + \partial_z)E' = \kappa u n \left[ \frac{\alpha_x + \alpha_y}{2} + \alpha_x - \alpha_y r_1 \right] (2\chi^2 \eta E_2 + \chi E_2) + a_0(r_1 - ir_2)\chi \eta E_1
\]

\[
(\partial_t^2 - \partial_z^2)E_1 - n^2 \Omega^2 E_1 = 0
\]

\[
E_1 \propto e^{n\Omega r t}
\]

\[
\Omega \propto \omega a_{eg} r_1
\]

\[
\rightarrow \text{Exponential dependence on n, t, r_1}
\]

and qualitatively...
- Macro superradiance in parahydrogen can be used to look for weakly coupled fields
- Need to develop $r_1 \sim 1$ in a $\text{pH}_2$ sample, recent progress towards this goal

maybe eventually find neutrino masses and detect cosmic neutrinos

Yoshimura et al. 2007-