Dark Photon Search at Yemilab, Korea

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ABSTRACT: Dark photons are well motivated hypothetical dark sector particles that could account for observations that cannot be explained by the standard model of particle physics. A search for dark photons that are produced by an electron beam striking a thick tungsten target and subsequently interact in a 3 kiloton-scale neutrino detector in Yemilab, a new underground lab in Korea, is proposed. Dark photons can be produced by “darkstrahlung” or by oscillations from ordinary photons produced in the target and detected by their visible decays, “absorption” or by their oscillation to ordinary photons. By detecting the absorption process or the oscillation-produced photons, a world’s best sensitivity for measurements of the dark-photon kinetic mixing parameter of $\epsilon^2 > 1.5 \times 10^{-13} (4.6 \times 10^{-13})$ at the 95% confidence level (C.L.) could be obtained for dark photon masses between 80 eV and 1 MeV in a year-long exposure to a 100 MeV electron beam with 100 kW (10 kW) beam power. In parallel, the detection of $e^+e^-$ pairs from decays of dark photons with mass between 1 MeV and $\sim$80 MeV would have sensitivities of $\epsilon^2 > O(10^{-17})$ at the 95% C.L. for the 100 kW beam power, which are comparable to those of the Super-K experiment.

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1 Introduction

The standard model of particle physics has been very successful at explaining phenomena in the visible universe. However, it has a number of clear limitations. It provides no explanations for dark matter, the muon g-2 anomaly, the $m_{ee} = 17$ MeV $e^+e^-$ excess from $^8$Be that is reported in refs. [1, 2], etc. In order to explain these “beyond the standard model” (BSM) observations, the introduction of a hypothetical sector of new particles and interactions, the dark (or hidden) sector has been proposed. In this scheme, there are only a few portals (or mediators) that connect the dark sector to the visible universe that have significant strength and satisfy Lorentz and gauge symmetries. These are the vector, higgs, neutrino, and axion portals that can be explored with different types of experiments.

In particular, in the vector portal, a dark photon (usually denoted as $A', \phi$, or $\gamma'$), that usually described by an extra $U(1)_D$ gauge symmetry group, is the dark sector particle that could be more readily explored than corresponding particles in the other portals because it can kinetically mix with an ordinary photon. As a result, any experiment that can produce photons and detect photons or leptons can, in principle, explore the vector portal [3].

The Lagrangian that describes the dark photon (DP) is:

$$\mathcal{L} \supset -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu} + \frac{m_{\phi}^2}{2} A'^{\mu} A'^{\mu},$$  \hspace{1cm} (1.1)$$

where $F'_{\mu\nu} \equiv \partial_{\mu} A'_\nu - \partial_{\nu} A'_\mu$ is the DP field strength tensor, $A'_\mu$ is the $U(1)_D$ gauge field, $\epsilon$ is the kinetic-mixing strength between the dark and ordinary photons, and $m_{\phi}$ is the dark photon mass.
The 1988 SLAC beam dump experiment (E137) was the pioneering search for dark photons [4]. More recently, in the last decade, there have been numerous reports of dark photon searches [5–26] based on data from fixed target accelerator experiments, $e^+e^-$ colliders, reactors and astrophysical measurements, that have set stringent limits to the dark photon parameter space. These limits could be further improved or, possibly, a dark-photon signal could discovered, by current or future experiments without huge costs. Figures 1 and 2 show the current constraints (or sensitivities) on $\epsilon$ for $m_\phi < 1$ MeV and $m_\phi > 1$ MeV, respectively; comprehensive reviews on the status of dark photon searches can be found in refs. [27, 28].

Yemilab, a new underground lab that is being constructed in Handuk iron mine in Jeongseon-gun, Korea, will have a cavern that will be capable of hosting a $\sim 3$ kiloton liquid target neutrino detector. A 100 MeV electron accelerator (100 kW or 10 kW beam power) located close to the neutrino detector, would make a dark photon search possible at Yemilab.

In the following sections, the proposed Yemilab neutrino detector 2, expected numbers of produced and detected dark photons 3, and the expected dark photon sensitivity 4 are described. These are followed by a summary 5.

2 A neutrino detector for Yemilab

By early 2022, the 2nd phase construction of Yemilab (~1000 m overburden under the eponymous Mt. Yemi) will be completed and experimental operation will commence (see Fig. 3). In addition to spaces for the upgraded COSINE [30] dark matter and AMoRE-II [31] $0\nu\beta\beta$ search experiments, a cavern suitable for hosting a $\sim 3$ kiloton neutrino detector/target.

**Figure 1**: Current limits on $\epsilon$ for $m_\phi < 1$ MeV dark photons from laboratory search experiments and astrophysical observations (from [29]).
Figure 2: Current limits (shaded regions) and sensitivities (solid lines) on $\epsilon$ ($m_\phi < 1$ MeV) from various experiments. The sensitivities that are expected to be achieved by 2021 (left), and beyond 2021 (right) (from [27]).

Figure 3: (Left) The Handuk iron mine location (latitude: 37.188639 deg, longitude: 128.659406 deg) in Jeongseon-gun, Gangwon province, Korea, where a new underground Yemilab (~1000 m overburden) is currently being constructed. (Right) The layout of Yemilab, including a cavern for a ~3 kiloton neutrino detector (LSC). The laboratory will be accessed by a 600 m vertical shaft and a 730 m entrance tunnel. Adapted from [32].
The ~3 kiloton Yemilab neutrino detector be primarily dedicated to precise determinations of solar neutrino fluxes to search for signs of BSM physics, study reactor neutrinos from the Hanul nuclear power plant with a 65 km baseline, and measurements of geo-neutrinos [32]. It would be the first kiloton-scale neutrino telescope in Korea and a follow-on to the successful programs of the smaller scale RENO [33] and NEOS [34] reactor neutrino experiments at the Hanbit Nuclear Power Plant. The Yemilab neutrino detector could also be used to for a dark photon search by the addition of an electron accelerator for underground experiments, as suggested in reference [35]. Figure 4 is a schematic diagram that shows how an electron linac (100 MeV, 100 kW or 10 kW), tungsten target & radiation shield (50 cm-thick), and the neutrino detector (D: 20 m, H: 20 m cylinder) could be configured at Yemilab.

3 Dark Photon Production, Detection and Expected Number

3.1 Dark photon production

In dark sector models with a vector portal there is a small mixing between dark photons and ordinary photons. As a result, dark photons could be produced via the electron bremsstrahlung process that is first kiloton-scale neutrino telescope in Korea and a follow-on to the successful programs of the smaller scale RENO [33] and NEOS [34] reactor neutrino experiments at the Hanbit Nuclear Power Plant. The Yemilab neutrino detector could also be used to for a dark photon search by the addition of an electron accelerator for underground experiments, as suggested in reference [35]. Figure 4 is a schematic diagram that shows how an electron linac (100 MeV, 100 kW or 10 kW), tungsten target & radiation shield (50 cm-thick), and the neutrino detector (D: 20 m, H: 20 m cylinder) could be configured at Yemilab.

Figure 4: A schematic diagram showing a possible experimental configuration for a dark photon search at Yemilab.
ergy. Recently, Liu and Miller [36] have reported an exact calculation of the darkstrahlung cross-section and, in addition, generalized versions of the WW and IWW approximations so that no restrictions on the dark photon mass apply. Liu and Miller compared their exact calculation with the generalized IWW approximation that was used by SLAC experiment E317 and found reasonable agreement for dark photon masses below 100 MeV.

\begin{equation}
\frac{d\sigma}{dx} = 2\epsilon^2 \alpha^3 \frac{|k| m^2_\phi (-2 + 2x + x^2) - 2(3 - 3x + x^2)xu_{\text{max}}}{3xu_{\text{max}}},
\end{equation}

where $x$ is the fraction of energy a dark photon carries away from electron energy ($E$), $|k|$ is the 3-momentum of the dark photon, $\epsilon$ is the kinetic mixing parameter, $\alpha (\simeq 1/137)$ is the fine structure constant, $u_{\text{max}} = -m^2_\phi \frac{1-x}{x} - m^2_e x$, and $\chi$ is the effective dark photon flux and given by

\begin{equation}
\chi = \int_{t_{\text{min}}}^{t_{\text{max}}} dt \frac{t - t_{\text{min}}}{t^2} [G_{2,\text{el}}(t) + G_{2,\text{in}}(t)].
\end{equation}

Here $t$ is the square of the four-momentum transfered to the target nucleus, which ranges from $t_{\text{min}} = \left(\frac{m^2_\phi}{2E}\right)^2$ to $t_{\text{max}} = m^2_\phi + m^2_e$ in the IWW approximation where the produced dark photon is assumed to be collinear to the incident electron, and $G_{2,\text{el}}(t)$ and $G_{2,\text{in}}(t)$ are elastic and inelastic form factors of the target nucleus, respectively. In the following, we only consider the elastic form factor because the contribution from the inelastic one is negligibly small. The $\chi/Z^2$ values are shown in Fig. 10 of reference [3] for 200 MeV, 1 GeV, and 6 GeV $e^-$ beams on a tungsten target. For $m_\phi < 100$ MeV with a 200 MeV $e^-$ beam, the $\chi/Z^2$ values from $\sim 1$ to $\sim 7$ and we infer from the figure that the range of $\chi/Z^2$ values for MeV-scale dark photon masses are similar for the case of a 100 MeV $e^-$ beam. For simplicity, in this work we use $\chi/Z^2 = 6$ and found that changes in this value over a reasonable range has negligible effects on our results.
Figure 6 shows the differential darkstrahlung cross-section for a 100 MeV $e^-$ beam on a tungsten target as a function of the fractional dark photon (DP) energy, $x$, where the cross-sections of the DP masses of 1 keV, 10 keV, 100 keV, 1 MeV, and 10 MeV are compared. As the dark photon mass gets heavier, the cross-section decreases as expected from Eq. (3.1), while the relative contribution from high $x$ values increases.

![Figure 6: The IWW differential cross-sections for DP production for a 100 MeV $e^-$ beam on a tungsten target for different DP masses. Here $x$ is the fraction of DP energy relative to that of the $e^-$ beam energy. Note that here the differential cross-section is scaled by $1/\epsilon^2$.](image)

### 3.2 Dark photon detection

If $m_\phi > 2m_e$, dark photons could decay to the visible $e^+e^-$ final state; if $m_\phi < 2m_e$ the only visible decay mode is the $\gamma\gamma\gamma$ channel. If the DP mass is greater than $2m_\mu$, it could also decay to $\mu^+\mu^-$ (see top plot of Fig. 7). In this study, the $e^-$ beam energy is taken to be 100 MeV and only the $e^+e^-$ (for $m_\phi > 1$ MeV) and $3\gamma$ (for $m_\phi < 1$ MeV) decay modes are considered. The expected DP decay length, taken from ref. [36], is

$$l_\phi = \frac{E_k}{m_\phi \Gamma_\phi},$$

where $\Gamma_\phi$ is the decay width of a dark photon and given in Eqs. (3.4) and (3.5) for $e^+e^-$ and $\gamma\gamma\gamma$ decays, respectively:
\[
\Gamma(\phi \rightarrow e^+ e^-) = e^2 \frac{\alpha}{2} m_\phi \left( 1 + \frac{2m_e^2}{m_\phi^2} \right) \left( 1 - \frac{4m_e^2}{m_\phi^2} \right)^{1/2},
\] (3.4)

\[
\Gamma(\phi \rightarrow \gamma\gamma) = e^2 \frac{\alpha^4}{2^7 3^6 5^2 \pi^3} m_\phi^9 \left[ \frac{17}{5} + \frac{67 m_\phi^2}{42 m_e^2} + \frac{128941 m_\phi^4}{246960 m_e^6} + \mathcal{O}\left( \frac{m_\phi^6}{m_e^6} \right) \right].
\] (3.5)

Dark photons can also interact with electrons in the material of the target, shield, and detector, thereby producing real photons in a process similar to Compton scattering as shown in the bottom plot of Fig. 7; this is called dark photon “absorption.” The DP absorption length is given by

\[
\lambda = \frac{1}{n_e \sigma_{abs}}.
\] (3.6)

where \( n_e \) is the electron number density of the medium and \( \sigma_{abs} \) is the total cross-section of the DP absorption and can be computed using Eq. (36) in ref. [36].

![Figure 7: Dark photon visible decay channels (top) and the absorption process (bottom).](image-url)
3.3 Expected number of dark photons

Using the DP production cross-section for the darkstrahlung process in a thick target, and
detection through visible decays and absorption interactions that are discussed above, the
expected number of dark photons that are either absorbed or decay in the detector is given
by

\[
N_{\phi} \approx \frac{N_e X}{M} \int_{E_{\text{min}}}^{E_0} dE \int_{x_{\text{min}}}^{x_{\text{max}}} dx \int_0^T dt I_e(E_0, E, t) \frac{d\sigma}{dx} \times e^{-\frac{L_{sh}}{\lambda_{\phi}} \left( 1 - e^{-\frac{L_{\text{dec}}}{\lambda_{\phi}} + \frac{1}{\lambda_{\det}}} \right)},
\]

(3.7)

where \(N_e\) is the total number of incoming electrons, \(X\) the radiation length of the target
material (6.8 gm/cm\(^2\) for tungsten); \(M\) is the mass of target atom; \(E_0\) is the incoming
electron beam energy; \(E_{\text{min}} = m_e + \max(m_\phi, E_{\text{cut}})\), \(x_{\text{min}} = \frac{\max(m_\phi, E_{\text{cut}})}{E}\), where \(E_{\text{cut}}\) is the
measured energy cutoff depending on the detector; \(x_{\text{max}}\) is very close to, but smaller than, 1
and is approximated to be \(1 - \frac{m_e}{E}\) if the DP and the initial and final electron states are
collinear; \(T = \rho L_{sh}/X\) where \(\rho\) is the density of the target; \(l_{\phi}\) is the decay length of the
DP in a lab frame; \(\lambda_{sh}(\lambda_{\det})\) is the absorption length of the DP passing through target
and shield (detector). Even though electrons enter the target with initial energy \(E_0\), DP
production could occur after some energy loss of the incoming electrons as they penetrate
the target. This is taken into account with an analytic function \(I_e(E_0, E, t)\) from ref. [36]
that was originally reported in [3]:

\[
I_e(E_0, E, t) = \left( \ln \frac{E_0}{E} \right)^{bt-1} \frac{E_0 \Gamma(bt)}{E_0 \Gamma(bt)},
\]

(3.8)

where \(b = 4/3\) for a vector boson like a DP, and \(t\) represents how many numbers of radiation
length traversed by the electron before “darkstrahlung” occurs, \(E\) is the \(e^-\) energy after
\(t\) radiation lengths and \(\Gamma\) is the Gamma function. For the Yemilab neutrino detector,
\(E_0 = 100\) MeV, \(E_{\text{cut}} = 200\) keV, \(N_e = 1.97 \times 10^{23}\) \((1.97 \times 10^{22})\) for 1 year of operation with
100 kW (10 kW) \(e^-\) beam power, \(L_{sh} = 50\) cm, \(L_{\text{dec}} = L_{\text{dec}} = 20\) m. (The decay distance
\(L_{\text{dec}}\) could be larger, depending on the distance between the shield and the detector, but
the final sensitivity result does not change by much when \(L_{\text{dec}}\) is doubled.)

Note also that DP signal loss can occur because of DP decay or absorption in the
shield that is required to attenuate all of the standard model particle background; this
loss in shield is accounted for by the \(e^{-\frac{L_{sh}}{\lambda_{\phi}} \left( 1 - e^{-\frac{L_{\text{dec}}}{\lambda_{\phi}} + \frac{1}{\lambda_{\det}}} \right)}\) term in Eq. (3.7). The DP detection
probability via either decay or absorption in the accounted for in the last term, the large
brackets in Eq. (3.7).

4 Dark Photon Sensitivity at Yemilab

Before obtaining the DP sensitivity at Yemilab, the DP decay and absorption lengths
are compared to check which process is dominant for different DP masses and mixing
parameters. Then DP sensitivities are obtained for decay-only, absorption-only, and both
combined. For light DP \((m_\phi < 1\) MeV), oscillation between ordinary and dark photons
Table 1: Dark photon decay and absorption length scales for three different kinetic mixing parameters and for two different DP mass values. These length scales depend on the fractional of DP energy (x) and electron energy (E) at the DP point of production, while for the allowed ranges of x and E the length scale values given in the table do not change.

| Kinetic mixing parameter \( \epsilon \) | DP mass \( m_\phi \) (MeV) | Decay length \( l_\phi \) (m) | Absorption length in shield: \( \lambda_{sh} \) (m) | Absorption length in target: \( \lambda_{det} \) (m) |
|----------------------------------------|-----------------------------|-----------------------------|---------------------------------|---------------------------------|
| \( 10^{-3} \)                          | 0.1                         | ~ 10^{18} (3\gamma)         | ~ 10^5                         | ~ 10^6                         |
| \( 10^{-3} \)                          | 10                          | ~ 10^{-5} (e^+e^-)          | ~ 10^5                         | ~ 10^6                         |
| \( 10^{-5} \)                          | 0.1                         | ~ 10^{22} (3\gamma)         | ~ 10^9                         | ~ 10^{10}                      |
| \( 10^{-5} \)                          | 10                          | < 1 (e^+e^-)                 | ~ 10^9                         | ~ 10^{10}                      |
| \( 10^{-8} \)                          | 0.1                         | ~ 10^{28} (3\gamma)         | ~ 10^{15}                      | ~ 10^{16}                      |
| \( 10^{-8} \)                          | 10                          | ~ 10^{5} (e^+e^-)           | ~ 10^{15}                      | ~ 10^{16}                      |

4.1 Dark photon decay and absorption lengths

Table 1 lists the DP decay and absorption lengths for \( \epsilon = 10^{-3}, 10^{-5} \) and \( 10^{-8} \) cases for 0.1 MeV and 10 MeV DP masses, which are taken as representative for the \( m_\phi < 2m_e \) and \( m_{phi} > 2m_e \) cases corresponding to the 3\gamma and \( e^+e^- \) decay modes, respectively. Note that the 3\gamma decay lengths are very large while the \( e^+e^- \) decay lengths are more compatible with the detector size. However, for large values of \( \epsilon \) (e.g., \( \epsilon = 10^{-3} \)) the \( e^+e^- \) decay length becomes quite small (\( 10^{-5} \) m), and DP decays occur primarily in the shield, and well before they reach the detector. The absorption lengths in target/shield (both tungsten) and detector material (water, WbLS or LS) are similar but the length at the target/shield is an order of magnitude shorter due to its higher density. Note that the absorption length-scales are shorter than the 3\gamma decay lengths and larger than those for the \( e^+e^- \) decays.

Figure 8 shows DP decay and absorption lengths for \( \epsilon = 10^{-3}, 10^{-5} \) and \( 10^{-8} \) cases for several different DP masses. The red horizontal line indicates detector diameter (20 m) where DP can either decay or be absorbed. If the DP decay and absorption lengths are longer or shorter than the detector size, the detection probability is suppressed.

4.2 Dark photon sensitivity

The expected number of dark photon signal events are obtained from Eq. (3.7), where the energy threshold of the detector (\( E_{cut} \)) is set at 5 MeV in order to discriminate against all radiogenic backgrounds. Cosmic muon backgrounds can be suppressed either by using a pulsed electron beam or by the addition of a muon veto system that, for example, may be plastic scintillator modules on top of the detector plus an outer water Cherenkov veto detector that surrounds the inner detector [32]. Cosmogenic neutron backgrounds can be removed by tagging neutrons in Gadolinium-loaded water, WbLS or an LS target. Neutrinos from \(^8\)B decays in the solar interior can contribute to the above 5 MeV background but
most of these could be removed by a directional veto in a water or WbLS detector, and/or by requiring very forward vertex positions for DP signals especially for an LS detector.

Assuming zero background, the 95% C.L. sensitivity \((N_\phi = 3)\) on the parameter space of DP mass \((m_\phi)\) vs kinetic mixing parameter \((\epsilon)\) at Yenilab is obtained as shown in Fig. 9. The gray areas represent regions that are excluded at the 95% C.L. The upper plot in Fig. 9 shows the DP sensitivity for visible decays \((3\gamma\text{ or } e^+e^-)\) only for a 100 MeV-100 kW electron beam, where the sensitivity for \(m_\phi < 2m_e\) decreases quickly for smaller \(\epsilon\) values because the \(3\gamma\) decay length exceeds the size of the detector as shown in Fig. 8; there is zero sensitivity for \(\epsilon^2\) values between \(10^{-6}\) and \(10^{-10}\) for \(m_\phi > 2m_e\) because of the short \(e^+e^-\) decay length, and below \(\epsilon^2 \sim 10^{-17}\) because of long \(e^+e^-\) decay length. The middle plot of Fig. 9 shows the DP sensitivity for the absorption-only process for the 100 MeV-100 kW \(e^-\) beam. Not shown in Fig. 9 is that the number of \(m_\phi > 2m_e\) DP events that are detectable via the absorption process, which is found to be much smaller than that of those detected via the decay process in the overlapping region of sensitivity in the parameter space. Note also that the sensitivity for the absorption process is nearly independent of DP mass for masses lighter than \(2m_e\). The lack of sensitivity for sub-MeV DPs for \(\epsilon^2\) values below \(1.5 \times 10^{-12}\) is because of their large absorption length. The bottom plot of Fig. 9 shows the DP sensitivity including both decay and absorption processes for a year-long run with a 100 MeV-10kW \(e^-\) beam. The 95%-C.L. exclusion level for the \(e^+e^-\) decay mode for \(m_\phi\) above 1 MeV is \(\epsilon^2 > 4.8 \times 10^{-17}\), which is comparable to that for Super-Kamiokande (see Fig. 4 in reference [35]), and would have the world’s best direct DP search sensitivity for \(2m_e < m_\phi < \sim 80\) MeV; for sub-MeV DPs, the exclusion level is \(\epsilon^2 > 1.5 \times 10^{-12}\). Figure 10 shows the DP sensitivity for the combined decay and absorption processes using 100 MeV-10kW \(e^-\) beam, where the 95% C.L. sensitivities are \(\epsilon^2 > 1.7 \times 10^{-16}\) for \(2m_e < m_\phi < \sim 80\) MeV and \(\epsilon^2 > 5.3 \times 10^{-12}\) for sub-MeV DPs.

4.3 Oscillation between ordinary and dark photons

Although it is not shown in Fig. 9, the DP sensitivity for the absorption process extends down to very low DP masses, even to the sub-eV level. However, as discussed in refs. [24, 26], for \(m_\phi < 2m_e\), oscillations between ordinary and dark photons (similar to neutrino oscillations) dominate. The oscillation probability is given in ref. [26, 37] to be

\[
P(\gamma \rightarrow A') = \epsilon^2 \times \frac{m_\phi^4}{(\Delta m^2)^2 + E_\gamma^2 \Gamma^2}, \tag{4.1}
\]

\[
P(A' \rightarrow \gamma) = \epsilon^2 \times \frac{m_\phi^4}{(\Delta m^2)^2 + E_\gamma^2 \Gamma^2} \times \Gamma L, \tag{4.2}
\]

where \(\Delta m^2 = \sqrt{(m_\phi^2 - m_\gamma^2)^2 + 2\epsilon^2 m_\phi^2 (m_\phi^2 + m_\gamma^2)} \approx |m_\phi^2 - m_\gamma^2|\), \(m_\gamma = \sqrt{4\pi\alpha m_e/m_e}\) is effective photon mass in matter, \(E_\gamma\) and \(\Gamma\) are ordinary photon energy and attenuation coefficient, respectively, and \(L\) is the length of the detector in the beam direction.
In the case of the Yemilab neutrino detector, the oscillation would have to occur twice, one at production ($\gamma \to A'$) and the other at detection ($A' \to \gamma$). In this case, the oscillation probability is

$$P(\gamma \leftrightarrow A') = \epsilon^4 \times \frac{m_{\phi}^8}{(m_{\phi}^2 - m_{\gamma}T^2)^2 + E_{\gamma}^2 \Gamma_T^2} \times \frac{(m_{\phi}^2 - m_{\gamma}W^2)^2 + E_{\gamma}^2 \Gamma_W^2}{\Gamma_W L}, \quad (4.3)$$

where, $m_{\gamma}^T$ ($m_{\gamma}^W$) is an effective photon mass in tungsten (water), i.e. 80 eV (21 eV), and $\Gamma_T$ ($\Gamma_W$) is a photon attenuation coefficient in tungsten (water), where $\Gamma_T^{-1} \approx 1$ cm ($\Gamma_W^{-1} \approx 45$ cm) at $E_{\gamma} = 10$ MeV according to NIST database. In the following extreme cases, the oscillation probability Eq. (4.3) becomes

$$P(\gamma \leftrightarrow A') = \epsilon^4 \times \frac{m_{\phi}^8}{m_{\gamma}^4 \times m_{\gamma}^W \times \Gamma_W L}, \quad (m_{\phi} \ll m_{\gamma}) \quad (4.4)$$

$$= \epsilon^4 \times \Gamma_W L, \quad (m_{\phi} \gg m_{\gamma}) \quad (4.5)$$

$$= \epsilon^4 \times \frac{m_{\phi}^8}{E_{\gamma}^2 \Gamma_T^2 \times ((m_{\gamma}^2 - m_{\gamma}W^2)^2 + E_{\gamma}^2 \Gamma_W^2)} \times \Gamma_W L, \quad (m_{\phi} \approx m_{\gamma}^T) \quad (4.6)$$

$$= \epsilon^4 \times \frac{m_{\phi}^8}{(m_{\gamma}^2 - m_{\gamma}W^2)^2 + E_{\gamma}^2 \Gamma_W^2} \times \Gamma_W L, \quad (m_{\phi} \approx m_{\gamma}^W) \quad (4.7)$$

For $m_{\gamma}^W < m_{\phi} < m_{\gamma}^T$, the oscillation probability is the same as Eq.(4.3). At resonance ($m_{\phi} \approx m_{\gamma}^T$ or $m_{\gamma}^W$), the oscillation probability is maximum. Using Eq.(4.3), the expected number of DP signal events from the oscillation is:

$$N_{\phi}^{osc} \approx N_e \times \int_{E_{\gamma}^{min}}^{E_{\gamma}^{max}} dE_{\gamma} P(\gamma \leftrightarrow A') \int_0^T dt \left( I_{\gamma}^{(1)}(t, E_{\gamma}) + I_{\gamma}^{(2)}(t, E_{\gamma}) \right), \quad (4.8)$$

where $I_{\gamma}^{(1)}$ and $I_{\gamma}^{(2)}$ are, respectively, the 1st and 2nd generations of photon flux in target per an incoming electron and given in the Eqs. (24) and (29) of [38]; $E_{\gamma}^{min} = 5$ MeV to remove radiogenic background and $E_{\gamma}^{max} \approx E_0 = 100$ MeV.

The 95% C.L. sub-MeV DP detection sensitivities for photon-DP oscillations determined from Eq. (4.8) are shown in Fig. 11. A comparison of Fig. 11 with Figs. 9 and 10 shows that the above 80 eV mass DP sensitivity from oscillations is better that for the absorption process; the best 95% C.L. direct DP search sensitivity, $\epsilon^2 > 1.5 \times 10^{-13}$ (4.6 $\times 10^{-13}$), is obtained in a year-long data-taking run with a 100 MeV-100 kW (10 kW) e$^{-}$ beam on a thick tungsten target and the Yemilab neutrino detector.

5 Summary

Dark photon searches are the focus of a variety of experiments and have been invoked to explain a number of anomalies that have cropped up in (astro-)particle physics observations. Many of the best constraints, especially for sub-MeV dark photons, are from helioscopic or astrophysical observations. However, the helioscopic/astrophysical constraints depend,
in a large part, on the choice of DP mean-free-path lengths inside stellar objects \[39\] and, therefore, direct search experiments at laboratories are absolutely necessary. Our study shows that a combination of a 3 kiloton-scale neutrino detector and an electron beam at Yemilab could constrain DP kinetic mixing parameters with the world’s best direct search sensitivity for sub-MeV and above MeV DPs produced via darkstrahlung ($e^- + Z \rightarrow e^- + Z + A'$) or oscillations ($\gamma \rightarrow A'$). By detecting DPs via their absorption ($A' + e^- \rightarrow \gamma + e^-$) or oscillations ($A' \rightarrow \gamma$) processes, a 95% C.L. direct search sensitivity for 80 eV $< m_\phi < 1$ MeV DP of $\epsilon^2 > 1.5 \times 10^{-13}(4.6 \times 10^{-13})$ could be achieved with one year of operation of a 100 MeV-100 kW (-10 kW) electron beam on a thick tungsten target. The best sensitivities for sub-MeV DPs are achieved by exploiting the oscillation between ordinary and dark photons. At the peaks of the oscillation resonances, i.e. $m_\phi = 21$ eV (in water) and 80 eV (in tungsten), the sensitivities are enhanced to $\epsilon^2 \sim \mathcal{O}(10^{-15})$. The dark photon sensitivity for masses below the $m_\phi < 21$ eV resonance peak rapidly decreases as $\epsilon^4 \propto m_\phi^8$ due to the oscillation. Sub-MeV dark photon detection via decays to $3\gamma$ highly are highly suppressed because of the very long decay lengths. For $2m_e < m_\phi < \sim 80$ MeV DPs, the direct search sensitivity for the kinetic mixing parameters using visible decays ($A' \rightarrow e^+e^-$) is $\epsilon^2 \sim \mathcal{O}(10^{-17})$ at the 95% C.L. for the 100 kW beam power; a sensitivity that is comparable to that of Super-K. With a higher energy electron beam, the sensitivity beyond 80 MeV DPs could also be explored but, it may not be practical to accommodate such a facility in the current Yemilab design configuration.

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Figure 8: Dark photon decay and absorption lengths in the Yemilab setup for a 100 MeV $e^-$ beam (100 or 10 kW) incident on a tungsten target (50 cm). The horizontal red line represents the diameter of the neutrino detector that is assumed in this study.
Figure 9: Dark photon excluded regions (95% C.L. sensitivities) in the Yemilab neutrino detector at Yemilab for visible decays only (top), absorption-only (middle) and for both visible decays and absorption (bottom) for one year of data-taking with a 100 MeV-100 kW $e^-$ beam on a tungsten target (50 cm).
Figure 10: Dark photon excluded region (95% C.L. sensitivities) in the Yemilab neutrino detector including both visible decays and absorption (bottom) for one year of data-taking with a 100 MeV-10 kW $e^-$ beam on a tungsten target (50 cm).

Figure 11: The dark photon sensitivity from the $\gamma \leftrightarrow A'$ oscillation for $m_\phi < 2m_e$ at the Yemilab neutrino detector for one year of data taking with a 100 MeV $e^-$ beam (100 kW: solid red line, 10 kW: dotted red line) on a tungsten target (50 cm), compared to those of other direct search experiments, TEXONO (dashed black line) [26] and NA64 (two solid black lines) [24].