Detection of Dark Photon Decaying into $e^+e^-$ using Cherenkov Radiation

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ABSTRACT: In dark photon search experiments with electron beam-dumps, it is difficult to access the smaller dark photon life-time region of phase space due to enormous backgrounds from low-energy particles emerging from the target. In order to reduce the background, a thick beam-dump target is usually necessary. We propose to detect the Cherenkov radiation in gas due to ultra-relativistic electron and positron from dark photon decay. The secondary particles emerging from the beam dump have very little chance to produce such Cherenkov radiation in gas. Making use of the direction of the Cherenkov radiation, low background dark photon search with thinner target is possible. This would allow one to access challenging regions of the dark photon parameter space with low power electron beams and low-cost experimental setup.

KEYWORDS: Dark photon, Beam dump experiment, Cherenkov detector

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1 Introduction

Understanding the nature of the dark matter content of the universe is one of the most important
problems in particle particle physics. Models with massive dark photon, an extra $U(1)$ gauge
boson with weak coupling to SM charged particles, are a bottom-up approach to its resolution with
interesting possibilities [1].

Many experiments had searched for an exotic particle in the MeV to GeV mass range that
decays into an electron-positron pair, without any significant signal so far. Null results from
these experiments have been reinterpreted and large parameter space have already been excluded,
especially for the long-lived dark photons (Fig. 5) [2]. Unexplored region of parameter is quite
challenging to probe experimentally and new techniques should be found. We propose to detect
Cherenkov radiation as a clean signature of dark photon decay.

In this letter, we consider the case where the dark photon decays into a pair of electron and
positron. We assume that the candidate for stable dark matter (DM) is massive enough that the
dark photon does not decay into a pair of DM particles. In this case, the property of dark photon is
fully determined by its mass ($m_{A'}$) and a coupling parameter ($\epsilon$) [3]. The dark photon couples to
standard model charged particles with coupling strength $ee$. For $m'_A < 2m_\mu$, $A'$ decays exclusively
into $e^+e^-.$

Production of $A'$ in electron beam dump is similar to the Bremsstrahlung process [3]. If
electron beam energy ($E_{beam}$) is much greater than $m_{A'}$, the energy of the $A'$ produced is close
to that of the incoming electron beam. Also, $A'$ is highly directional, forming a very small angle
$\theta \ll m_A/E_{A'}$ with respect to the incident electron beam direction. If the dark photon decays after
emerging from the beam dump, the visible decay particles can be detected. For a long-lived dark
photon, a way of detecting its decay would be to sum the electron and positron energies. This
should be close to $E_{beam}$ [3].
Figure 1. GEANT4 simulation of a dark photon event $A' \rightarrow e^+e^-$ with $E_{A'} = 3 \text{ GeV}$, $m_{A'} = 0.1 \text{ GeV}$, $\epsilon = 2 \times 10^{-5}$. The shaded narrow column is the air radiator. Shields surrounding the radiator have been omitted to permit better view. The two clusters of lines are due to Cherenkov photons produced by relativistic electron and positron.

2 Deficiency of Calorimetric Method of Dark Photon Detection

A method of detecting the $A' \rightarrow e^+e^-$ with long decay length involve calorimeters for energy measurement of electron and positron. This method is adequate for detecting very long decay lengths of $A'$, since with thick enough target and shielding, almost all secondary particles can be stopped.

For promptly decaying dark photons, precision spectrometer combined with thin targets are used. Due to limited acceptance of spectrometers, they are not as well suited to detect long-lived $A'$ decays. In order to access the unexplored region of intermediate lifetime region of parameter space, the detector needs to be closer to the target and the target needs to be thinner as well. A good example of this is the Heavy Photon Search (HPS) experiment at JLAB, which uses vertex detectors in addition to calorimeters. The HPS experiment is sensitive to both prompt and events with displaced vertex [4]. However, due to low rate of interaction in thin targets, accelerator with large beam current is required.

In accelerators with lower current, we must use thicker targets or run for longer periods to be competitive. For targets of intermediate thicknesses, copious low-energy secondary particles would be produced. To be able to track and measure the electron and positron signal would require fine tracking and calorimetry, which increases the cost and complexity. Careful optimizations are need to make it feasible. Obviously, use of a very thick target would eliminate many secondaries, but this region is already excluded by other experiments.

In the next section, we outline a method that allows us to use a target of intermediate thickness. We will exploit the fact that the secondary particles emerging from the target have extremely small chance to produce Cherenkov radiation in gases, while electron and positron from $A'$ decay produce
Cherenkov radiation in gases with high probability.

3 Detection of $A' \to e^+ e^-$ from Cherenkov Radiation

Cherenkov photons are produced in air when a relativistic charged particle of $\gamma > 40$ travels at standard temperature and pressure (STP) whose index of refraction is 1.0029 for air. These photons are highly directional, forming a small angle with respect to the charged particle $\theta = \cos^{-1} \frac{1}{n\beta} = 0.024$. Such a relativistic charged particle traveling through 1 meter of air will produce about 90 photons in the wavelength range of 200–700 nm. This number gets reduced to less than half for wavelengths in the 200–300 nm range. Since the speed of light in air at STP is very close to that in vacuum, the Cherenkov photons that are continually produced as the particle travels, will occupy the similar longitudinal position. Therefore, the arrival time of the photons at the far end would be almost coincident with little spread. We can exploit the directional and coincident nature of the Cherenkov photons.

There are two sources of backgrounds that need to be considered. The first one is scintillation from nitrogen gas in the air. When low energy particles that emerge from the target lose their energies in the air volume, nitrogen molecules emit scintillation light during de-excitation. The nitrogen scintillation is in the range of 300–400 nm [5, 6]. The lifetime of nitrogen gas scintillation is on the order of a nanosecond at STP, while the Cherenkov radiation is prompt. However, separating the scintillation photons from Cherenkov photons using timing will not be possible. One distinguishing feature is that the scintillation photons are not directional, while Cherenkov photons are. By exploiting this fact, Nitrogen scintillation background can be suppressed with suitable optical reflection system that directs Cherenkov photons with high efficiency towards photodetector.

Another way to reduce sensitivity is to use UV-sensitive photomultiplier tubes. Another source of backgrounds are energetic electrons that can produce Cherenkov radiation. If the target is not thick enough, electromagnetic shower is not fully contained and electrons whose energy is above the 40 MeV threshold, may escape the target. This limits the thinness of the target. Another way Cherenkov radiation can be produced is if high-momentum proton knocks electrons free inside the radiator volume or the surrounding shielding. Although extremely rare, protons can be knocked free from the target material by incoming electron beam. If a pulse of electron beam contains large number of electrons, it may release large number of energetic protons. If the delta rays created by proton has enough energy, it can produce Cherenkov photons. These Cherenkov photons, however, may form larger angles with incident electron beam direction., due to the wide spread of delta electron directions.

In the next section, we examine the potential reach of this method with a conceptual experiment using a low current 3 GeV electron linear accelerator (LINAC) in Korea. With this example, we demonstrate the potential benefits of this method.
Figure 2. Distribution of number of optical photons from 10000 dark photon signal events reaching the detector for \( m_{A'} = 0.1 \text{ GeV} \) and \( \epsilon = 2 \times 10^{-5} \).

4 An example case: Dark Photon Search Experiment Concept at Pohang Accelerator Lab

The Pohang Light Source II (PLSII) at Pohang Accelerator Laboratory (PAL) in Korea is a synchrotron radiation facility [7]. A 3 GeV electron LINAC supplies the electrons to the circular electron storage ring in a top-up mode in order to keep the current constant in the storage ring. The LINAC produces electron beam bunches of 0.5 nC each with 10 Hz repetition rate.

The PLSII has a beam dump where a dark photon search experiment can be performed when the storage ring is not in use. Compared to other electron beam LINAC, the PLSII LINAC is not the most powerful machine. However, one advantage of the PLSII is its low repetition rate. This means that the slow secondary particles emerging from the beam dump do not affect the measurement if the timing information is used. The Cherenkov method can turn this moderate facility into a competitive site for dark photon search.

In order to test the feasibility of the Cherenkov radiation method, we use GEANT4 detector simulation library, which contains the accurate physics of particle and nuclei interactions in matter [8]. We used the known electromagnetic and hadronic interactions through the “QGSP_BERT” physics list. To investigate the optical photon production and propagation in air, we used the Cherenkov radiation physics and implemented the nitrogen gas scintillation, based on the measurements from real data. The dark photon decay physics was implemented to study the acceptances [5, 6].

We consider a 20 cm thick beam dump target made of tungsten, which has a high density and short radiation length of \( X_0 = 0.32 \text{ cm} \). However, this is not enough to stop all the secondaries produced in the target. For each incident 0.5 nC electron beam, the sum of energy of the particles
Figure 3. Distribution of incident angle due to photons with wavelengths in 200–300 nm range from dark photon signals for $\epsilon = 2 \times 10^{-5}$. Histograms are normalized to unity.

emerging from the target amounts to a few TeV’s. Although probability for secondaries to emerge from the target is very low, with enough incident electrons, the total amount could be sizable.

In contrast, dark photon signal would deposit an energy of 3 GeV, which is quite small compared to the level of backgrounds. Using calorimetry alone would make it difficult to separate the signal from the backgrounds. In this case, a thick target is needed and access to the smaller lifetime parameter space becomes difficult. Fine grained calorimetry together with fine-grained tracking might mitigate the effects, but a careful study is necessary to understand the issues of high occupancy.

Instead of a calorimeter, we place air Cherenkov radiator, whose dimension is $10 \times 10$ cm$^2$ transversely and 100 cm longitudinally. The volume of air is surrounded by 1 cm thick tubular tungsten shielding. At the far end of this radiator, we place a pseudo-detector to measure the angle of incidence of optical photons. For a realistic detector, one should place a mirror at the end of the radiator and reflect the optical photons onto a strategically placed photo-detectors. A dark photon that would emerge from the target subsequently decays into a $e^+e^-$ pair. The electron and positron, each has 1.5 GeV in energy, and whose gamma factor $\gamma \approx 3000 \gg 40$ is large enough to produce Cherenkov photons while traveling through air (Fig. 1).

The distribution of the number of optical photons reaching the end of the air column is shown in Fig. 2 for $\epsilon = 2 \times 10^{-5}$ and $m_{A'} = 0.1$ GeV from 30000 dark photon events. We restrict the wavelengths of photons from 200 nm to 300 nm, since we want to block scintillation photons. The dark photon parameter chosen corresponds to a dark photon mean decay length of 6 cm. Due to the short decay lengths, about 94% of the events do not produce significant signal. For smaller values
Figure 4. Angular distribution of optical photons reaching the detector for $5 \times 10^8$ 3 GeV electrons on the tungsten target.

of $\epsilon$, the efficiency rises as more dark photons decay behind the beam dump. For much smaller values of $\epsilon$, where the decay length becomes longer than the Cherenkov radiator, efficiency starts to decrease.

Two broad peaks above 20 are visible in Fig. 2. The first peak is due to events where only one of electron or positron travels through the volume and produces Cherenkov photons that reach the detector. The second peak corresponds to the case when Cherenkov photons from both the electron and positron reach the detector. A larger radiator in the transverse direction would allow one to capture all the photons.

Figure 3 shows the directional property of the Cherenkov photons that reach the pseudo-detector. Nitrogen scintillation photons, on the other hand, do not have preferred directions. Therefore, this property of Cherenkov photons can be exploited by using optical systems to select only the forward-going photons, in a realistic experiment.

In order to estimate the backgrounds we inject $5 \times 10^8$ electrons on the tungsten target in GEANT4 simulation. This is about one sixth of the number of electrons in 0.5 nC electron beam pulse. Despite the large number of electrons hitting the target, only 163 photons whose wavelengths are in 200—700 nm, reach the detector. The distribution of angle of incidences of these photons are shown in Fig. 4.

Most of these photons are due to nitrogen gas scintillation, while 14 photons under the peak at 0.3 radians are due to a single instance of an electron producing Cherenkov radiation. If we restrict to wavelengths in 200—300 nm, only the event in the peak would remain and the number of photons would be reduced to 7. To be insensitive to the nitrogen gas scintillation photons, one should use either short pass optical filter and/or a photo-cathode of a photo-detector that is sensitive
Figure 5. Reach of dark photon search experiment using 3 GeV electron beam dump at PAL PLSII with seven days-equivalent of data-taking.

in the ultraviolet range and insensitive to wavelengths above 300 nm. Another way to achieve this is to use a different gas, such as carbon dioxide, which doesn’t produce photons in the optical range.

If we assume that the Cherenkov photons produced by delta rays follow the angular distribution of the scintillation photons, we can expect 10 Cherenkov photons on average to fall within 0.1 radians. Probability for 10 photons to fluctuate to 30 or more photons is $8 \times 10^{-8}$. In Fig. 5, we show the region of parameter space ($m_A, \epsilon$) that can be explored by the experiment with 7 day-equivalent experiment at PAL PLSII. This translates into approximately 6 million beam pulses on target. We expect approximately 0.5 events due to backgrounds. The figure shows the region where we expect to see 10 signal events or more in 7 days of data collection. Obviously, for a more realistic performance of an experiment, one has to carefully optimize the optics and choose a suitable photo-detector considering its quantum efficiency and other characteristics. Since the Cherenkov photons would form a circular image, if multi-anode photodetectors are used, additional rejection of backgrounds may be possible

5 Conclusion

We propose a novel method of detecting the dark photon that decays into a pair of electron and positron, based on Cherenkov radiation of highly relativistic charged particles in gas. With this technique, dark photon search becomes possible in the challenging phase space with low power electron accelerators due to extremely low backgrounds. This has been demonstrated for a conceptual experiment using 3 GeV electron LINAC at PAL PLSII in Korea. Since no active detector material or geometry is needed, realization of such an experiment would be simple and
low cost. This method could augment the existing methods to enhance the signal-to-background fraction.

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