Simulation for Dark Photon Detection

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An experiment for the detection of hidden photons is currently in progress at the University of California Davis, making use of coupling of hidden photons to electromagnetism. In support of this project, Python code has been written to explore possible analysis techniques to find small signals in noisy data. Additionally, simulations of the experimental setup containing an antenna in a room with conducting walls have been constructed in COMSOL to characterize the antenna response. Agreement between the COMSOL model and manufacturer data for the biconical model in free space give confidence to the accuracy of the later models. The antenna factor for the model of the biconical antenna in the room will ultimately be useful for analysis of a dark photon signal to determine electric field and therefore the coupling constant, and the dark photon mass will be determined from the frequency of the signal.

Dark matter is a fascinating area of research in the physics community in recent years due to its elusive nature. Dark matter is a term used to refer to mysterious, unexplained matter understood to exist in our universe. Gravitational behavior has been observed that cannot be accounted for with only the visible matter in galaxies. Redshift measurements of high speeds in outer parts of galaxies and gravitational lensing measurements of star clusters, among other measurements, observe substantially greater amounts of mass than we can account for with visible matter [1], so there is likely some undetected matter that is causing this behavior (unless current theories of gravity are simply incorrect, but that is a whole other discussion).

Dark matter is believed to make up 84% of the matter in the universe. There are many theories about what known and unknown objects might make up this huge, unaccounted for percentage of our universe. The predicted local density of dark matter is known, but the matter itself could be any of a wide range of masses and interaction strengths. Current popular theories range from heavier WIMPS (weakly interacting massive particles) to much lighter axions [2]. One theory of particular interest is that dark matter is made up of very light particles called dark photons. At UC Davis, the Tyson group is currently running an experiment to detect dark photons through their coupling with electromagnetism. This summer, I supported this project by performing simulations of the experiment and writing code for the analysis of the data.

Dark Photon Theory

Cosmological models of the early stages of the universe allow for the existence of dark photons [3]. They are massive vector bosons whose predicted behavior involves an interaction with the standard model through kinetic mixing that allows them to penetrate conductors. This can be understood by looking at the solutions to Proca's equations for the behavior of massive vectors. Proca's equations are analogous to Maxwell's equations with the addition of a mass term,

$$(\partial_t^2 - \nabla^2 + m_\gamma^2)V' = \epsilon\rho$$

$$(\partial_t^2 - \nabla^2 + m_\gamma^2)\vec{A}' = \epsilon\vec{J} \qquad \dot{V}' + \vec{\nabla}\cdot\vec{A}' = 0 \tag{1}$$

where m_γ is the mass of the hidden photon, ρ is the charge density, and $\vec{J}$ is the current density. Equations (1) show that the dark fields are sourced by charges and currents similarly to massless photon fields, though suppressed by a factor of ϵ. The solution to these equations yields both transverse and longitudinal planes waves, whereas massless photons have only transverse waves. While transverse waves are prevented from penetrating a perfectly conducting wall, longitudinal waves are permitted. Therefore these massive photons are able to pass through conducting surfaces where regular photons would not. A full derivation can be found in [4].

As mentioned previously, the local dark matter density is predicted to be $\rho_{DM} = 0.3$ GeV/cm^3. It might be expected that this high density will result in strong electric fields which would be easy to detect, but one consequence of the ϵ suppression in equations (1) is that the measured electric field due to these hidden photons will also be suppressed according to

$$E_{DM} = \epsilon E'_{DM} = \epsilon\sqrt{\frac{2\rho_{DM}}{\epsilon_0}} \approx \epsilon 33V/cm \tag{2}$$

where E'_{DM} is the dark field and E_{DM} is the measured electric field due to this dark field. This means that the detectable electric field produced by these photons could be very small, and it may require a significant removal of noise before it could be detected.

Radio Detection of Dark Photons

The proposed experimental setup for detection of these massive photons involves detection of this electric field E_{DM}. Because the value of the suppression constant ϵ and the mass of dark photons m_γ are unknown, the amplitude and frequency of the signal that would be detected are also unknown. Within the parameter space of ϵ vs m_γ, there is a substantial space ruled out by previous measurements, as shown in Figure 1, but there is still much to explore.

The Tyson group at UC Davis is performing this dark photon detection experiment for the specified range of parameter space shown in Figure 1 as Phase-1 and Phase-2, using an antenna in a shielded room to detect the coupled electric field from the dark photons that has penetrated the conducting walls

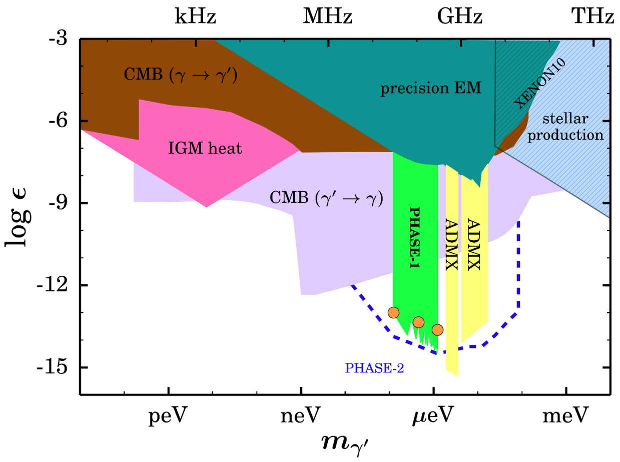

FIG. 1: Parameter space of proposed dark photon detection experiment, comparing suppression constant ϵ and mass of dark photon m_{γ}. Phase-1 and Phase-2 refer to anticipated work of the Tyson group at UC Davis.

of the room. A detected signal at a certain amplitude and frequency will allow for the calculation of the coupling constant and mass of the dark photon. The current stage of the project uses a biconical antenna with operating frequency range of 50 to 300 MHz in a 10 $\times$ 12 $\times$ 8 ft shielded room connected to a RIGOL spectrum analyzer. Measurements of power in dBm are taken for the full range of available frequencies.

In order for an electric field value to be determined from the measured power, it must be converted to a voltage and a quantity called the antenna factor must be used. Antenna factor relates measured voltage from an antenna to the detected electric field strength according to the following equation.

$$AF = \frac{E}{V} \tag{3}$$

This is not an autonomous quantity. It is dependent on the presence of nearby conducting materials and other objects that might be acting as antennas. This is why a thorough understanding of the antenna factor in the context of the specific experimental setup is important in anticipation of the analysis of a detected signal.

Data Collection & Analysis

The RIGOL operates by taking a real time FFT (Fast Fourier Transform) at 800 frequencies in a specified span and averaging for a specified time. In order to collect data for the full range of frequencies with appropriate precision, the RIGOL is currently set up to record many spans with $\sim$1 MHz range (varied depending on the bandwidth), averaging each span for 10 s before going to the next. It repeats this process many times so that the spans can be further averaged in post-processing to remove additional noise. The recently completed run contains over 10,000 s of data for every span, and the full spectrum is shown in Figure 2.

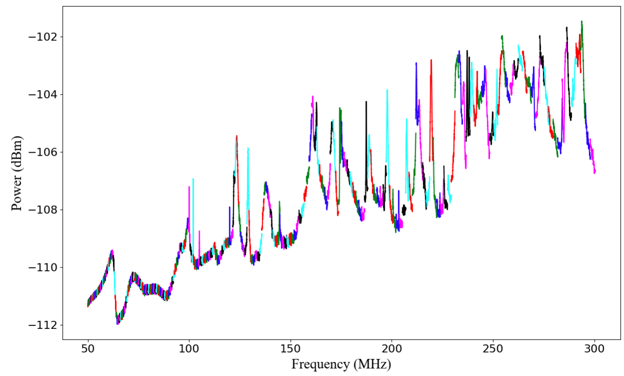

FIG. 2: Power spectrum collected using biconical antenna in shielded room. Each color is a span with 10,000 s of averaged data.

The analysis of this data must include several steps in order to sufficiently reduce noise and search for a dark photon signal. These steps might include: averaging over the many spans, subtracting off sloping and windowing functions, removing known noise sources such as radio stations that have penetrated the shielded room, then computing Z-score values to locate points that persist significantly above the baseline.

Injection Test

One method for testing the sensitivity of our analysis techniques is to inject a small signal into the room at a known frequency and try to detect it. This was performed with a bow-tie antenna in the corner of the room emitting a 70 MHz signal at -113 dBm. 3520 s of data were taken for one span from approximately 69.7 to 70.3 MHz. After averaging all the spans together, the signal is clearly visible above the noise. This result along with calculated Z-score values are shown in Figure 3.

Though this analysis clearly detected the signal at 70.00 MHz with a Z-score of 5.24, this signal was injected at a relatively flat part of the full spectrum and in the center of the chosen span. If either of these factors were different, the signal may have been much more difficult to detect.

Effort was also put into writing Python code that more easily performs these averages and subtracts a simple slope. Additional work needs to be done to remove windowing shapes and other more complicated analyses.

Simulation of the Experiment

As mentioned previously, understanding the response, especially the antenna factor, of our specific antenna under controlled conditions is important for further analysis once a sig-

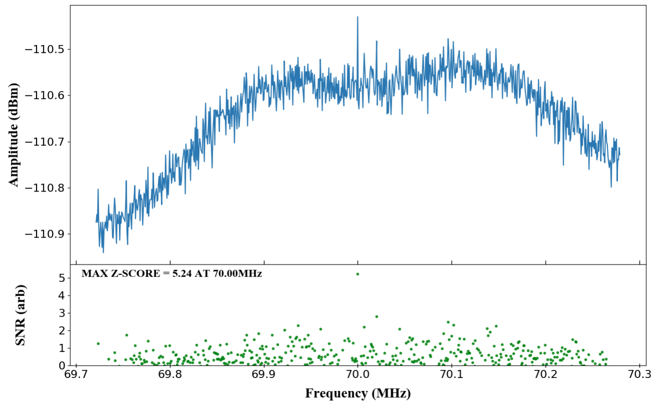

FIG. 3: Signal Injection Test Results. After averaging for 3520 s, the injected signal is visible at 70 MHz. The Z-score is calculated for each point and a maximum of 5.24 is observed at 70 MHz.

nal is detected. For this purpose, numerical simulation software is a useful tool to model the behavior of the antenna. COMSOL Multiphysics is one such simulation software that uses finite element analysis (FEA). FEA works by dividing up a given geometry into finite sections, then COMSOL is able to solve differential equations for the relevant physics.

Several simulations of antennas were created in COMSOL that model the behavior of dipoles and biconical antennas in free space and in various room models. The basic method for construction and operation of these models involves first importing and creating the desired geometry. We used detailed CAD models of the biconical antenna and shielded room created in AutoDesk Inventor. All other geometry parts were created in COMSOL itself. Next, materials were assigned to the components, usually aluminum for the antenna and air for the surrounding space.

The RF module of COMSOL was implemented which allowed for use of the electromagnetic frequency domain solver. Initial conditions and boundary conditions were set in this module. The perfect electric conductor boundary condition was set to the boundaries of the antenna and walls of the room. The impedance boundary condition was set to 180 Ω on the surfaces of the antenna. In free space models, a scattering boundary condition, perfectly matched layer, and far-field domain were applied to a sphere to prevent any reflection at the edges of the simulation. A lumped port was set up at the feed points of the antenna. This requires two specified areas, between which the simulation will measure a voltage difference for the antenna. The geometry then had to be meshed into a discrete set of points for the solutions to be computed. This proved to be more tricky for the biconical antenna than for other models because of narrow regions. It therefore required the use of mapped meshing over the antenna surface instead of the default tetrahedral mesh throughout.

Once the geometry, physics, and mesh are set up, the solution is computed for a designated set of frequencies. Values for electric field, lumped port voltage, and many other quantities can be extracted from the results and plotted. A sampling of the best results are described in the following.

Simulation Results

First a simple dipole antenna was constructed as a pair of cylinders and put in a sphere to simulate free-space. A 1 V/m plane wave was produced in the model and the lumped port voltage was measured for varied frequencies to observe the behavior. The result is shown in Figure 4. The expected resonance for a simple dipole is at a wavelength of 4 times the arm length of the antenna. For this 1 m dipole antenna, the resonance is expected at 75 MHz.

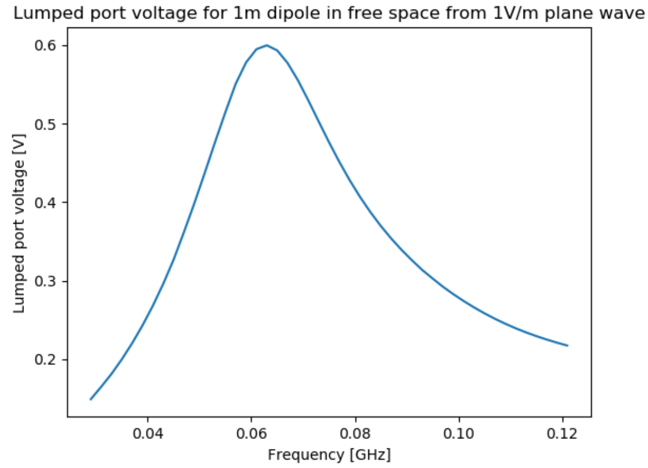

FIG. 4: Lumped port voltage of a 1 m dipole antenna model in free space interacting with a 1 V/m plane wave in COMSOL. The peak in voltage indicates a resonance of ∼65 MHz.

The resonance of the dipole antenna model is observed to be ∼65 MHz from Figure 4. This difference is a result of the width of the antenna. An infinitely skinny antenna would approach the correct resonance, though this was not tested further because of time constraints.

The next model created was of a biconical antenna in free space. Again lumped port voltage was measured when interacting with a 1 V/m plane wave for a wide range of frequencies. The antenna factor was calculated using equation (3) and the result is shown in Figure 5. There is a significant difference in amplitude between the COMSOL model and the manufacturer data. This is believed to be a result of the lack of a balun transformer, a device included on the antenna to connect it to lines of differing impedance, in the model, whereas the manufacturer data was likely taken with the balun transformer attached. The difference in the impedance would cause an amplitude shift of several dBm. The COMSOL model does agree more closely with another model created in a similar simulation software called CST using the same antenna model.

The biconical antenna was then modelled in a conducting box of dimensions $10 \times 12 \times 8$ ft, again interacting with a 1

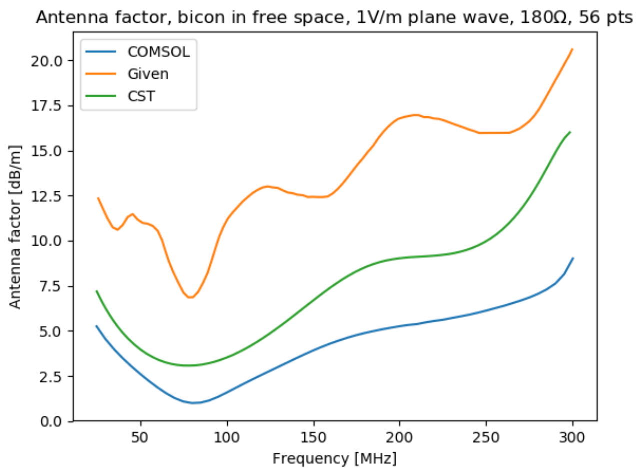

FIG. 5: Antenna factor of a biconical antenna model in free space interacting with a 1 V/m plane wave in COMSOL (blue). The minimum indicates a resonance of ∼75 MHz, which agrees with the CST model (green) and the manufacturer data for the real antenna (orange).

V/m plane wave. The result is a much more complex response from the antenna, as shown in Figure 6. There appears to be some agreement between the modelled resonances and the experimental data, such as around 100 MHz and 175 MHz, but clearly there is still substantial difference between the two.

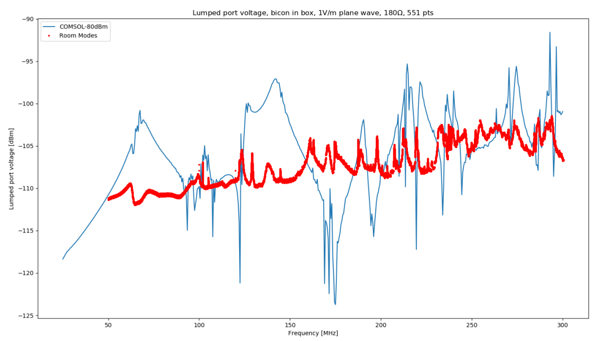

FIG. 6: Lumped port voltage of a biconical antenna model in a conducting box interacting with a 1 V/m plane wave in COMSOL (blue). Many resonances due to the box are observed, which can be compared to actual data taken using the real antenna in the shielded room (red).

The next task, then, is to add more detail to the room model and see if it improves the agreement. Using components from a very detailed CAD model of the shielded room, three components were added that were expected to make a difference in the resonant behavior of the antenna, specifically a door handle, 6 ceiling lights, and a breaker box. The change in the modelled results are shown in Figure 7.The addition of these few components to the model caused mostly minor shifting in the resonant behavior of the room, but it notably added two large peaks at 200 and 205 MHz. The comparison of this updated model to the experimental data is shown in Figure 8

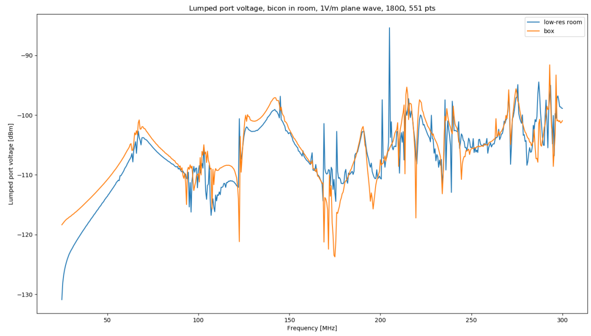

FIG. 7: Lumped port voltage of a biconical antenna model in a conducting box interacting with a 1 V/m plane wave in COMSOL with varied detail, first with a simple conducting box (orange), then with the addition of a door handle, 6 ceiling lights, and a breaker box (blue).

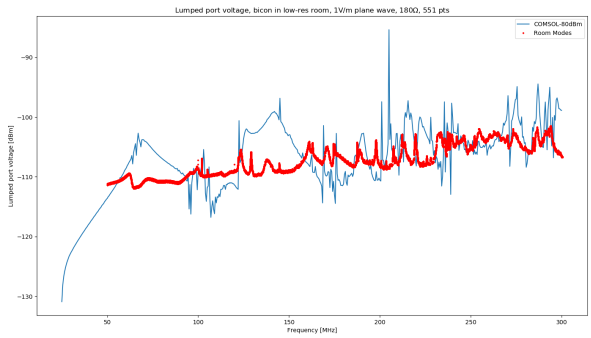

FIG. 8: Lumped port voltage of a biconical antenna model in a more-detailed conducting room interacting with a 1 V/m plane wave in COMSOL (blue). A door handle, 6 ceiling lights, and a breaker box were added to the simple box model. This is compared to actual data taken using the real antenna in the shielded room (red).

At this point the comparison is merely visual, and it would be constructive to compare the COMSOL model results to other data taken, but the agreement does qualitatively appear to improve with the addition of detail in the room.

Conclusion

Several types of work were done this summer that support the experiment to detect dark photons with a radio antenna. Specifically, possible analysis techniques were explored for the data from the recently completed run. Most notably, a detailed simulation of the experiment was created in COMSOL that gives responses of the port voltage and antenna factor of the biconical antenna when it is in the shielded room. Agreement between the COMSOL model and manufacturer data for the biconical model in free space give confidence to the accuracy of the later models. The antenna factor for the model of the biconical antenna in the room will ultimately be useful for analysis of a dark photon signal to determine electric field and therefore the coupling constant ϵ, and the dark photon mass m_γ will be determined from the frequency of the signal.

Additional work can be done to further explore the antenna response in COMSOL. Possible tests include adding more detail to the model and changing the location of the antenna in the room. The next stage of the experiment involves a Vivaldi antenna with frequency range of 300 MHz to 6 GHz, so a CAD model is being created and more COMSOL simulations will be performed to characterize its response. Next stages also involve switching to a better spectrum analyzer with the capability to sweep the full frequency range in one span and the addition of a cryogenic amplifier for more noise reduction. Additional work will continue to be done to analyze the data from the recent run and search for a signal.

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