論文の内容の要旨

論文題目 Experimental search for hidden photon CDM in the eV mass range with a concave mirror

(凹面鏡を用いた質量 eV 領域における hidden photon ダークマター探索)

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The existence of invisible matter (dark matter, DM) is supported by a lot of astronomical observations, and direct detection of dark matter is one of the most important tasks of cosmology and particle physics today. Although many groups around the world have paid a lot of effort to directly detect DM particles, it has not yet been achieved.

Most of experiments aiming at DM detection assume that dark matter is mainly composed of Weakly Interacting Massive Particles (WIMPs) and looking for their elastic scattering off atomic nuclei. However, there exist alternative candidates which account for DM features, and Weakly Interacting Slim Particles (WISPs), like axions and hidden photons, can be the main component of DM via the misalignment mechanism.

Hidden photons X^μ are gauge bosons of light extra U(1) symmetry beyond the Standard Model, and they interact with ordinary photons A^μ via a kinetic mixing term $(-\chi/2)F_{\mu\nu}X^{\mu\nu}$, where $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ and $X_{\mu\nu} = \partial_\mu X_\nu - \partial_\nu X_\mu$ and have non-zero mass $m_{\gamma'}$ via the Higgs or the Stueckelberg mechanism. We can thus survey hidden photons by using the mixing with ordinary photons, although the signal would be very faint because the photon-HP mixing parameter χ is assumed to be extremely small. We therefore need some amplification method, together with a sensitive detector, to search for hidden photon CDM.

One of the amplification methods is the use of a microwave cavity. It is pointed out that past experiments for axion DM is also sensitive for hidden photon, and their non-detection results for axion DM were translated to upper limits for the mixing parameter χ .

Additionally, a novel method using a dish antenna was recently proposed. Figure 1 is a schematic diagram of the method using a dish. Propagation of hidden photons inevitably induces accompanying ordinary electromagnetic component because of the existence of the mixing $(-\chi/2)F_{\mu\nu}X^{\mu\nu}$. A reflector thus reacts with the electromagnetic field and emits

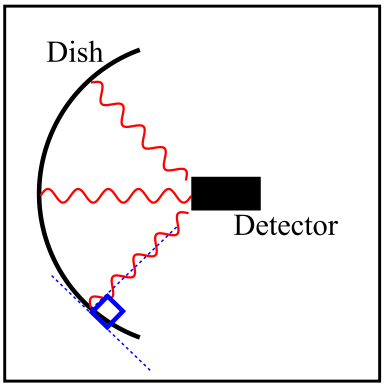

図 1: Schematic diagram of the method using a dish to search for hidden photon CDM.

ordinary photons to make the boundary condition be satisfied at the surface. DM hidden photons are non-relativistic, and the velocity v is assumed to be $v \sim 10^{-3}$ for an isothermal halo, which makes the wavelength of the massive state by far longer than that of ordinary photons. This nature leads to the emission of photons induced by DM hidden photons almost perpendicular to the surface of the reflector. Using a spherical surface, we can therefore concentrate photons induced by DM hidden photons to the center of the sphere.

In this thesis, we report on the first experimental search for hidden photon CDM with this amplification method. We used an optical set-up, a photodetector and a concave mirror, to survey DM hidden photons in the eV mass range.

We utilized a parabolic mirror as a 'dish' in the method. The parabolic mirror was previously used in the solar HP search experiment carried out in 2010, and is 500mm in diameter, 19mm thick, 1007mm focal length. The parabolic surface of the mirror is well approximated to be a spherical shape because of the long focal length in comparison with the mirror diameter.

A photomultiplier tube was used as the detector of induced emissions. We selected a photomultiplier R3550P (Hamamatsu Photonics, Japan) because of its low dark count rate of $\sim$ 5 counts/s. This photomultiplier tube has a low noise bialkali photocathode whose effective area is 22 mm in diameter, and is sensitive for photons of wavelength range 300–650 nm with a peak quantum efficiency of 17 %. Cosmic muons may emit Cherenkov light in the window of the photomultiplier. We reduced the effective area of the photomultiplier tube to 11 mm in diameter by a black paper shield in order to diminish the effect of the Cherenkov light reflected by the parabolic mirror and entering the window again.

We used a motorized stage to shift the position of the photomultiplier tube, which enabled us to measure background noise. A pair of mechanical micro-switches were equipped to calibrate the position of the stage even under the light-tight condition.

The mirror and the detector were mounted on a steel frame made out of slotted angle bars. We confirmed the stability of the optical alignment by checking the position of the detector before and after a month of test runs. The frame is wrapped with 150 μm thick black polyethylene sheets to shield from ambient light. Additionally, in order to attain higher light-tightness, we built another light-tight box of 1 m $\times$ 1 m $\times$ 3 m, inside which the apparatus described above was installed. The photodetector for the DM search was therefore in two-

図 2: Pictures of the setup. (Left) The framework made out of slotted angle bars. After installing optical instruments, the frame was wrapped with black polyethylene sheets. (Right) Two-fold light-tight box. The framework wrapped with black sheets was installed inside the larger light-tight box.

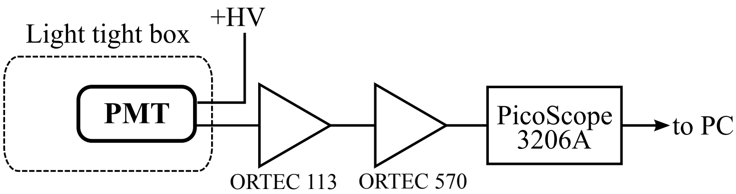

図 3: Schematic of the data acquisition. The output current of the photodetector is connected to a charge-sensitive preamplifier (ORTEC 113) followed by a shaper (ORTEC 572), then digitized by an oscilloscope (PicoScope 3206A).

fold light-tight box. We placed another photomultiplier tube between the inside light-tight box and the outside light-tight box for light-leak detection.

Figure 2 shows pictures of the setup. On the left panel, the framework to hold the arrangement is shown. After installing optical instruments, the frame was wrapped with black polyethylene sheets, and installed inside the larger box to form a two-fold light-tight box as shown in the right panel.

Figure 3 shows a schematic diagram of the data acquisition system. The output current of the photodetector is connected to a charge-sensitive preamplifier ORTEC 113 (ORTEC, the United States) followed by a shaper ORTEC 572 (ORTEC, the United States). The signal is then sent to a digital oscilloscope PicoScope 3206A (Pico Technology, the United Kingdom), which digitizes the signal at a sampling rate of 10M samples/s, and streams the data to a PC. Event triggering and pulse-height analysis are carried out in a software, which records pulse heights and arrival times.

After test runs to ensure that our method works well, we performed the experimental search from February 2015 to March 2015. The experimental set-up was placed in the underground laboratory of the University of Tokyo at East longitude $139°45'47''$, North latitude $35°42'50''$, and the mirror was directed to the West. The photodetector was operated for 8×10^5 s in total both at the center of the mirror sphere (position S) and at the position displaced from S by 25 mm (position B). The motorized stage shifted the detector between position S and position B repeatedly. The motorized stage was operated as follows: (i) halt

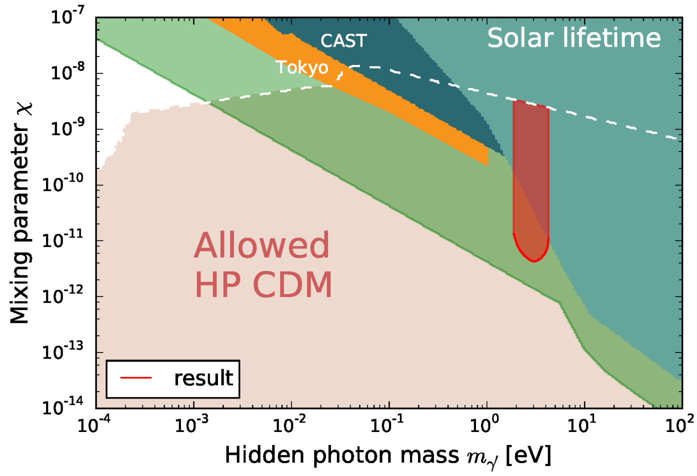

図 4: Excluded region of $\chi - m_{\gamma'}$ parameter space (red filled area around $m_{\gamma'} \sim$ eV).

at position S for 30 seconds, (ii) shift the position of the PMT from S to B, (iii) halt at position B for 30 seconds, (iv) restore the position from B to S.

Pulse height spectra for data taken at position S and position B are constructed. The spectrum for position B is subtracted from the spectrum for position S to extract the possible signal of hidden photon CDM. The result of subtraction was then fitted with a template function obtained by the calibration using LED pulses, and the difference of the count rate between at position S and at position B is estimated to be

$$N_{\rm fit} = (-1.9 \pm 3.8) \times 10^{-3}\,{\rm counts/s},$$

where we found no evidence for an excess.

We then translated this result to an upper limit to the photon-HP mixing parameter χ, assuming that DM is dominated by hidden photons, its local density is $\rho_{\rm CDM}^{\rm local} = 0.4\,{\rm GeV/cm^3}$, and the direction of hidden-photon vector is randomly distributed. Figure 4 shows a plot of the excluded region in $\chi - m_{\gamma'}$ parameter space of the model, where our result is colored red. Fig. 4 also shows constraints from other sources, including the study on hidden photons produced in the Sun in longitudinal mode (colored light green). Although the upper limit for χ obtained in this experiment is nominally weaker than the solar constraint, it is still significant because the solar limit strongly depends on the model of the Sun, in which severe discrepancy with the real situation may occur, while our experimental limit only assumes that DM is mainly composed of hidden-sector photons. In addition, the sensitivity of our experiment surpasses that of a preliminary run of a competitor with a 70 times larger mirror, which proves the superiority of our methodology. We are thus confident that the detailed description in this thesis is helpful for more sensitive experiments of the next generation.