On a Search for Hidden Photon CDM by a Multi-Cathode Counter

A.V.Kopylov[1], I.V.Orekhov and V.V.Petukhov

Institute for Nuclear Research of Russian Academy of Sciences,
117312, Prospect of 60th October Revolution 7A, Russia
E-mail: beril@inr.ru

ABSTRACT: We report on a new technique of a Multi-Cathode Counter (MCC) developed to search for hidden photon (HP) cold dark matter (CDM) with a mass from 5 to 500 eV. The method is suggested in the assumption that HP-photon mixing causes emission of single electrons from a metal cathode if the mass of hidden photon $m_{\gamma'}$ is greater than a work function of the metal φ_W. The measured effect from HP should be dependent on φ_W and on the structure of electronic shells of the metal used as a cathode. Potentially this can be used for a verification of the results obtained. Some preliminary results for the upper limit for mixing parameter χ have been obtained for HP with a mass from 5 eV to 10 keV as a pure illustration of the potential of this technique. The efforts are continued to refine the procedure of data treatment and to improve the work of MCC. A new detector with a more developed design is under construction.

KEYWORDS: Multiwire Counter, Gaseous Detectors, Hidden Photons

1. Introduction

The present data on the structure formation in the Universe indicate that most Dark Matter (DM) is "cold" i.e. should be non-relativistic. Neutrino in a Hot Dark Matter concept can be envisaged only in combination with Cold Dark Matter (CDM). Now the most attractive DM candidates appear to be Weakly Interactive Massive Particles (WIMP). Great progress in this field of research is outlined in [1]. However there are other alternatives, among them axion and axion-like particles (ALP) which is probably a next, most promising field. The efforts to discover axion are described in details in [2]. Another interesting opportunity is a hidden photon which is a light extra U(1) gauge bozon. As it was suggested in [3, 4] hidden photons (HP) may be observed in experiment through a kinetic mixing term $(\chi/2)F_{\mu\nu}X^{\mu\nu}$ with the ordinary photons, where χ is a parameter quantifying the kinetic mixing . Here $F_{\mu\nu}$ is the field stress of the ordinary electromagnetic field A^{μ} and $X^{\mu\nu}$ is the field stress of the HP field X^{μ}. Recently the eV mass range of HP was investigated with a dish antenna [5], a novel method proposed in [6]. The idea is to detect electromagnetic wave which is emitted by the oscillation of electrons of the antenna's surface under tiny ordinary electric field. A dark matter solution for HP with a mass $m_{\gamma'}$ reads [6]

$$\left.\begin{pmatrix}\mathbf{A}\\ \mathbf{X}\end{pmatrix}\right|_{\mathrm{DM}} = \mathbf{X}_{\mathrm{DM}}\begin{pmatrix}-\chi\\ 1\end{pmatrix}\exp\left(-i\omega t\right) \qquad (1)$$

i.e. has a spatially constant mode k = 0, oscillating with frequency $\omega = m_{\gamma'}$. This method works well only if the reflectance of antenna is high. The principal difference of our approach from [6]

[1] Corresponding author.

is that here we focus on shorter wavelengths, i.e. higher masses of HPs for which the reflectance of antenna is low. We make an assumption that in this case a HP-photon conversion will cause emission of single electrons from the surface of antenna similar to what one observes when metal is exposed to UV radiation. The details of how electrons are created after photons get absorbed by a metal photocathode are described in many papers, see, for example [7]. To register this conversion the detector should be highly sensitive to single electrons emitted from metal. Here we would like to draw attention to the fact that the detector in this case is sensitive exclusively to HP-photon conversion, not to photon-HP conversion. For the latter one this method does not work. We assume here that probability for the electron to be emitted after a hidden photon gets converted into ordinary electric field in a metal cathode would be equal to quantum efficiency η for a given metal to emit electron after absorption of a real UV photon of energy $\omega = m_{\gamma'}$. The obvious difference between these two processes is that UV photons are strongly absorbed by the metal while HPs move freely through the metal, but this lead only to some underestimation of the effect from HP-photon conversion. We did not take this into account. We neither took into account the effects of surface roughness of the cathode. We consider this to be small corrections and leave it for our further study. To make a practical implementation of this idea a special technique of a Multi-Cathode Counter (MCC) has been developed and some very preliminary data as a pure illustration of the potential of this technique in the search for hidden photons has been obtained.

2. Experimental apparatus

To count electrons emitted from a metal cathode we used a gaseous proportional counter filled by argon – methane (10%) mixture at 0.2 MPa. To detect single electrons the counter should have high ($\geq 10^5$) coefficient of gas amplification. The general view of the counter is presented on Fig.1 and the electronic scheme on Figure 2. Present design of MCC first described in [8] is a further development of the work with the aim to make an apparatus to register neutrino - nucleus coherent scattering [9, 10]. The cathode of the counter is 194 mm in diameter and 400 mm in length. It has relatively large (≈ 0.2 m^2) surface which acts in this experiment as "antenna" for HP but instead of reflecting electromagnetic waves it emits single electrons. The counter has a central anode wire of 20 μm and 4 cathodes, 3 of them are composed of an array of 50 μm nichrome wires tensed with a pitch of a few mm around anode one after another, and a fourth one, more distant from anode, is a cathode made of copper.

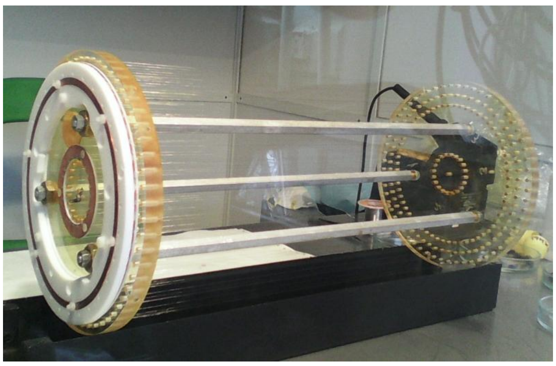

Figure 1. The central part of the counter.

The apparatus is counting electrons emitted from the walls of a cathode at short wavelengths $\omega = m_{\gamma'} \approx 5$ - 500 eV. The diameter of the first cathode D_1 is 40 mm to ensure high ($\geq 10^5$) coefficient of gas amplification in the central section of the counter. Three different configurations of the same counter are used to measure the count rate of single electrons. In the first configuration electrons, emitted from copper drift freely to the central section with high gas amplification. The highest negative potential is applied in this configuration to the copper cathode. The rate R_1 measured in this configuration

$$R_1 = R_{Cu} + R_{sp} \qquad (2)$$

Here R_{Cu} is the count rate from single electrons emitted from copper and R_{sp} – the rate from spurious pulses generated in the volume limited by a diameter 194 mm. The spurious pulses are generated by several sources. One of them is nichrome wires which have been used for cathodes in this detector. The micro protrusions (spearheads) on the surface of wires may generate single electrons in strong electric fields. Another source is not ideal dielectric used in the construction of the counter. It is very similar to a dark current observed for PMTs which was the main limiting factor in experiment with a dish antenna [5]. In the second configuration the highest negative potential is applied to the third cathode $D_3 = 180$ mm. In this configuration the count rate

$$R_2 = 0.11 \cdot R_{Cu} + R_{sp} \qquad (3)$$

Because the geometry of the counter in 1st configuration is very similar to its geometry in second configuration we assume that the rates from spurious pulses in these two configurations are equal. The factor 0.11 was obtained by calibration of the counter in 1st and 2nd configurations by UV source of the same intensity. In the third configuration the highest negative potential is applied to a second cathode $D_2 = 140$ mm. The rate R_3 measured in this configuration is determined by spurious pulses generated within a volume limited by smaller diameter 140 mm:

$$R_3 = r_{sp} \qquad (4)$$

As a measure of the effect from HPs we use the count rate

$$R_{MCC} = (R_1 - R_2)/0.89 = R_{Cu} \qquad (5)$$

The measurements were performed in each configuration by switching the counter consecutively in three different configurations, by calibration of the counter and by measuring the rates R_1, R_2 and R_3. Then from a number of measured points the average rates $\overline{R}_1$, $\overline{R}_2$ were found and from here - the average rate $\overline{R}_{MCC}$. Then from the scattering of the experimental points the uncertainties were calculated for each rate and, finally, for R_{MCC}. The count rate R_3 has been used to monitor the counting process to exclude some possible interference by external sources of electromagnetic disturbances.

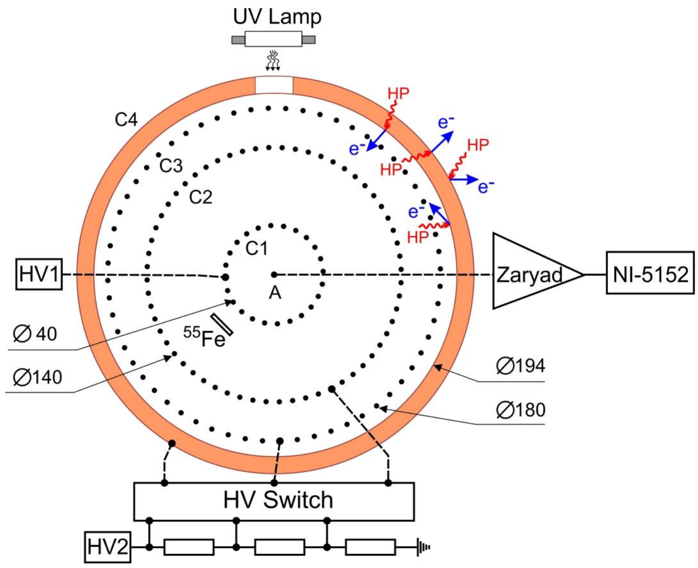

Figure 2. A simplified electronic scheme of a multi-cathode counter (MCC).
A – anode, C1 – C4 – cathodes, “Zaryad” – charge sensitive preamplifier.

3. Energy calibration and analysis

The calibration of the counter has been conducted by ^{55}Fe source and by UV light of the mercury lamp. The aim of the calibration was to determine the counting efficiency in all three configurations. The physics and techniques of single electron counting were described in details in many devoted articles; see, for example [11 - 13]. The X-ray source of ^{55}Fe has been placed inside the counter between first and second cathodes facing the anode wire. By performing this calibration we followed the standard technique described in many papers, for example in [14]. It was also described in our earlier papers [9, 10]. High voltage at first cathode was 2060 V and high voltages from the voltage divider has been used for all three configurations such as to ensure the amplitude of the pulse corresponding to peak 5.9 keV from K-line of ^{55}Mn, which is eradiated as a result of K-electron capture by ^{55}Fe, on the output of charge sensitive preamplifier to be at the level 1400 mV what corresponds to a gas amplification $A \approx 10^5$. The amplitude of the escape peak of argon at the energy 2.9 keV (5.9 keV minus 3.0 keV of K X-ray of argon escaping the detection region) was shifted from the due position in case of a linear response at about 700 mV to the one at approximately 1000 mV. This nonlinearity in the spectrum indicates that we have the regime of limited proportionality. From the approximation done through three points: zero and two peaks: 5.9 keV at 1400 mV and 2.9 keV at 1000 mV one can find that at energies less than 100 eV a gas amplification $A \approx 1.8{\cdot}10^5$ and the conversion factor is ≈ 2.3 eV/mV. It takes approximately 27 eV to create one electron-ion pair in argon. It means that single electron pulses should be observed in the region below 50 mV. The calibration by UV photons demonstrates that this is really so. The ^{55}Fe source has been removed and the internal walls of the counter were irradiated by UV light from a mercury lamp placed outside through a window made of melted silica. Figure 4 shows the single electron spectra obtained in measurements in 1st and 2nd configurations.

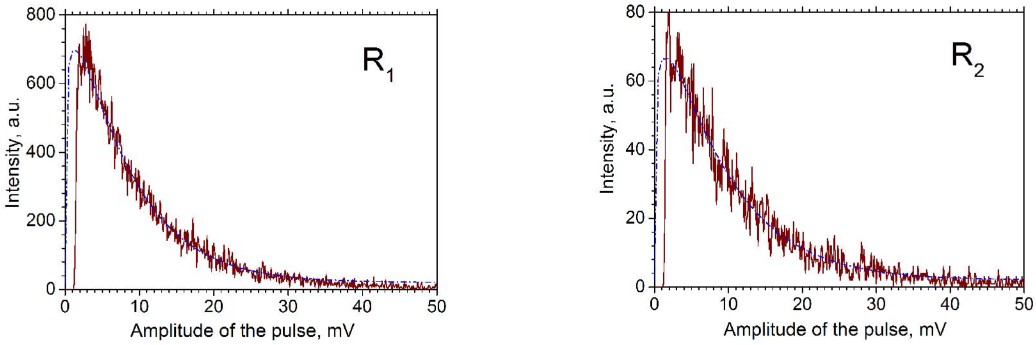

Figure 3. The single electron spectra obtained in measurements in 1st (R_1) and 2nd (R_2) configurations at the same flux of UV photons. The dashed curves indicate the Polya distribution.

Comparing the count rates R_1 and R_2 presented on Fig.3 one can see that in the 2nd configuration the count rate of single electrons was about 0.11 of the rate measured in the first one. It proves that in the 2nd configuration the electrons emitted from the walls of the counter were really rejected back by the 3rd cathode. It means that the counter in the 2nd configuration can be used for measurement of the background. To compare the gains in different configurations we used the same procedure as a one described in [15]; the inverse indexes of exponents were used as a measure of the gain of the counter. For the pulses above a threshold 3 mV the deviation from exponential distribution was small and could be neglected. The inverse indexes of exponent for all three configurations were in the range 8.4 ± 0.5 mV. The counting efficiency for the amplitudes of the pulses to be in the range [3 – 30] mV was found to be 76 ± 5 %. This number has been obtained by using Polya distribution [16]

$$P(A) = \left(\frac{A(1+\theta)}{\overline{A}} \right)^{\theta} \exp\left(\frac{-A(1+\theta)}{\overline{A}} \right) \qquad (6)$$

where A – gas amplification and θ - parameter which depends on a working gas and electric field configuration. From the approximation of the measured spectrum by Polya curve it was found that $\theta \approx 0.16$ what is in a reasonable agreement with the expected one for our working gas and electric field configuration. The counting efficiency has been corrected upon the results of calibrations performed in each of three configurations. The possibility to increase the counting efficiency is a subject of our further study. To have a further progress we need to lower the threshold.

In the measurements the shapes of the pulses on the output of a charge sensitive preamplifier are recorded by 8-bit digitizer. The “true” pulses have typically a relatively short front edge (a few microseconds) corresponding to the drift of positive ions to cathode and long (hundreds of microseconds) tail corresponding to the time of the baseline restoration of the charge sensitive preamplifier. The “wrong” pulses usually have a wrong (too fast or too slow or irregular) front edge or non exponential tail. In the analyses of the data only pulses with a baseline within ± 2 mV were taken into analyses with a proper evaluation of the resulted live time. Figures 4, 5 show the distribution of the events on the diagram “duration of front edge – parameter β” for the UV lamp and for real measurements. The parameter β is proportional to first derivative of the baseline approximated by a straight line in the interval 50 μs before the front edge. We used it as a measure of the quality of baseline in the prehistory of the event. The region of interest (ROI) box contains "true" pulses with amplitude in the interval [3 – 30] mV with a front edge in the interval [2 - 25 μs] and a parameter β in the interval 0.0 ± 0.1. The pulses beyond this region were rejected as "noisy" pulses. One can see that a ROI region contains 95 ± 5 % of all pulses (crosses) from UV lamp. By inspecting directly a small sample of the real pulses we found that inside of ROI region one can see only about 10% of the pulses with the "wrong" shape (circles).

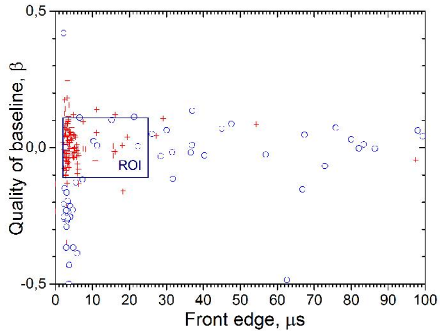

Figure 4. The distribution of the events for UV lamp.

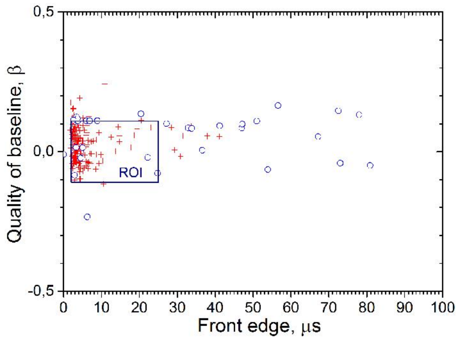

Figure 5. The distribution of the real events.

To reduce the background from external γ-radiation the counter has been placed in a cabinet with 30 cm iron shield. It resulted in decrease of the count rates of single-electron events by a factor of 2 (detector on a porch of a cabinet versus detector inside a cabinet) while the flux of gamma rays in the region around 200 keV has been attenuated in these lay-outs by a factor of 50. From here one gets a simple estimate of the background: inside a cabinet the γ-radiation can't be a major source of the single electron events, its contribution is not more than a few percent. The main source is spurious pulses similar to what one observes with PMT, this was also a limiting factor in experiment with a dish antenna [5]. To reduce this dark current we should make further improvements in the construction of the detector. This is our task for future.

The data were collected frame by frame. Each frame contained 2M points each point 100 ns. After collection of the data they were stored on a disk then the collection resumed. The analysis of the collected data was performed off-line. Only pulses with a baseline within ± 2 mV were taken into analyses with proper evaluation of a live time in each measurement. The frames with the signs of excessive noisiness were removed from analysis.

4. Sensitivity of the method

Here we follow the same ideology as developed in [6] for a dish antenna with one principal difference: instead of detecting electromagnetic waves we look for single electrons emitted from the surface of antenna. That is why we use in our experiment not antenna, but gaseous proportional counter (see Fig.1). We assume that similar to the emission of single electrons from metal by UV light or by X-rays the probability for the electron to be emitted when HP of the mass $m_{\gamma'}$ gets converted into an ordinary electric field in metal is equal to the quantum efficiency η for the photon's energy $\omega = m_{\gamma'}$. According to [6] if DM is totally made up of hidden photons, the power collected by antenna is

$$P = 2\alpha^2\chi^2\rho_{CDM}A_{dish} \qquad (7)$$

Where: $\alpha^2 = \cos^2\theta$, θ is the angle between the HP field, when it points in the same direction everywhere, and the plane of antenna, and $\alpha^2 = 2/3$ if HPs have random orientation; χ is the dimensionless parameter quantifying the kinetic mixing, $\rho_{CDM} \approx 0.3$ GeV/cm^3 – is the energy density of CDM which is taken here to be equal to the energy density of HPs and A_{dish} – the antenna's surface. In our case of gaseous proportional counter $P = R_{MCC}m_{\gamma'}/\eta$ and this expression will look

$$R_{MCC}m_{\gamma'} = 2\eta\alpha^2\chi^2\rho_{CDM}A_{MCC} \qquad (8)$$

Here A_{MCC} is the surface of the metal cathode of our counter. From here one can easily obtain

$$\chi_{sens} = 2.9\times10^{-12}\left(\frac{R_{MCC}}{\eta\ 1\ \mathrm{Hz}}\right)^{1/2}\left(\frac{m_{\gamma'}}{1\ \mathrm{eV}}\right)^{1/2}\left(\frac{0.3\ GeV/cm^3}{\rho_{CDM,halo}}\right)^{1/2}\left(\frac{1\ \mathrm{m}^2}{A_{MCC}}\right)^{1/2}\left(\frac{\sqrt{2/3}}{\alpha}\right) \qquad (9)$$

5. First data obtained

The detector was placed at the ground floor of a building in Troitsk, Moscow in a specially constructed cabinet with 30 cm iron shield. All count rates were in a few Hz range. The average value of R_{MCC} calculated for "quiet" interval during 28 days of measurements was found to be: $\overline{R}_{MCC} = -0.06 \pm 0.36$ Hz. The uncertainty has been found from the real scattering of the experimental points. So if we take the normal distribution for uncertainties, then we obtain that at 95% confidence level: $\overline{R}_{MCC} < 0.66$ Hz. The quantum efficiency η was taken from [17] for masses of HPs $m_{\gamma'}<11.6$ eV (magenta), from [18] for 10 eV $< m_{\gamma'} <$ 60 eV (red), from [19] for 20 eV $< m_{\gamma'} <$ 10 keV (green) and from [20] for 50 eV $< m_{\gamma'} <$ 10 keV (blue). From the expression (9) we obtain an upper limit for a mixing constant χ. The values of a mixing constant χ allowed by this experiment are below the curve presented on Figure 6. The systematic uncertainty is mainly determined by the uncertainty in quantum efficiency which is taken to be about 30% following the estimates done in [17]. To decrease this limit one should construct a detector with lower count rate of spurious pulses. The difference in the curves presented at Fig.6 is explained by different purity of copper used in measurements. The data from [17] and [20] were obtained for atomically clean copper samples prepared by evaporation of copper in high vacuum while routinely cleaned (by solvents) copper samples were used in [18, 19]. For atomically clean copper one can see the effect of electronic shells while for routinely cleaned copper the spectra are rather smudged. In our detector for cathode we used routinely cleaned (by solvents) copper. There is a strong dependence of the effect not only on the work function but also on the structure of the electronic shells of the metal used for a cathode. Potentially this can be used for verification that the obtained result is really from HPs. For this we should make measurements using cathodes made of different metals.

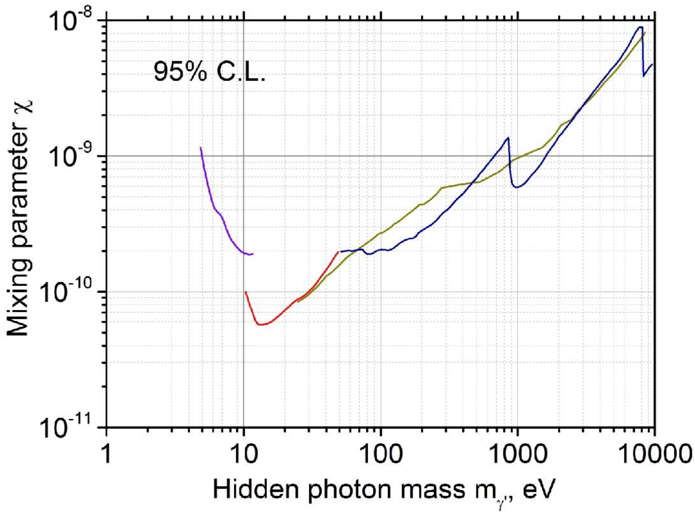

Figure 6. The limit for a mixing constant χ.

These numbers are first, very preliminary result for hidden photons with a mass from 5 to 500 eV. Stellar astrophysics provides stringent constraints for this value. The limits obtained by using some astrophysical models, see for example [21, 22] and references therein, were about two - three orders of magnitude lower. This result has been obtained in direct measurements in a laboratory experiment by observing single electrons emitted from the surface of a copper cathode. At present time this is the only experiment for the mass range from 5 to 500 eV using this technique which is sensitive only to HP-photon conversion and is not sensitive to photon-HP conversion. The limits obtained from stellar astrophysics are based on the models when both conversions are alike. We plan to continue the measurements to collect more data and in our plans also to make further improvements in the construction of MCC mainly with the aim to reduce count rate of spurious pulses.

6. Conclusion

A new technique of Multi Cathode Counter (MCC) has been developed to search for hidden photon CDM in the assumption that all dark matter is composed of hidden photons (HP). It was assumed also that if HPs have a mass greater than a work function of the metal of a cathode, they will induce emission of single electrons from a cathode. The technique used in this experiment is sensitive to HP – photon conversion and is not sensitive to photon – HP conversion. First preliminary result has been obtained for HPs with a mass from 5 to 500 eV which demonstrate that this method works. The upper limit is above the ones obtained from stellar astrophysics by two - three orders of magnitude (see Fig.7 taken from [22]), but our result (MCC, yellow lines) has been obtained in direct measurements in a laboratory experiment.

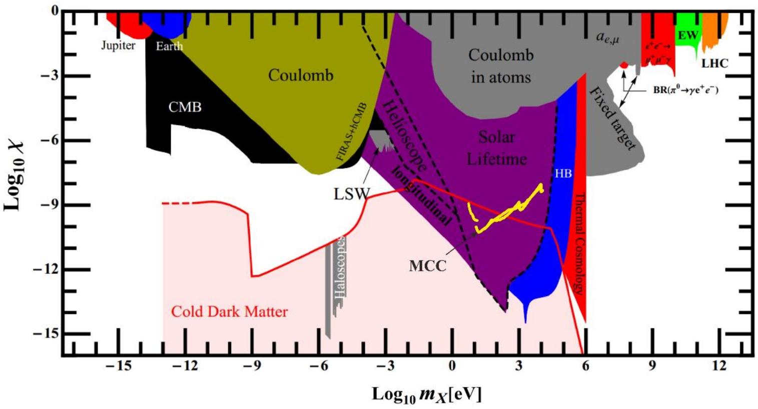

Figure 7. Constrained and still testable regions of photon/hidden-photon mixing.

Further progress will depend upon how successful will be our efforts to construct a detector with a reduced count rate of spurious pulses. If they are successful and all sources of spurious pulses are eliminated then the only source will be left, which can be eliminated by no means, it's a dark matter. The same will be true also for PMTs provided that dark matter is really composed of hidden photons and their mass is greater than a work function of a metal used for internal elements of detector. In our plans are to continue the measurements to collect more data and to refine the procedure of data treatment. At present time we are also constructing a new detector with a more developed design.

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Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

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