A Search for Hidden Photon CDM in a Multi-Cathode Counter (MCC) data

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Abstract

A search for hidden photon cold dark matter in a mass range from 5 to 500 eV in data collected during 60 days in November and December, 2015 by a Multi-Cathode Counter (MCC) is reported. From the analyses of this data we found no evidence for the existence of HP CDM and set an upper limit on the photon-HP mixing parameter $\chi$. This is the first result obtained by direct measurements in this mass range for hidden photon CDM using a single electron event in MCC as a signature.

Key words: dark matter, gaseous detectors
1 Introduction

Hidden-sector photons as massive particles having only a tiny interaction (kinetic mixing) with known particles was suggested in [1] where it has been also emphasized that stellar evolution can place a strong limit for these species. However recently the interest to HPs as the candidate for CDM has been revived probably because the experiments on WIMPS as a paradigm for dark matter produce negative results what stimulates researchers to look for new horizons.

The low energy Lagrangian of this model

\[ \mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\chi}{2} F_{\mu\nu} X^{\mu\nu} + \frac{m_{\gamma'}}{2} X_{\mu} X^{\mu} + J^\mu A_\mu \]  

where \( F_{\mu\nu} \) is the field strength of the ordinary electromagnetic field \( A^\mu \), and \( X_{\mu\nu} \) is the field strength of the HP field \( X^\mu \). Lagrangian contains a mixing term with \( \chi \) - the mixing parameter for a given mass \( m_{\gamma'} \) of a HP [2] which determines the probability of HP-photon conversion by which HP can be “seen” in experiment. Recently the eV mass range of HP CDM was investigated with a dish antenna [3] a novel method proposed in [4]. The method suggests detection of a reflected from metallic mirror (antenna) electromagnetic wave which is emitted by the oscillation of electrons of the antenna’s surface induced by the tiny electric field of HP. Noteworthy, the target in this novel method is not a mass but a surface of the detector because the conversion of HP into photon occurs at the interface of metal-dielectric. The method should work only if the reflectance of mirror is high. But what would be if the reflectance of mirror is low? Here in our work we made a focus exactly on this case, assuming that at higher masses of HPs the oscillation of electrons of antennas surface induced by HPs will produce with certain quantum efficiency the emission of single electrons from metal. We take this value equal to the quantum efficiency for real photon with energy \( \omega = m_{\gamma'} \) to emit electron from the surface of a metal. Thus we proposed as a method for detection of hidden photon CDM to search for the events with single-electron emission from metallic surface as a signature of the conversion HP-photon. To record these events a detector should be highly sensitive to single electrons emitted from the surface and also should be devised a way for subtraction of the background from other sources what is very essential part of the work. As a special technique to solve this task we devised a Multi-Cathode Counter (MCC) which has been designed, assembled and tested during last year. This counter has been described in detail in [5], [6]. We report here the result obtained from data collected during 60 days in November and December, 2015 on this multi-cathode counter.
2 Experimental part

The general view of the counter can be found in [5], the simplified electronic scheme is presented on Fig. 1. It is a gaseous proportional counter filled with argon-methane (10%) mixture at 0.2 MPa with four cathodes. The counter has a central anode wire of 20 mm, three cathodes made of 100 mm nichrome wires tensed with a pitch of a few mm and a fourth metal cathode which acts as “antenna” for HPs. The external (4th) cathode of the counter made of copper cylinder has 194 mm in diameter and 400 mm in length. The cathode has been cleaned by a routine technique. Commercially available copper was chemically etched, rinsed with distilled water and ethanol. It has relatively large (≈ 20.2 m²) surface which acts as a “mirror”. The detector is counting electrons emitted from a copper cathode under the impact of hidden photons with $\omega = m_{\gamma'} \approx 5 \div 500$ eV. Because the reflectance of the “mirror” is low at these energies it is assumed that one should observe not photons reflected from the “mirror” but electrons emitted from a copper cathode.

Fig. 1. Simplified electronic scheme.

The counter is used in three different configurations. In first configuration used to measure the count rate $R_1$ of single electrons emitted from a copper cathode electrons emitted from copper drift freely into the central section with high gas amplification. In 2nd configuration electrons emitted from copper are scattered back in argon at 0.2 MPa by higher negative potential of 3rd cathode which acts as a barrier. In 3rd configuration the highest negative potential is applied to 2nd cathode which acts as a barrier. As a measure of the effect from hidden photons we use the expression

$$R_{MCC} = R_1 - (R_2 - D_3/D_2 \cdot R_3)$$

(2)

here $R_2$ ($R_3$) is the count rate in 2nd (3rd) configurations, $D_3$ ($D_2$) is a diameter.
of the 3\textsuperscript{rd} (2\textsuperscript{nd}) cathode. This expression enables to subtract the background from the ends of the counter with distorted electric fields and also the one from single electrons drifted from a gas phase outside of the cathode in 2\textsuperscript{nd} configuration as it was explained with all details of counting procedure in \cite{6}. The counter has been placed in a steel cabinet with 30 cm iron shield. The count rate of single-electron events decreased by a factor of 2 in comparison with the one when detector was outside of the shield while the flux of gammas in the region between peaks 511 and 661.6 keV was attenuated by a factor of 30. For further reduction of background count rates it would be highly desirable to collect data in an underground chamber where the flux of muons is decreased by many orders of magnitude. This part of the work is in our plans also.

For calibration of the counter we used $^{55}$Fe source and UV light of the mercury lamp. High voltages in all three configurations were picked up to get a gas amplification of about $10^5$ so that amplitude of 5.9 keV peak on the output of charge sensitive preamplifier reached a level 1400 mV. The counter was working in a mode of limited proportionality which could be observed by two peaks of $^{55}$Fe source as it was explained in \cite{6}. Then the internal walls of the counter were irradiated by UV light of a mercury lamp through a window made of melted silica. Fig. 2 shows the single electron spectra obtained in measurements in 1\textsuperscript{st} and 2\textsuperscript{nd} configurations by the same intensity of UV light.

![Fig. 2. The single electron spectra obtained in measurements in 1\textsuperscript{st} (a) and 2\textsuperscript{nd} (b) configurations at the same flux of UV photons. The conversion factor is $\approx 2.27$ eV/mV.](image)

One can see that in the 2\textsuperscript{nd} configuration the count rate was about 10 times lower than in the first one. It means that electrons emitted from the walls of the counter in 2\textsuperscript{nd} configuration were scattered back and did not reach a central section. Thus a count rate in 2\textsuperscript{nd} configuration is a background and should be subtracted. Single electron spectra obtained in all 3 configurations had an exponential shape with the same inverse index of exponent in the range $8.4 \pm 0.4$ mV. By the conversion factor 2.27 eV/mV it is near to the average energy 27 eV to produce electron-ion pare in argon. Data were collected by
frames. Each frame contained 2M points, each point 100 ns. The collected data were stored on a disk then the collection resumed. The analysis of the collected data was done off-line. The noisy periods were removed from analysis.

3 Sensitivity of the method

By conducting this experiment it was assumed that if hidden photons have a mass greater than a work function of a metal of the cathode then passing through a cathode they will induce the oscillation of the current on the surface of a cathode which will stimulate emission of electrons from metal. The very substantial point is that the conversion of HPs into electrons emitted from the metal occurs at the interface metal – dielectric. The counter detects fields, not particles, so the effect from HP is proportional to the surface of the cathode. As it was suggested in [4] for antenna, here it was assumed that if DM is totally made up of hidden photons, the power concentrated on the cathode of the counter is

\[ P = 2\alpha^2 \chi^2 \rho_{CDM} A_{MCC} \]  \hspace{1cm} (3)

where \( A_{MCC} = 0.2 \ m^2 \) is the surface of the cathode of the counter and \( \alpha = |\cos(\theta)| \) if HPs are oriented in the same direction but \( \alpha = \sqrt{2/3} \) if HPs have random orientation. For our detector we should take for \( P \) the value \( R_{MCC} m_{\gamma}/\eta \). Then from the expression Eq.(3) taking \( \alpha = \sqrt{2/3} \) one can easily obtain sensitivity:

\[ \chi_{sens} = 2.9 \cdot 10^{-12} \left( \frac{R_{MCC}}{\eta \text{ 1 Hz}} \right)^{\frac{1}{2}} \left( \frac{m_{\gamma}}{\text{eV}} \right)^{\frac{1}{2}} \left( \frac{0.3 \text{ GeV/cm}^3}{\rho_{CDM, halo}} \right)^{\frac{1}{2}} \left( \frac{1 \text{ m}^2}{A_{MCC}} \right)^{\frac{1}{2}} \left( \frac{\sqrt{2/3}}{\alpha} \right) \]  \hspace{1cm} (4)

4 The results obtained from data collected on MCC

We report results from data collected during 60 days of the search for HPs in November and December, 2015. The scattering of the experimental points \( R_1, R_2, R_3 \) has been used for the evaluation of the total uncertainty of measurements. The average value of \( R_{MCC} \) calculated for this period was found to be \( \bar{R}_{MCC} = 0.06 \pm 0.18 \text{ Hz} \). If to take the normal distribution for uncertainties then we obtain that at 95% confidence level: \( R_{MCC} < 0.42 \text{ Hz} \). We found no
evidence of the existence of HP CDM. Fig. 3 shows the upper limit obtained from the expression Eq. (4) as a function of the mass of the hidden photon. Here for masses of HPs $m_{\gamma'} < 11.6$ eV (magenta) the quantum efficiency $\eta$ was taken from [8], for $10 \text{ eV} < m_{\gamma'} < 60 \text{ eV}$ (red) – from [7], for $m_{\gamma'}$ from 20 eV till 10 keV (green) – from [9] and from 50 eV till 10 keV (blue) – from [10].

![Graph showing the upper limit for a mixing constant $\chi$.](image)

Fig. 3. The upper limit for a mixing constant $\chi$.

One can see that the highest sensitivity has been reached in the interval from approximately 10 eV till about 20 eV (red line). The major source of systematic error is the uncertainty in quantum efficiency. The estimated uncertainty in determination of $\eta$ for copper in this range of masses is about $\pm 30\%$ [7]. The difference between green and blue line is explained by difference in cleaning procedure of copper. Green line - when quantum efficiencies are taken for routinely cleaned copper (by solvents) while blue line - for meticulously done preparation of copper specimen by evaporation in high vacuum without any contact with atmosphere. For meticulously cleaned copper the impact of electron shells is clearly seen in the data while for routinely cleaned copper the effect of electron shells is rather smoothed. This can explain also a divergence at 10 eV (magenta – carefully prepared clean Cu films while red – routinely cleaned copper).

5 Conclusion

A new technique of Multi Cathode Counter (MCC) has been developed to search for hidden photon CDM by single electrons emitted from the surface of metal. The sensitivity was estimated in the assumption that all dark matter is composed of hidden photons (HP). In method suggested it was assumed that HPs of the mass greater than a work function of the metal, the cathode of the counter is fabricated induce emission of single electrons from a cathode. The peculiarity of this signature means that conversion of HP in photon occurs at the interface metal-dielectric. The results have been obtained for HPs with
a mass from 5 to 500 eV from data collected during 60 days in November and December, 2015. From the analysis of this data we found no evidence for the existence of HP CDM and set an upper limit on the photon-HP mixing parameter $\chi$ with a minimum on the level of about $5 \cdot 10^{-11}$ at 95% CL for the hidden photon mass $12 \div 15$ eV. Stellar astrophysics provides stringent constraint for this value. Our result is deep inside the regions excluded by astrophysical models; see for example [11] and references therein. The new thing is that this result with HP CDM was obtained in direct measurements with a very peculiar signature of conversion HP-photon at the interface metal-dielectric. 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 and with this new detector we are planning to collect data in an underground laboratory with a very low flux of muons.

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