Search for dark matter in the form of axion-like particles and hidden photons in the XMASS detector

Kazufumi Sato for the XMASS collaboration
Institute for Space-Earth Environmental Research, Nagoya University, Nagoya, Aichi
464-8601, Japan
E-mail: kazufumi@isee.nagoya-u.ac.jp

Abstract. Axion-like Particles (ALPs) and Hidden Photons (HPs) are candidates of cold dark matter. These bosons are experimentally interesting because they are absorbed by materials through an interaction analogous to a photoelectric effect, transferring the energy equivalent to their rest mass to recoil electrons. XMASS is an experiment aiming at direct detection of dark matter, using single-phase liquid-xenon scintillator at the Kamioka Observatory in Japan. With its low background environment, the XMASS detector has a good sensitivity to the electron recoil signals from ALPs and HPs. Analyzing 800 live-days of XMASS data with 327 kg liquid xenon in the fiducial volume, we set the most stringent upper limits on the coupling constant $g_{Ae}$ of ALPs and the parameter for kinetic mixing $\alpha'/\alpha$ of HPs in the mass range from 40 to 120 keV/$c^2$.

1. Introduction
Very weakly interacting slim particles, such as Hidden Photons (HPs) and Axion-like Particles (ALPs), are candidates of cold DM [1]. HP is predicted as a gauge boson of hidden U(1) sector, and ALPs appears in some string theory as a pseudo-Nambu-Goldston boson. A wide mass region is allowed for these bosons. According to the allowable parameter space shown in Fig. 5 of Ref. [1], HP with a mass of less than $O(100\text{keV})$ can be a cold DM candidate. In high mass region, the kinetic mixing parameter of HP, $\alpha'/\alpha$, is strongly limited to $\alpha'/\alpha < 10^{-26}$ by indirect searches. Such indirect limits are, however, relatively weak ($\alpha'/\alpha < O(10^{-24})$) around 90 keV/$c^2$, where a detector dedicated for direct dark matter search has a high sensitivity.

XMASS is one of the experiments for the direct dark matter search using a liquid xenon scintillator. XMASS searches for an interaction of DM with xenon target resulting in scintillation emissions induced by recoiled particles. XMASS has a sensitivity not only for a standard WIMPs producing nuclear recoils, but also for other types of DM producing recoil electrons. HPs and ALPs are expected to produce the recoil electron signals, as described in detail in Section 3.1.

XMASS continued a stable data taking from November 2013 to March 2019. With the large data exposure, XMASS is exploring the variety of physics [2]. In this report, we present results of the searches for ALPs and HPs using 800 live-days of XMASS data taken in 2013–2016.

2. XMASS detector
The XMASS detector [3] is located 2700 m.w.e underground at Kamioka Observatory in Japan. The detector consists of an inner detector contained in a vacuum-insulated copper vessel, and
an outer detector surrounding the vessel. The inner detector is a liquid xenon scintillator with 832 kg of sensitive volume. A scintillation emission resulting from the interaction between DM and the xenon target is detected by 642 photomultiplier tubes (PMTs) which cover ~62% of the inner surface of the sensitive volume. The outer detector is a cylindrical-shaped water-Cherenkov counter used as an active veto for cosmic-ray muons and as a passive shield for neutrons and γ-rays from outside environment.

3. Analysis

3.1. Expected signal

HPs and ALPs can interact with electrons; ALPs can have a coupling constant \( g_{\text{Ae}} \) with electrons and HPs can kinetically mix with normal photons with strength \( \alpha'/\alpha \). As the results, both bosons are absorbed by materials through an interaction analogous to a photoelectric effect [4], transferring their total energy to recoiled electrons. Assuming the bosons are non-relativistic, the energy they deposit in the detector is equivalent to their rest mass.

The event rate of the absorption of ALPs (HPs) in the xenon target, \( R_{\text{ALP}}(\text{HP}) \), is expressed in the term of the cross-section of photoelectric effect \( \sigma_{\text{pe}} \) replacing the photon energy \( \omega \) by the mass \( m_{\text{ALP}}(\text{HP}) \), as [4]:

\[
R_{\text{ALP}}[1/\text{kg/day}] = \frac{1.2 \times 10^{19}}{A} g_{\text{Ae}}^2 \sigma_{\text{pe}}(\omega = m_{\text{ALP}})[\text{barn}] \cdot m_{\text{ALP}}[\text{keV}] \tag{1}
\]

for ALPs and

\[
R_{\text{HP}}[1/\text{kg/day}] = \frac{4 \times 10^{23} \alpha' \sigma_{\text{pe}}(\omega = m_{\text{HP}})[\text{barn}]}{\alpha} m_{\text{HP}}[\text{keV}] \tag{2}
\]

for HPs, where \( A = 131.3 \) is xenon’s atomic mass and we assume that a DM density is 0.3 GeV/cm\(^3\). Because the absorption is an analogue of photoelectric effect, the detector response to ALPs (HPs) with mass \( m_{\text{ALP}}(\text{HP}) \) was evaluated using a Monte Carlo (MC) simulation for standard photons whose energies are equal to \( m_{\text{ALP}}(\text{HP}) \). The expected energy spectrum is an almost Gaussian which peaks around \( m_{\text{ALP}(\text{HP})} \), as shown in Fig. 1.

3.2. Data reduction

We searched for the signal peaks in the observed energy spectrum. The details of analysis are presented in [2].

We analyzed events where at least 4 PMTs have hits over 0.2 PE threshold in the inner detector and no significant activities in the outer detector. XMASS standard cuts [2] were applied to reject events originating from PMT after-pulses and electronic noise.

In this stage, dominant backgrounds (BGs) come from β-rays and γ-rays from radioactive isotopes (RIs) contained in the detector materials, such as the PMTs and its support structure. The xenon volume itself serves as an effective shield for such radiations. An event vertex is reconstructed based on a maximum-likelihood evaluation of the observed PE distribution in the PMTs [3]. By requiring the vertex to be reconstructed inside a fiducial volume which is an inner region less than 30 cm radius, these BGs were effectively suppressed by three orders of magnitude.

The energy spectrum after the fiducial volume cut is shown in Fig. 2, where the energy deposit of the event is reconstructed from the total number of PEs (NPE\(_{\text{cor}}\)) with corrections for the position dependence of the PE detection efficiency and for time-dependent change of xenon optical properties [2]. Avoiding a low energy region where we found the contribution from mis-reconstructed events [2] due to dead PMTs, we searched for the signals from ALPs and HPs in the region from 590 to 1760 NPE\(_{\text{cor}}\) corresponding to 40–120 keV, where the event rate is \( \sim 5 \times 10^{-4} \) counts/day/kg/keV. The dominant BGs came from RIs dissolved in liquid xenon, such as \(^{85}\)Kr, \(^{214}\)Pb which is a \(^{222}\)Rn daughter, \(^{39}\)Ar, and \(^{14}\)C. The quantitative evaluation for
abundances of these RIs as well as RIs with smaller contribution, such as RIs in the detector materials and xenon isotopes activated by external neutrons, is described in [2].

3.3. Peak search

We searched for a signal peak by fitting the histogram of the observed energy spectrum (Fig. 2) with MC expectations for BG RIs and signals. For ALPs, the fitting chi-square was defined as:

$$
\chi^2_{fit}(m_{ALP}, g_{AE}) = \sum_i \frac{(R^i_{obs} - R^i_{BGtot} - R^i_{ALP}(m_{ALP}, g_{AE}))^2}{(\delta R^i_{obs})^2 + (\delta R^i_{BGtot})^2 + (\delta R^i_{ALP})^2} + \chi^2_{sys},
$$

where $R^i_{obs}$, $R^i_{BGtot}$, and $R^i_{ALP}$ are event rates in the $i$-th bin for the data, BG MC, and signal MC, respectively, and $\delta R_{obs}, \delta R_{BGtot}$, and $\delta R_{ALP}$ are their respective statistical errors. The chi-square for HPs is obtained by replacing $R^i_{ALP}(m_{ALP}, g_{AE})$ to $R^i_{HP}(m_{HP}, \alpha'/\alpha)$. The $R_{BGtot}$ is the sum of BG MCs for each RI, i.e.:

$$
R_{BGtot} = \sum_{j:RI \text{ types}} p_j R_{j-th \text{ BG}},
$$

where the $R_{j-th \text{ BG}}$ is the expected event rate from the $j$-th RI and $p_j$ is its scale parameter whose initial value is unity. The chi-square was minimized separately for every 2.5 keV/c$^2$ step in the mass between 40–120 keV/c$^2$ and for each fine step of $\alpha'/\alpha$ in the $\alpha'/\alpha > 0$ region, by fitting the $p_j$s. We thus obtained the chi-square profile as a function of $\alpha'/\alpha$ for each mass. The systematic uncertainties are taken into consideration through a penalty term $\chi^2_{sys}$ in Eq. (3). It handles the uncertainty of the abundance of each RI and the uncertainties of MC.
Figure 3. Constraints on $g_{Ae}$ of ALPs (left) and $\alpha'/\alpha$ of HPs (right). The red line shows the 90% CL constraint presented in this report. The limits from other direct searches [5, 6, 7, 8] and indirect searches [9] are also shown.

parameters which are the non-linearity of xenon scintillation yield, the energy resolution and position resolution of the detector, and BG increases due to dead PMTs. The detail descriptions of $\chi^2_{sys}$ and the systematic uncertainties are found in [2].

4. Result
We did not find any finite signal peaks, and thus set 90% CL upper limits on $g_{Ae}$ and $\alpha'/\alpha$ in a 40–120 keV/$c^2$ mass region, as shown in Fig. 3. Our limits, $g_{Ae} < 1.6 \times 10^{-13} - 4 \times 10^{-13}$ for ALPs and $\alpha'/\alpha < 2 \times 10^{-27} - 6 \times 10^{-26}$ for HPs, are the most stringent limits over this mass range. Limits from other direct and indirect searches are also shown in the figure. Our results compensate the HP mass region where the indirect limits are relatively weak, and cover the higher ALP mass region than limits from LUX and PandaX-II.

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