Search for exotic neutrino-electron interactions using solar neutrinos in XMASS-I

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Abstract. In recent years, the larger size and lower background of dark matter search detectors have opened up a new frontier of searching for new physics other than dark matter using these detectors. One of them is the search for new properties of neutrinos by observing the interaction of neutrinos at low energy. XMASS is a multi-purpose experiment using xenon exclusively in its liquid xenon (LXe) and is located at the Kamioka Observatory in Japan. We searched for exotic neutrino-electron interactions that could be produced by either a neutrino millicharge, a neutrino magnetic moment, or by dark photons, which might affect the interaction cross section of solar neutrinos in XMASS. We analyzed data taken between November 2013 and March 2016 amounting to 711 live days. No significant signal has been found above the predicted background level in detector. We obtained an upper limit for neutrino millicharge of $5.4 \times 10^{-11}e$ for all flavors of neutrino. We also set individual flavors limits for $\nu_\mu$ and $\nu_\tau$, which are the best limits obtained by direct detection. We also obtain an upper limit for the neutrino magnetic moment of $1.8 \times 10^{-10} \mu_B$. In addition, we obtain upper limits for the coupling constant of dark photons in the $U(1)_{B-L}$ model. This result almost excludes the possibility to understand the muon $g-2$ anomaly by dark photons.

1. Introduction

Dark matter search detectors, which require both a low threshold and low background have the potential to enable searches for deviations from standard model expectations that may result from new physics. Furthermore, in recent years, dark matter search detectors have become larger, $O(\text{ton})$ size, and the accuracy of searching for new physics has improved.

XMASS is a single phase liquid xenon detector [1]. XMASS-I searched for various dark matter candidates in various ways; for example by annual modulation [2] and in a fiducial volume [3]. XMASS-I also focused on another physics target taking advantage of its large volume, low threshold and low background. Here we present the analysis result of a search for a potential neutrino-electron exotic interaction using XMASS-I [4] and also investigate neutrino millicharge, magnetic moment and dark photons via $U(1)_{B-L}$.

These kinds of exotic interactions arise in certain extensions of the standard model. For example, neutrinos may have a very slight charge, a millicharge, as charge quantization has not been proven [5]. Some extensions of the Standard Model also yield neutrino magnetic moments at currently observable levels, which are of $O(10^{-12} \sim 10^{-10} \mu_B)$ [6]. In both cases, an electro-magnetic term has to be added in the cross section of neutrino-electron interactions. In another scenario dark photons included in the hidden sector can be gauge bosons which influence...
neutrino-electron interactions \[7\]. In this paper we report on a search for dark photons from a gauged $U(1)_{B-L}$ theory, which have mass $M_{A'}$ and a coupling constant $g_{B-L}$.

We used solar neutrinos to search for all these exotic interactions. Solar neutrinos are generated by nuclear fussion in the Sun. The majority of solar neutrinos come from the proton-proton ($pp$) reaction. The energy spectrum of the $pp$ solar neutrino is continuous with its endpoint at 422 keV.

The cross section terms for the interations we study cannot be fully discussed in the short paper. We take into account atomic effects when calculating interaction probabilities both with and without the additional exotic interaction terms; as the resulting differences are concentrated at the lowest energies, a low threshold DM detector like XMASS-I is well suited to study them.

2. Analysis

The XMASS-I detector \[8\] is located underground at Kamioka Observatory in Japan. The detector’s active volume is about 80 cm in diameter and contains 832 kg of liquid xenon. XMASS-I was the world’s first ton-scale liquid xenon dark matter detector. Its liquid scintillation oriented design easily scalable and optimized for high light collection. Xenon’s high atomic number ($Z=54$) and high density ($\sim 2.96 \text{g/cc}$) allow for a compact detector in which self-shielding in the LXe target can protect an inner fiducial volume from external gamma rays. The 632 2inch PMTs are mounted in a pentakis-dodecahedral OFHC Cu holder inside an OFHC Cu cryostat. Photocathode coverage in the detector is about 62%. The cryostat is installed in a cylindrical water tank of 10 m diameter and 11 m height which contains 72 20-inch PMTs and ultra pure water and functions as the outer detector (OD), providing a muon veto.

Commissioning the XMASS-I detector started in September, 2010; after detector refurbishment and addition of FADC readout five years of continues data taking started in November 2013. During this period, the scintillation light yield was traced by inserting a $^{57}\text{Co}$ source into the inner detector and/or bringing a $^{60}\text{Co}$ source to the outside of the cryostat every one or two weeks. Data taking with the XMASS-I detector was completed in February 2019.

For the analyses presented here we analyzed data accumulated between November 2013 and March 2016. The total livetime is 711 days. First, among the events that do not have an OD trigger, the afterpulse of ID PMTs and Cherenkov events generated by the interaction of $\beta$-rays from $^{40}\text{K}$ in the PMT photocadode are rejected. Then the fiducial volume cut is applied to reduce the external background events using a timing based positional event reconstruction ($R(\text{timing}) < 38 \text{ cm}$) and PE based reconstruction ($R(\text{PE}) < 20 \text{ cm}$). The fiducial volume target mass is about 97kg.

The expected signal from exotic interactions is simulated with the XMASS MC and the same event selection is applied and systematic uncertainty is estimated. The main contribution to the overall systematic uncertainty comes from the scintillation efficiency.

For the background evaluation, all detector materials had been assayed using high purity germanium detectors or a surface $\alpha$-ray counter. $^{238}\text{U}$, $^{235}\text{U}$, $^{232}\text{Th}$, $^{40}\text{K}$, $^{60}\text{Co}$ and $^{210}\text{Pb}$ are present in the PMTs and $^{210}\text{Pb}$ in the copper used in the detector structure holding the PMTs. The energy spectrum without fiducial volume cut and $\alpha$ events are also used to measure the RI activity of the detector components. Impurities in liquid xenon such as $^{222}\text{Rn}$, $^{85}\text{Kr}$, $^{39}\text{Ar}$, $^{14}\text{C}$ and xenon isotopes are evaluated too. Background MC is generated for each material and RI with the XMASS MC, and optical parameters in the MC follow the evaluation traced by the calibration data. The same event reduction is applied. For less than 30 keV, events mainly originated at the surface of the detector, and such surface events are often mis-reconstructed as fiducial volume events. The additional timing based reconstruction reduces the impact of this unfortunate aspect of our detector design. For more than 30 keV, event reconstruction becomes more reliable. The largest contribution to the systematic uncertainty in the background estimate is due to the detector surface condition and an uncertainty related to dead tubes which affect
the reconstruction of event happening in front of these tubes.

3. Results

We searched for signatures of exotic interactions by fitting the energy spectrum of the data, with our MC based BG estimate and the prospective MC signal component. Following the expected MC signal and BG shapes the fitting range is adjusted to 2-15 keV for millicharge and 2-200 keV recoil energy for others. A $\chi^2$ fit was then made to the data in the respective energy range with the respective signal and BG MC shapes to evaluate a potential signal contribution in the data, expected signal and energy distribution of the background MC.

Figure 1 shows the result for the millicharge analysis with the best fit millicharge signal + background MC and the derived 90% CL upper limit according for the expected signal efficiency. No significant signal was observed. We thus estimate the 90% CL upper limit to $5.4 \times 10^{-12} e$ if all three species for neutrino have a common millicharge. The upper limits for individual flavors were evaluated according for neutrino oscillations in solar neutrinos to $7.3 \times 10^{-12} e$ for $\nu_e$, $1.1 \times 10^{-11} e$ for $\nu_\mu$, and $1.1 \times 10^{-11} e$ for $\nu_\tau$. XMASS gave the strongest limit for positively charged neutrinos so far.

The magnetic moment and dark photon analysis results are shown in figure 2. Again the figure shows the data, best fit signal + background MC and 90% CL upper limit of signal for the neutrino magnetic moment and in the dark photon case for masses $M_{A'}$ of $1 \times 10^{-3}$MeV/c^2 and $10$MeV/c^2. Again, no signal was observed, and an upper limit was obtained under this assumption. The 90% CL upper limit for a magnetic moment is $1.8 \times 10^{-10} \mu_B$. For dark photons the 90% CL upper limit depends on the dark photon mass: the upper limits for $g_{B-L}$ with $M_{A'} = 1 \times 10^{-3}$MeV/c^2 and $M_{A'} = 10$MeV/c^2 are $1.3 \times 10^{-6}$ and $8.8 \times 10^{-5}$ at 90% CL, respectively. The 90% excluded region for dark photon parameters $g_{B-L}$ and $M_{A'}$ is overlaid with those of other analyses in figure 3. The new XMASS limits are comparable to those form other experiments and exclude most of the dark photon parameter space that could explain $(g - 2)$ anomaly.

![Figure 1](image-url)
Figure 2. The energy distribution of the data, the best fit signal + BG and the 90% CL signal limit from 2 to 200 keV for the neutrino magnetic moment analysis (top) and the dark photon analysis (middle: dark photon mass $M_{A'} = 1 \times 10^{-3}$ MeV/$c^2$, bottom $M_{A'} = 10$ MeV/$c^2$). The black points show the data. The blue histogram shows the signal + BG MC for the best fit with $1\sigma$ errors shown by the green histograms. The red-dotted histogram shows the 90% CL upper limit for the signal.

Figure 3. 90% CL exclusion limits and allowed region for the coupling constant $g_{B-L}$ as a function of the dark photon mass $M_{A'}$. The black-solid line shows the exclusion limit of our analysis (XMASS). The 2$\sigma$-allowed-region band from the muon $(g-2)$ experiment is shown as “$(g-2)$ DP” as the red-meshed region. The blue and magenta regions are excluded by laboratory experiments respectively. The cyan and orange regions are excluded by cosmological and astrophysical constraints. The dotted lines are the estimated limit curves from neutrino-scattering experiments (GEMMA ($\bar{\nu}_e$), Borexino (solar $\nu$), TEXONO-CsI ($\bar{\nu}_e$) and CHARM II ($\bar{\nu}_\mu$)). These exclusion regions and curves are summarized in [7].
4. Conclusion
XMASS is an ultra-low background multipurpose detector with about 1 ton of liquid xenon target mass. This analysis used 711 days of data taken with this detector between November 2013 to March 2016. Searches for neutrino millicharge, magnetic moment, and dark photon-mediated interactions were performed on this data set. As no signal was found in these searches, upper limits for the corresponding parameters were obtained for each analysis.

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