Search for sub-GeV dark matter by annual modulation using XMASS-I detector

Byeongsu Yang
Center for Axion and Precision Physics Research, Institute for Basic Science, Room C214, Creation Hall, KAIST Munji Campus, 193 Munji-ro, Yuseong-gu, Daejeon 34051, South Korea.
E-mail: byang@ibs.re.kr

Abstract.
A search for dark matter (DM) with mass in the sub-GeV region (0.32–1 GeV) was conducted by looking for an annual modulation signal in XMASS, a single-phase liquid xenon detector. Inelastic nuclear scattering accompanied by bremsstrahlung emission was used to search down to an electron equivalent energy of 1 keV. The data used had a live time of 2.8 years (3.5 years in calendar time), resulting in a total exposure of 2.38 ton-years. No significant modulation signal was observed and 90% confidence level upper limits of $1.6 \times 10^{-33}$ cm$^2$ at 0.5 GeV was set for the DM-nucleon cross section. This is the first experimental result of a search for DM mediated by the bremsstrahlung effect.

1. Introduction
Weakly interacting massive particles (WIMPs) at $O(100$ GeV$)$ are strong DM candidates [1]. They have been investigated extensively via nuclear recoil [2, 3, 4]; however, no significant detections of WIMPs have been confirmed. Other theories predict light DM types, light-mass WIMPs [5], asymmetric DM [6, 7, 8], or hidden sector DM [9] and many others; the mass of these DM candidates ranges from sub-GeV to a few GeV. Semi-conductor and crystal detectors have searched for these light DM candidates by lowering their nuclear recoil energy thresholds [10, 11]. A search via DM-electron scattering by existing detectors have also been performed [12, 13]. In addition to these detectors, conventional xenon detectors have also been performed [14, 15], due to the irreducible contribution of the bremsstrahlung effect accompanying nuclear recoils [14]. The bremsstrahlung effect can occur when DM collides with a nucleus causing it to recoil and accelerate. In the case that a mass of DM particle is 1 GeV, the energy deposited by the bremsstrahlung photon is at most 3 keV. This energy is considerably more than that deposited by elastic nuclear recoil (~0.1 keV).

The annual modulation of the bremsstrahlung signal from the sub-GeV DM is evaluated by following the study in [14]. The corresponding differential event rate is a function of the velocity of the Earth relative to the galactic rest frame. Assuming that the relative velocity between DM and detector varies sinusoidally [16, 17], we calculated the event rate as a function of bremsstrahlung energy and time. Figure 1 shows the expected bremsstrahlung spectra for 0.5 GeV DM at June (red) and December (blue) corresponding to the maximum and minimum $v_E$, respectively, as well as the averaged spectrum (green). The expected modulation amplitude is about 30% of the average event rate at 1 keV before considering the effect of the detector such as energy non-linearity or resolution.
The recently published paper [18] reports on the first experimental search for sub-GeV DM (0.32–1.0 GeV) utilizing the bremsstrahlung effect. This search was conducted by looking for the annual modulation of the event rate in the XMASS data. The XMASS-I detector is described in detail in [19]. This work used the data collected between November 20, 2013 and June 20, 2017. The dataset has a total live time of 2.8 years, and the exposure is 2.38 ton-years.

The energy calibration of XMASS can be found in [18, 19, 20, 21, 22]. Particularly, a new calibration below 5.9 keV was performed [18]. The weighted mean energy of these escape peaks was 1.65 keV. The energy threshold for sub-GeV DM analysis via bremsstrahlung was set to 1.0 keV, since the uncertainty below that energy considerably increases.

2. Analysis and results for sub-GeV DM

Minimum-$\chi^2$ fitting was performed in the annual modulation analysis. In this analysis, the ‘pull method’ [23], one of the two different methods in previous analyses [20], was used to fit all energy and time bins simultaneously and to treat the correlated errors. The sub-GeV DM analysis was conducted for DM masses between 0.32 and 1.00 GeV. Figure 2 shows the observed event rate with the best fit and expected time valuation for 0.5 GeV at 1.0–1.5 and 1.5–2.0 keV. The black points indicate data with the statistical uncertainty of the count rate. The red brackets indicate the 1 $\sigma$ systematic error for each time bin. The green line indicates the best-fit result for the bremsstrahlung spectrum. The blue dash line indicates the expected amplitude for 0.5 GeV DM at $3 \times 10^{-32}$ cm$^2$ sensitivity. All data points and lines are corrected for the efficiency curve with the best-fit parameters.

Considering that we found no significant signal, the 90% confidence level (CL) upper limit on the DM-nucleon cross section was calculated by the Bayesian approach [24]. The result of the DM search via the bremsstrahlung effect is shown in the sub-GeV region of Fig. 3.

3. Conclusion

We carried out the annual modulation analysis for XMASS-I data to search for the sub-GeV via the bremsstrahlung effect. The search limits the parameter space of DM with a mass of 0.5 GeV to below $1.6 \times 10^{-33}$ cm$^2$ at 90% CL. This is the first experimental result for a sub-GeV DM search focused on annual modulation and bremsstrahlung photons emitted by inelastic nuclear recoils.
Figure 3. Summary of the search results. The red line is the result of the bremsstrahlung analysis for 0.32–1 GeV DM, and the black line shows the result of the nuclear recoil search at 4–20 GeV [18]. For comparison, data from other experiments are shown in each colour. Details are in [18].

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