Search for event bursts in XMASS-I associated with gravitational-wave events

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1. Introduction

In 2015, the gravitational-wave (GW) signal from a binary black-hole merger was firstly detected by the Advanced LIGO experiment [1]. During LIGO/Virgo’s observing periods O1 (September 2015–January 2016) and O2 (November 2016–August 2017), 10 binary black-hole mergers and a binary neutron-star merger were observed [2]. Moreover, the electromagnetic counterparts were detected, for the first time, associated with the GW event from the binary neutron-star merger named GW170817 [3]; a short gamma-ray burst was detected \( \sim 1.7 \) s after the GW event, and subsequent ultraviolet, optical, and infrared emissions were also observed [4]. Thus, a new era of the field of GW astronomy with multi-messenger observations has begun.

The follow-up searches for neutrino events associated with these GW events have also been conducted by gigantic neutrino detectors all over the world, however, no significant neutrino signal has been observed yet [5, 6, 7, 8, 9, 10, 11, 12]. The neutrino follow-up searches are of interest because, for

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instance, there are some theoretical predictions of emission of neutrinos with energy of a few tens MeV \cite{13, 14}, and much higher-energy neutrinos \cite{15, 16} are expected from binary neutron-star mergers. The expected range for detecting several neutrinos from a binary neutron star merger is, however, \( < 10 \) Mpc with a future megaton-scale water Cherenkov detector \cite{13}. There also exist scenarios of production of short gamma-ray bursts \cite{17} or ultrahigh-energy neutrinos \cite{18} from binary black-hole mergers.

XMASS-I is a large single-phase liquid xenon (LXe) detector located underground \((2700 \text{ m water equivalent})\) at the Kamioka Observatory in Japan \cite{19}. It is a multi-purpose detector suitable for detecting particles with energy deposition in the wide energy range from keV to MeV under an ultra-low background environment. The XMASS-I detector accumulated data with a stable condition continuing from November 2013 until February 2019, resulting in the entire data set with a total live time of 4.4 years. Using the XMASS-I data, various searches for astroparticles such as dark matter particles \cite{20, 21, 22, 23}, solar axions \cite{24}, and solar Kaluza-Klein axions \cite{25} have been performed. Furthermore, the possibility to detect galactic supernova neutrinos via coherent elastic neutrino-nucleus scattering (CEvNS) has been studied \cite{26}.

In this paper, we report results from a search for event bursts in the XMASS-I detector associated with the 11 GW events detected during LIGO/Virgo’s O1 and O2 periods.

### 2. XMASS-I detector

The XMASS-I detector holds an active target of 832 kg of LXe inside a pentakis-dodecahedral copper structure that hosts 642 inward-looking 2-inch Hamamatsu R10789 photomultiplier tubes (PMTs) on its approximately spherical inner surface at a radius of about 40 cm. The photocathode coverage of the inner surface is 62.4\%. The LXe detector is placed at the center of a cylindrical water Cherenkov detector. The outer detector, which is 11 m in height and 10 m in diameter, is equipped with 72 20-inch Hamamatsu H3600 PMTs. This detector acts as an active veto counter for cosmic-ray muons as well as a passive shield against neutrons and γ-rays from the surrounding rocks.

Data acquisition is triggered if at least four inner-detector PMTs record a signal within 200 ns or if at least eight outer-detector PMTs register a signal within 200 ns. A 50 MHz clock is used to measure the time difference between triggers. One-pulse-per-second (1PPS) signals from the global positioning system (GPS) are fed as triggers for precise time stamping. The GPS 1PPS triggers are also used to flash the LED for the PMT gain monitoring.

The gains of the PMTs are monitored weekly using a blue LED embedded in the inner surface of the detector. The scintillation yield response is traced with a \(^{57}\text{Co}\) source \cite{27} inserted along the central vertical axis of the detector every week or two. Through measurements with the \(^{57}\text{Co}\) source at the center of the detector volume, the photoelectron (PE) yield was determined to be \(~15\) PE/keV for 122 keV γ-rays. The nonlinear response of the scintillation yield for electron-mediated events in the detector was calibrated over the energy range from 5.9 keV to 2614 keV with \(^{55}\text{Fe}\), \(^{241}\text{Am}\), \(^{109}\text{Cd}\), \(^{57}\text{Co}\), \(^{137}\text{Cs}\), \(^{60}\text{Co}\), and \(^{232}\text{Th}\) sources. In this paper, the energy above 2614 keV is extrapolated using the energy scale derived by the \(^{232}\text{Th}\) calibration. Hereinafter, this calibrated energy is represented as keV\(_{\gamma}\) where the subscript stands for the electron-equivalent energy.

The timing offsets for the PMT channels owing to the differences in their cable lengths and the electronic responses were also traced by the \(^{57}\text{Co}\) calibration.

### 3. Data set and event selection

Table I shows a list of the GW events detected during LIGO/Virgo’s O1 and O2 periods and the data-taking situation of the XMASS-I detector around the detection time of each GW event. The event burst search is conducted in a time window between \(~400\) and \(+10,000\) s from each GW event. This search window is motivated by two reasons. The time window within \(+400\) s from each GW event is considered in the search for neutrinos as described in Sec. 2. In addition, the extended time

| GW event   | GW detection time \(t_{\text{GW}}\) (UTC) | Data-taking situation of XMASS-I |
|------------|-----------------------------------------|---------------------------------|
| GW150914   | Sep. 14, 2015 09:50:45                  | Continuous data-taking          |
| GW151012   | Oct. 12, 2015 09:54:43                  | No data in 1, 183 < \(t - t_{\text{GW}}\) < 1, 583 s due to run change |
| GW151226   | Dec. 26, 2015 03:38:53                  | No data in 4, 191 < \(t - t_{\text{GW}}\) < 4, 388 s due to run change |
| GW170104   | Jan. 04, 2017 10:11:58                  | No data in 196 < \(t - t_{\text{GW}}\) < 275 s due to run change |
| GW170608   | Jun. 08, 2017 02:01:16                  | No data in \(t - t_{\text{GW}}\) > 6, 339 s due to detector calibration |
| GW170729   | Jul. 29, 2017 18:56:29                  | Continuous data-taking          |
| GW170809   | Aug. 09, 2017 08:28:21                  | Continuous data-taking          |
| GW170814   | Aug. 14, 2017 10:30:43                  | Continuous data-taking          |
| GW170817   | Aug. 17, 2017 12:41:04                  | Continuous data-taking          |
| GW170818   | Aug. 18, 2017 02:25:09                  | Continuous data-taking          |
| GW170823   | Aug. 23, 2017 13:13:58                  | Continuous data-taking          |

Table 1: List of the GW events during the whole XMASS-I data taking period. The data-taking situation of the XMASS-I detector in a time window between \(~400\) and \(+10,000\) s from each GW event \((t_{\text{GW}})\) is also noted.
window up to 10,000 s is considered in the model independent search because more massive particles, axion-like particles for instance, might arrive later timing. For the GW151012, GW151226, and GW170104 events, there exists a few-minute dead time due to run change. For the GW170608, data-taking stopped 6, 339 s after the GW event for the detector calibration. Otherwise, data were taken continuously during the search window.

We use the full 832 kg of xenon as an active target in this analysis. In order to perform a search for event bursts with a minimal bias, only simple and loose cuts are applied. Events with four or more hits in the inner-detector without an associated outer-detector trigger are initially selected. We have then applied four selection cuts that mostly remove obvious backgrounds. To remove events caused by after-pulses in the PMTs following bright events, one requires that the standard deviation of the inner-detector hit timing distribution is less than 100 ns, approximately <30, 30–300, 300–3500, and >3500 keVee, respectively. The average event rate in these four energy ranges are estimated from the pre-search window, to be 0.223±0.004, 0.559±0.006, 0.987±0.008, and 0.023±0.001 Hz, respectively.

4. Model independent event burst search

4.1. Results for the GW170817 binary neutron star merger

Figures 2 shows the event rate history within ±400 s from GW170817 (August 17, 2017, 12:41:04 UTC). From top to bottom, the Low-E, Middle-E, High-E, and V. H. E. samples are shown. The horizontal dashed lines correspond to the average background event rate estimated from the pre-search window.
At each timing $t - t_{GW}$, we first minimize the test statistics as a function of $t_{\text{width}}$. Then, we scan the test statistics as a function of the timing $t - t_{GW}$ to find minimums as possible burst candidates.

To calculate a global significance of each candidate, we estimate the probability distribution of the test statistics under the null hypothesis by performing the same analysis on 100,000 dummy data sets. In each dummy data set, events are randomly generated based on the average event rate estimated in the pre-search window for each energy region. Possible time-correlated backgrounds due to short-time consecutive decays of radioisotopes in the detector material are also considered. $^{222}\text{Rn}$ in the LXe decays through the $^{222}\text{Rn}$ ($T_{1/2} = 3.82$ d) – $^{218}\text{Po}$ ($T_{1/2} = 3.10$ min) – $^{214}\text{Pb}$ ($T_{1/2} = 26.8$ min) chain, and 5.49 and 6.00 MeV $\alpha$-ray events could occur in the same time window in the V.H.E. energy range. This background is taken into account in the dummy data generation based on the measured $^{222}\text{Rn}$ activity of $\sim 8$ mBq in the active LXe volume [22]. The contributions from short-time consecutive decays in the $^{238}\text{U}$ and $^{232}\text{Th}$ chains contaminated in the detector material are turned out to be negligible. Figure 5 shows the distributions of the observed number of events in coincidence windows with various widths for the data of the pre-search window overlaid with the simulation. The simulated distributions well reproduce the data of the pre-search window.

Finally, the look-elsewhere effect due to the search using 4 energy windows is accounted for. For small $p$-values, this correction can be made by multiplying the $p$-value by the number of energy ranges, that is 4.
As the result of the model independent search, no coincidence time window with a global significance of more than 3σ was found in the time range between −400 and +10,000 s from the GW170817 event.

4.2. Results for the binary black hole mergers

The same analysis is performed for other 10 GW events classified as binary black hole mergers. Figure 6 shows the distributions of the TS observed in each energy range for 10 binary black-hole mergers and a binary neutron-star merger. Among them, a burst candidate with small probability of \( P(TS) = 7.8 \times 10^{-4} \) was found in the High-E energy range for the GW151012 event. As seen in Fig. 7, 15 events are clustered within 2 s centered at \( t - t_{GW} = 1802.95 \) s. Figure 8 shows the test statistics as a function of the coincidence time width in the High-E energy range around \( t - t_{GW151012} = 1802.95 \) s. The coincidence time width of 2 s gives the lowest TS value, and hence the most significant result. After considering the look-elsewhere effect of the 4 energy ranges, the global significance of this burst candidate identified in association with GW151012 is 3.0σ. Since we perform the analysis separately on the 11 GW events, there is an additional look-elsewhere effect. The significance of finding such a burst candidate in any of the 11 GW events is 2.1σ.

The energy and vertex position of those events are reconstructed based on a maximum-likelihood evaluation of the observed NPE of all the PMTs [19]. Note that the XMASS-I detector observes the LXe scintillation light, and therefore provides no directional information on detected particles. Figure 9 shows the reconstructed energy and radial position distributions.
of those 15 events overlaid with the ones for the background estimated using the pre-search window. The $p$-value of the Kolmogorov-Smirnov (KS) test for the energy and radial position distributions between those 15 events and the background are 0.87 and 0.96, respectively. Therefore, no significant deviation from the background distributions is found.

To investigate whether the radial distribution of the burst candidate is consistent with that of potential signal uniformly distributed inside the detector, we overlay the radial distribution for uniformly distributed electron events (blue dashed in Fig. 9) using our GEANT4-based detector simulation. Since we do not have any signal model predicting the energy spectrum, a flat energy spectrum up to 3 MeV is assumed. A dip at $(R/42.5 \text{cm})^3 \sim 0.7$ in the reconstructed radial distribution for the simulation is due to a slight position dependent bias in the radial direction. Note that the edge of the pentakisdodecahedral detector locates between $(R/42.5 \text{cm})^3 = 0.83$ and 1. The $p$-value of the KS test for the uniformly distributed events is 0.055.

We concluded that the radial distribution of the burst candidate is compatible with both that of the background and that of the uniform distribution since the obtained $p$-values of the KS test under both hypotheses are above 0.05 (or within $2\sigma$). We also estimated the frequency that 15 events in the High-E energy region are observed within 2 s due to statistical fluctuation during the entire data-taking period of XMASS-I to be $0.21\,\text{yr}^{-1}$, based on the average event rate in the pre-search window.

5. Constraints on neutrino fluence for GW170817

For the GW170817 event, we also derive constraints on neutrino fluence for the sum of all neutrino flavors via CEvNS under the assumption of two types of neutrino energy distributions: a Fermi-Dirac spectrum with average neutrino energy of 20 MeV and mono-energetic neutrinos in the range between 14 and 100 MeV. The relative difference in propagation time for GW and such neutrinos and GWs from the source, for example, at a 40 Mpc distance is expected to be $<\mathcal{O}(1)\,\text{s}$. For this neutrino signal search, we use the $\pm 400\,\text{s}$ search window, which is a similar size of the search window as the one used in searches by other neutrino detectors [5, 6, 7, 8, 9, 10, 11, 12].

The Fermi-Dirac energy distribution is expressed as

$$f(E_{\nu}) = \frac{C}{(k_B T)^3} \frac{E_{\nu}^2}{e^{E_{\nu}/k_B T} + 1},$$

where

$$C = \left( \int_0^\infty \frac{x^2}{e^x + 1} \, dx \right)^{-1} = \frac{2}{3\zeta(3)}$$

is the normalization factor, $k_B$ is the Boltzmann constant, $T$ is temperature, and the average energy of neutrinos is given by $\langle E_{\nu} \rangle \sim 3.15T$.

The differential cross section of CEvNS is

$$\frac{d\sigma}{dE_{\nu}}(E_{\nu}, E_{\nu}) = \frac{G^2_F M}{2\pi} \frac{G_F^2}{G_F^2} \left[ 1 + \left(1 - \frac{E_{\nu}}{E_{\nu}}\right)^2 - \frac{4M\nu - E_{\nu}}{E_{\nu}} \right],$$

Figure 9: Reconstructed energy (top) and radial position (bottom) of the 15 events in the burst candidate overlaid with the distributions for background estimated using the pre-search window (black solid). The simulated radial distribution for the uniformly distributed events (blue dashed) is also shown for comparison. The distributions for background and the uniformly distributed events are normalized to the observed number of events.
where $G_F$ is the Fermi constant, $M$ is the target nuclear mass, $E_{nr}$ is the nuclear recoil energy, and

$$G_V = \frac{1}{2} + 2 \sin^2 \theta_W Z - \frac{1}{2} N F(q^2).$$

(5)

Here, $\theta_W$ is the weak mixing angle, $Z$ and $N$ are the numbers of protons and neutrons in the nucleus, and $F(q^2)$ is the nuclear form factor, respectively. More detail for the calculation of the CEvNS interaction in XMASS-I can be found elsewhere [24].

Figure 10 shows the simulated NPE spectra and detection efficiency as a function of NPE for the Fermi-Dirac spectrum with $\langle E_\nu \rangle = 20$ MeV. The simulated neutrino events concentrate in a time window between 0.02 and 10 s and the search was conducted utilizing the inverse beta decay ($\bar{\nu}_e + p \rightarrow e^- + n$) for $\bar{\nu}_e$ and neutrino–electron elastic scattering ($\nu + e^- \rightarrow \nu + e^-$) for $\nu_e$ and $\nu_{\mu,\tau}$, our limits are for the sum of all the neutrino flavors using CEvNS. The XMASS limit is comparable to the $\nu_{\mu,\tau}$ limits of Super-Kamiokande.

No significant event burst is observed in the Low-E sample as described in the previous section, the 90% confidence level (CL) upper limit on neutrino fluence ($\Phi_{90}$) is calculated by

$$\Phi_{90} = \frac{N_{90}}{N_T \int \int f(E_\nu) \frac{dE_{nr}}{dE_{ee}}(E_\nu, E_{nr}) \epsilon(E_{nr}) dE_{nr} dE_{ee}}$$

(6)

where $N_T$ is the number of target nuclei, $\epsilon(E_{ee})$ is the detection efficiency as a function of recoil energy and is estimated using our detector simulation. $N_{90}$ is the 90% CL upper limit on the number of signal events, derived from the relation

$$\frac{\int \int P(\mu_{sig} + \mu_{bg}|N_{obs}) d\mu_{sig} \mu_{sig}}{\int \int P(\mu_{sig} + \mu_{bg}|N_{obs}) d\mu_{sig} \mu_{bg}} = 0.9,$$

(7)

where $P(\mu|N)$ is the Poisson probability, $N_{obs}$ is the observed number of events in the coincidence time window with a width $t_{width}$, and $\mu_{sig}$ and $\mu_{bg}$ are the average number of signal and background events, respectively. $\mu_{bg}$ is estimated based on the average event rate estimated in the pre-search window, and we assume a uniform prior on $\mu_{sig}$.

Figure 11 shows the 90% CL upper limits on neutrino fluence for the Fermi-Dirac spectrum with $\langle E_\nu \rangle = 20$ MeV as a function of the coincidence time width $t_{width}$. The upper limit from the on-time window centered at $t = t_{GW}$ with a width $t_{width}$ is drawn as a line while the range of limits from the sliding window with a width $t_{width}$ within the ±400 s search window is drawn as a band. The obtained upper limit from the on-time window was $(1.3\pm 2.1) \times 10^{11}$ cm$^{-2}$.

Figure 12 shows our 90% CL upper limits on fluence for mono-energetic neutrinos as a function of neutrino energy between 14 and 100 MeV. Limits obtained by Super-Kamiokande [11] are also shown. While their limits were derived utilizing the inverse beta decay ($\bar{\nu}_e + p \rightarrow e^- + n$) for $\bar{\nu}_e$ and neutrino–electron elastic scattering ($\nu + e^- \rightarrow \nu + e^-$) for $\nu_e$ and $\nu_{\mu,\tau}$, our limits are for the sum of all the neutrino flavors utilizing CEvNS. The XMASS limit is comparable to the $\nu_{\mu,\tau}$ limits of Super-Kamiokande.

6. Conclusion

We conducted a search for event bursts in the XMASS-I detector associated with 11 GW events detected during LIGO/Virgo’s O1 and O2 periods. We used the full 832 kg of xenon as an active target. Simple and loose cuts were applied to the data collected around the detection time of each GW event and the data were divided into four energy regions ranging from keV to MeV. Without assuming any particular burst model, we looked for event bursts in sliding windows with various time width from 0.02 to 10 s and the search was conducted in a time window between $-400$ and $+10,000$ s from each GW.
event. For the binary neutron star merger GW170817, no significant event burst was observed in the XMASS-I detector, and hence we set 90% confidence level upper limits on neutrino fluence for the sum of all the neutrino flavors via coherent elastic neutrino-nucleus scattering. The obtained upper limit was (1.3–2.1)×10^{11} \text{cm}^{-2} under the assumption of the Fermi-Dirac spectrum with the average neutrino energy of 20 MeV. The neutrino fluence limits for mono-energetic neutrinos in the energy range between 14 and 100 MeV were also calculated. Among the other 10 GW events detected as the binary black hole mergers, a burst candidate with a 3.0\sigma significance was found at 1801.95–1803.95 s in the analysis for GW151012. However, the reconstructed energy and position distributions were consistent with those expected from the background. Considering the additional look-elsewhere effect of analyzing the 11 GW events, the significance of finding such a burst candidate associated with any of them is 2.1\sigma.

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