Search for WIMP-$^{129}$Xe inelastic scattering using particle identification in the XMASS experiment

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Abstract. The inelastic scattering of Weakly Interacting Massive Particles (WIMPs) and $^{129}$Xe nuclei was searched for in the XMASS experiment. When excited by the inelastic scattering, the nuclei emit 39.6 keV $\gamma$-ray. The exposure of the data was 327 kg $\times$ 800.0 days. To improve the sensitivity of the signal, the events were classified by their pulse shapes, which discriminates between $\gamma$-rays and $\beta$-rays. As no significant signal was found, the upper limits of the inelastic channel cross section at the 90% confidence level were set. For a 200 GeV/$c^2$ WIMP, the limit was $4.1 \times 10^{-39}$ cm$^2$. This is the most stringent limit of the SD WIMP-neutron interaction.

1. Introduction

Weakly Interacting Massive Particles (WIMPs) are among the primary candidates of dark matter. There are two main types of the interactions between nuclei and WIMPs: Spin-Independent (SI) and Spin-Dependent (SD) interactions. SD interactions occur when the WIMP has a non-zero spin. Both elastic and inelastic scattering are allowed in this case. The target nuclei should have an effective nuclear spin. As the $^{129}$Xe nucleus contains an unpaired neutron, its SD WIMP-neutron cross section should be larger than that of a Xe nucleus with no unpaired neutron. An observation of WIMP-nuclei inelastic scattering indicates the existence of an SD interaction as well as that WIMPs possess spin since inelastic scattering process can be led by SD interaction.

2. XMASS detector

The XMASS detector is a single-phase detector containing 832 kg of liquid xenon (LXe) located 1,000 meters (2,700 meter water equivalent) underground in the Kamioka mine (Gifu Prefecture, Japan) [1]. The scintillation photons from the sensitive volume (a pentakis-dodecahedron with an inscribed radius of approximately 43 cm) are detected by 642 Hamamatsu R10789 Photo-Multiplier Tubes (PMTs). The outer shell of LXe shields the inner fiducial volume against the...
γ-rays from the detector’s structure, particularly emitted by the PMTs. The PMT responses are recorded by CAEN V1751 (1 GHz) waveform digitizers.

The detector is surrounded by a water tank of height 10.5 m and diameter 10 m. This water tank plays the dual roles as a muon veto and a shield against neutron and environmental γ-rays.

3. Inelastic scattering signals
In the inelastic scattering process, a WIMP scatters off and excites a $^{129}$Xe nucleus. The recoil $^{129}$Xe loses its excitation energy by emitting a 39.6 keV γ-ray or radiations from the atom. The scintillation signal from the recoil nucleus depends on the velocity distribution of the WIMPs and the form factor of $^{129}$Xe for SD interactions. The energy spectrum of the nuclear recoil is calculated similar to elastic scattering in an SI channel.

The energy spectrum of the inelastic scattering and the background (BG) spectra were simulated by the Monte Carlo (MC) technique. The histograms in Figure 1 are the simulated energy spectra of the inelastic scatterings of 20, 200, and 2000 GeV/$c^2$ WIMPs.

4. Data selection and event classification
The analysis is detailed in [2]. The data were collected at the XMASS detector from November 20 of 2013 to July 20 of 2016. The data collection was stable throughout the measurement period. The data were divided into periods 1–4 depending on the detector’s condition.

In the pre-selection stage, the events from after pulses of PMTs caused by previous events were removed.

The event position was then reconstructed from the light distribution of the PMTs [1]. The events whose reconstructed positions were inside the fiducial volume (a sphere of radius 30 cm from the detector center) were selected. The LXe in the fiducial volume weighed 327 kg, including 86 kg of $^{129}$Xe.

A major source of BG is the progeny of $^{222}$Rn. The abundance of this BG was estimated from the events in the fiducial volume by tagging $^{214}$Bi. The tagging was performed by detecting the coincidences of the $^{214}$Bi-$^{214}$Po decay sequence.

After tagging and rejecting the $^{214}$Bi events, the α-events from the detector surface were selected as the events with a shorter-than-30 ns scintillation decay constant of their summed PMTs. These events were also removed from the sample.

After rejecting the α-events, the samples were separated into β-depleted and β-enriched samples depending on their LXe scintillation decay constants. Specifically, a β-ray’s scintillation lengthens with increasing energy of the β-ray [3], enabling particle identification. The γ-ray and inelastic scattering events have shorter scintillation decay constants than a β-ray event with the
Figure 3. Spectra of $\beta$-depleted samples for a 200 GeV/$c^2$ WIMP with a 90% CL upper limit cross section. Black points are the observed data. Shown are the stacked spectra of WIMP (red filled), $^{125}$I (green filled), $^{14}$C (cyan filled), $^{39}$Ar (magenta filled), $^{85}$Kr (blue filled), $^{214}$Pb (yellow filled), $^{136}$Xe (gray filled), and external $\gamma$-rays (brown filled).

The $\gamma$-ray and inelastic scattering events were primarily chosen as the $\beta$-depleted samples.

The p-value of an event originating from a $\beta$-ray, denoted by $\beta$CL, was computed using the cumulative distribution function (CDF) of the $\beta$-ray’s scintillation timing distribution [2, 4, 5]. This measure is defined as follows:

$$\beta\text{CL} = P \sum_{k=0}^{N-1} \frac{(-\ln P)^k}{k!} \left( P = \prod_{k=0}^{N-1} \text{CDF}_\beta(E_{\text{evt}}, t_k) \right)$$

where $N$ is the number of PMT pulses, $E$ is the energy of the event, $t_k$ is the detection time of the $k$-th pulse, and $\text{CDF}_\beta(E, t)$ is the CDF of the pulse detection time $t$ of an $\beta$-event with energy $E$. The $\text{CDF}_\beta(E, t)$ was obtained by checking the tagged $^{214}$Bi events. By definition, the $\beta$CL of $\beta$-ray events is uniformly distributed from 0 to 1. In contrast, the $\beta$CL of particles with scintillations shorter than that of $\beta$-rays peaks at 0. Therefore, the inelastic scattering and $\gamma$-ray events can be separated from the $\beta$-ray events by setting a threshold $\beta$CL ($\beta$CL$_{\text{th}}$) for the target WIMP mass. In a 200 GeV/$c^2$ WIMP search, $\beta$CL$_{\text{th}}$ was determined as 0.06. The $\beta$CL$_{\text{th}}$ was optimized by the MC samples to maximize $S/\sqrt{B}$, where $S$ and $B$ are the probabilities that the signal and $\beta$-ray events, respectively, are classified as $\beta$-depleted samples.

The result of the classifications for the WIMP MC and the data are shown in Figure 2.

5. Results and conclusion

The energy spectra of the $^{214}$Bi, $\beta$-enriched, and $\beta$-depleted samples were fitted using the MC spectra of the signals and the BG for WIMP masses ranging from 20 GeV/$c^2$ to 10 TeV/$c^2$. 

The BG abundances were obtained in this fitting process. In the best fitting result, the cross section was $7.0 \times 10^{-40}$ cm$^2$. As no significant signal was found, the 90% CL upper limit of the SD WIMP-neutron cross section was given. For a 200 GeV/c$^2$ WIMP, the limit was $4.1 \times 10^{-39}$ cm$^2$. Figure 3 plots the spectra of the $\beta$-depleted samples in each period of the 200 GeV/c$^2$ WIMPs (at the 90% CL upper-limit) obtained by the fitting. The $^{14}$C abundance decreased over time as the LXe was increasingly purified using heated getters. Meanwhile, the $^{39}$Ar abundance increased over time, presumably because adsorbed Ar was released from the detector’s inner structure. The Ar was originally applied as a leak check during the detector’s construction.

The upper limits of the WIMP masses searched in this analysis are shown in Figure 4. The most stringent limit among the WIMP searches via the inelastic channel was obtained using 327 kg × 800.0 days data in this analysis. This result has been published in [2].

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