Recent results of direct dark matter search with XMASS

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XMASS project

- XMASS: a multi purpose experiment with liquid xenon
  - Xenon detector for Weakly Interacting MASSive Particles (dark matter)
  - Xenon MASSive detector for solar neutrino (pp/\(^7\)Be solar neutrino)
  - Xenon neutrino MASS detector (double beta decay)

- Features
  - Low energy threshold
  - Sensitive to e/\(\gamma\) events as well as nuclear recoil
  - Large target mass and its scalability
Single-phase LXe detector: XMASS-I

- Located in the Kamioka mine in Japan (~2,700m water equivalent)
- ~830kg LXe viewed by 642 PMTs (Photocathode coverage >62%)
- Active water shield for cosmic-ray muons
- Large photoelectron yield ~14 PE/keV for 122keV γ-ray
Direct dark matter searches with XMASS-I

Low mass WIMP search
*Phys. Lett. B719 (2013) 78*

WIMP-$^{129}$Xe inelastic scattering
*PTEP (2014) 063C01*

**Latest results**

- Annual modulation search

- Bosonic super-WIMPs search
  *Phys. Rev. Lett. 113 (2014) 121301*
Search for annual modulation

- Expect annual modulation of event rate of dark matter signal due to Earth’s rotation around the Sun.
- DAMA/LIBRA claims modulation at 9.3σ
  - Total exposure of 1.33 ton year (14 cycles)
  - Modulation amplitude of \((0.0112\pm0.0012)\) cpd/kg/keV for 2-6 keV

Annual modulation search in XMASS
  - 359.2 live days x 832 kg (=0.82 ton year)
  - Analysis threshold 1.1 keVee (=4.8 keVnr)
  - Look for event rate modulation not only for nuclear recoil but also for e/γ events
Modulation analysis

- Two different fitting methods
  - Pull term (Method-1)
  - Covariance matrix (Method-2)

- Our data demonstrate high sensitivity to modulation

$$
\chi^2 = \sum \sum \left( \frac{(R_{i,j}^{\text{data}} - R_{i,j}^{\text{ex}} - \alpha K_{i,j})^2}{\sigma \left( \text{stat} \right)_{i,j}^2 + \sigma \left( \text{sys} \right)_{i,j}^2} \right) + \alpha^2
$$

$$
\chi^2 = \sum_{k,l} \left( R_k^{\text{data}} - R_k^{\text{ex}} \right) (V_{\text{stat}} + V_{\text{sys}})^{-1} (R_l^{\text{data}} - R_l^{\text{ex}})
$$

XMASS data

- $s = 2 \times 10^{-40}$ cm$^2$, $M = 7$ GeV/c$^2$
- $s = 2 \times 10^{-40}$ cm$^2$, $M = 8$ GeV/c$^2$

DAMA/LIBRA

CoGENT

CDMS Si

LUX (2013)

XENON100 (2012)
Modulation analysis: WIMP results

- Expected event rate
  \[ R_{i,j}^{\text{ex}} = \int_{t_j - \frac{1}{2} \Delta t_j}^{t_j + \frac{1}{2} \Delta t_j} \left( C_i + \sigma_{\chi n} \cdot A_i(m_{\chi}) \cos 2\pi \left( \frac{t - t_0}{T} \right) \right) dt \]
  - T = 1 year, t₀ = 152.5 day (fixed)
  - Ai(m_{\chi}): modulation amplitude
  - Ci: unmodulated event rate

- WIMP mass range 6 to 20 GeV/c²
- Both fitting methods give similar results
- Exclude almost all the DAMA/LIBRA allowed region by modulation search
Without assuming any specific model except for $T=1$ year, $t_0=152.5$ day
- Includes both NR and $e/\gamma$ signals
- Shows slightly negative amplitudes in the 1.6-4.1 keVee range.
- $P$-values
  - $0.014$ ($2.5\sigma$) for method-1
  - $0.068$ ($1.8\sigma$) for method-2
- Gives 90% CL limits for positive and negative amplitude separately

(*) We estimated the XENON100 90% CL limit based on
Search for bosonic super-WIMPs

● Bosonic super-WIMPs
  - Lighter and more weakly interacting than WIMPs
  - Candidate for lukewarm dark matter
  - Can be pseudoscalar or vector boson.
  - Can be detected by absorption of the particle, which is similar to the photoelectric effect.

● Search for bosonic super-WIMPs in XMASS
  - 165.9 days data taken in Dec. 2010 – May 2012
  - 41 kg fiducial mass
  - Remaining event rate $\sim 10^{-4}$ dru ($^{214}$Pb from $^{222}$Rn)

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Pre-selection
-- Fiducial volume cut
-- Timing balance cut
-- Topological cut
Constraint on coupling constants

- Vector boson case
  - The first direct search in the 40–120 keV range.
  - We exclude the possibility that such particles constitute all of dark matter.

- Pseudoscalar case
  - The most stringent direct constraint on $g_{\text{aee}}$.

*Pseudoscalar*

*Vector boson*

**Phys. Rev. Lett. 113 (2014) 121301**
Comparison of background rate in fiducial volume including both nuclear recoil and e/γ events

- XMASS achieved low background rate of $O(10^{-4})$ dru in a few 10s keV including e/γ events
- Low background rate for e/γ events is good for searching for dark matter other than WIMPs.

Original figure taken from D. C. Mailing, Ph.D (2014) Fig 1.5
Diversity of XMASS (non dark matter physics)

- **New!** Solar axion search via axio-electric effect

\[ g_{aee} < 5.4 \times 10^{-11} \text{ (90\%CL)} \]

*Phys. Lett. B724 (2013) 46*

- **New!** Search for two-neutrino double electron capture (2νECEC) on \(^{124}\text{Xe},^{126}\text{Xe}\)

\[ T_{1/2}^{2\nu ECEC}(^{124}\text{Xe}) > 4.7 \times 10^{21} \text{ years} \]

\[ T_{1/2}^{2\nu ECEC}(^{126}\text{Xe}) > 4.3 \times 10^{21} \text{ years} \]

*Phys. Lett. B759 (2016) 64*

- **New!** Possibility of detecting galactic supernova neutrinos via coherent scattering (CEvNS)

Observed data
Expected signal

\[ (10^4) \text{ events in the case of Betelgeuse (200 pc)} \]

*arXiv: 1604.01218*

- Supernova at 10kpc (Livermore model)

\[ 214\text{Pb background} \]

\[ \text{Expected signal} \]

\[ \text{Background} \]

\[ \text{Number of events} \]
Prospects for pulse shape discrimination (PSD) using LXe scintillation

- LXe scintillation processes
  - Excitation:
    - Singlet ($^1\Sigma_u^+$): $\tau \sim$ a few ns
    - Triplet ($^3\Sigma_u^+$): $\tau \sim$ 20 ns
  - Recombination: $\tau \sim$ 30 ns or more
- Singlet/triplet ratio, recombination time depend on ionization density
- Early study of PSD with a small set up
  - Electron rejection power of $\sim$8x10^{-2} for 50% NR efficiency at 4.8-7.2 keVee
- Detail measurement of scintillation time profile for low energy $e/\gamma$ has been conducted

New!

Electron rejection power for 50% NR efficiency

- 4.6 PE/keV
- 20.9 PE/keV

NIM A659 (2011) 161
Measurement of LXe scintillation time profile for low energy gamma-ray induced events

- Using $^{55}\text{Fe}$, $^{241}\text{Am}$, and $^{57}\text{Co}$ sources ($E_\gamma=5.9\text{-}120\text{keV}$)
- Waveforms are decomposed into “single PE” pulses
- MC simulation takes into account optical parameters (absorption, scattering, ...), electronics response
- Timing distributions of data and MC are compared to obtain intrinsic decay time parameters.
Measurement of LXe scintillation time profile for low energy gamma-ray induced events

\[ f(t) = \frac{F_1}{\tau_1} \exp\left(-\frac{t}{\tau_1}\right) + \left(1 - \frac{F_1}{\tau_2}\right) \cdot \exp\left(-\frac{t}{\tau_2}\right) \]

- Fast decay component is needed to reproduce our calibration data.
  - \( \tau_1 = 2.2 \text{ ns (fixed)} \)
  - \( F_1 : 0.05 \sim 0.15 \) (increase at low energy)

- Energy dependence of decay time was studied as a function of mean kinetic energy of electrons induced by \( \gamma \)-ray

- Time profile for neutron under study

arXiv: 1604.01503 (accepted to NIM A)
Next step: XMASS-1.5

- Total ~6 tons (Fiducial mass ~3 tons)
- Newly developed low-background 3-inch dome-shape PMT
- R&D detail presented in poster “Future XMASS project” by K. Abe
- Background level of ~1x10^-5 dru (\(pp\) solar neutrinos) assumed
- Sensitivity to WIMP SI cross section (1-3)x10^-47 cm^2 @50 GeV/c^2
Sensitivity to low mass WIMPs/bosonic super-WIMPs

**Low mass WIMPs**

- Analysis threshold \(\sim 1\) keVee
- Whole volume (no vertex reconstruction)
- Expect to reduce BG to 1/500 (<10\(^{-2}\) dru)

**Bosonic super-WIMPs**

- Higher energy \(O(100\) keV) e/\(\gamma\) events
- Background level \(10^{-5}\) dru assumed
- Ultimate BG: \(pp\) solar neutrino & \(^{136}\)Xe 2\(\nu\beta\beta\)
Summary

• XMASS is a large-volume single-phase LXe detector designed for multiple particle and astroparticle physics targets.
• Various dark matter searches have been conducted with XMASS-I.
  – The first extensive modulation search with an exposure comparable to DAMA/LIBRA shows a slight negative amplitude but not significant.
  – Search for bosonic super-WIMPs gives stringent limits on their coupling constants.
• XMASS demonstrate high sensitivity to $e/\gamma$ events and diversity of physics targets of the experiment.
  – Solar axion, 2νECEC on $^{124}$Xe, supernova neutrino, etc.
• XMASS is stably taking data for more than 2 years. More results will come soon.
• The next phase, XMASS-1.5, will reach the WIMP SI cross section sensitivity of $(1-3) \times 10^{-47}$ cm$^2$ @50 GeV/c$^2$. 
Backup slides
Search for light WIMPs

- Use full volume of LXe
- 6.7 days x 835 kg
- 0.3 keVee threshold

Search for $^{129}$Xe inelastic scattering by WIMPs

- $\chi + ^{129}$Xe $\rightarrow \chi + ^{129}$Xe$^*$
  $^{129}$Xe$^*$ $\rightarrow ^{129}$Xe + $\gamma$ (39.6 keV)
- Natural abundance of $^{129}$Xe: 26.4%

Signal MC for 50 GeV WIMP:
(1) = pre-selection
(2) = (1) & radius cut
(3) = (2) & timing cut
(4) = (3) & band cut

Observed data (165.9 days)

Asymptotic cross section ($\sigma^{as}$) [pb]

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