KIMS : Dark Matter Search Experiment in Korea

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For the KIMS Collaboration

DSU2006, Madrid
KIMS
Korea Invisible Mass Search

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WIMP

SUSY model with R-parity conservation
Neutralino : stable LSP
weak interactions scale annihilation cross section
proper relic density for dark matter

⇒ Excellent CDM candidate

Neutralino: super-partner of neutral gauge and Higgs bosons

\[
\tilde{\chi}_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W} + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0
\]
Direct WIMP Search

Signature: WIMP-nucleus elastic scattering

→ Signal by recoiled nucleus

\[ L = f_q (\bar{\chi}\chi) \cdot (\bar{q}q) + d_q (\bar{\chi}\gamma^\mu \gamma^5 \chi) \cdot (\bar{q}\gamma_\mu \gamma^5 q) + .... \]

**scalar interaction**

**spin-dep. interaction**

\[ \sigma_{\text{scalar}} = \frac{4}{\pi} m_r^2 \left[ Z f_p + (A - Z) f_n \right]^2 \]

\[ \sigma_{\text{spin}} = \frac{32}{\pi} G_F^2 m_r^2 \Lambda^2 J(J+1) \]

\[ \propto A^2 \]

\[ \Lambda \equiv \frac{1}{J} (a_p < S_p > + a_n < S_n >) \]
SNU Seoul
3.5 hours by car
SNU
Yangyang
Yangyang Underground Laboratory

Korea Middleland Power Co.
Yangyang Pumped Storage Power Plant

Minimum depth: 700 m / Access to the lab by car (~2km)
CsI(Tl) Crystal

Advantage

- High light yield ~60,000/MeV
- Pulse shape discrimination
- Moderate background rejection
- Easy fabrication and handling
- Easy to get large mass with an affordable cost
- Good for AM study

Disadvantages

- Emission spectra does not match with normal bi-alkali PMT
  => Effectively reduce light yield
- $^{137}$Cs($\tau_{1/2}$ ~30y), $^{134}$Cs($\tau_{1/2}$ ~2y) may be problematic

<table>
<thead>
<tr>
<th></th>
<th>CsI(Tl)</th>
<th>NaI(Tl)</th>
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<tbody>
<tr>
<td>Photons/MeV</td>
<td>~60,000</td>
<td>~40,000</td>
</tr>
<tr>
<td>Density(g/cm³)</td>
<td>4.53</td>
<td>3.67</td>
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<tr>
<td>Decay Time(ns)</td>
<td>~1050</td>
<td>~230</td>
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<tr>
<td>Peak emission(nm)</td>
<td>550</td>
<td>415</td>
</tr>
<tr>
<td>Hygroscopicity</td>
<td>slight</td>
<td>strong</td>
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</table>
Pulse shape discrimination of gamma background

\[
\langle t \rangle = \frac{\sum A_i t_i}{\sum A_i}
\]
1. External gamma
   - Isotopes in surrounding materials (Rock)
     - Decay chain of $^{238}U$ and $^{232}Th$
     - Isotopes ($K^{40}$, ...)
     - $Rn^{222}$ in air
   - Shielding structure made of pure and high Z materials
   - Partially or fully distinguishable from WIMP signal by PSD
   - $N_2$ flowing to remove air contaminated by $Rn^{222}$

2. Neutron background
   - Indistinguishable from WIMP signal (Nuclear recoil)
     - $(\alpha, n)$ reaction
     - Nuclear fission
     - Induced by cosmic muon ($E_{\text{mean}} \sim 230$ GeV)
       - possible to veto with muon detector
   - Neutron moderator made of material with High Hydrogen density
   - Veto system using Muon detector
KIMS

Neutron shield / Muon det.

Lead shield

Polyethylene

Copper shield

CsI(Tl) crystal
Muon Detector

- $4\pi$ coverage muon detector: 28 channels
- Liquid Scintillator (5%) + Mineral Oil (95%) = 7 ton
- Measured Muon flux = $2.7 \times 10^{-7} \text{ /cm}^2\text{/s}$
- Position resolution: $\sigma_{x,y} \sim 8 \text{ cm}$
- Reconstructed muon tracks with hit information
- Muon veto efficiency $\sim 99.9\%$
Neutron Monitoring Detector

1 liter BC501A liquid scintillator
n/g separation using PSD
$E_{vis} > 300$ keV

2722 events for 67.41 days
Rate: 33.65 counts/liter/day
Muon induced neutrons

2 events of Muon induced neutron during 67.4 days
~ 0.03 counts/day/liter
Neutron Monitoring Detector

$^{214}$Bi $\beta$-decay $\rightarrow$ $^{214}$Po $\alpha$-decay

**Gamma-Alpha Coincidence**

Lifetime = 0.155 +/- 0.008 ms
Lifetime of 214Po = 0.1643 ms
471 coincidence events and 5 background events

$^{222}$Rn $\alpha$-decay $\rightarrow$ $^{218}$Po $\alpha$-decay

Energy = 523.5 +/- 2.2 keV
Among 605 events
553 events of alpha's from 222Rn 5590 keV
26 events of alpha's from 220Rn 6405 keV
26 events of alpha's from 224Ra 5789 keV
Quenching factor = 9.4 %

Energy = 617.9 +/- 2.4 keV
Among 605 events
553 events of alpha's from 218Po 6115 keV
26 events of alpha's from 216Po 6086 keV
26 events of alpha's from 220Rn 5405 keV
Quenching factor = 10.1 %
Neutron Monitoring Detector (cont’d)

\( ^{230}\text{Ra} \) dominant contamination in \( ^{238}\text{U} \) chain
- 6.66 \( \pm \) 0.27 cnts/liter/day – 1.5 \( \times 10^{-6} \) ppt of \( ^{230}\text{Ra} \) level

\( ^{232}\text{Th} \) dominant contamination in \( ^{232}\text{Th} \) chain
- 0.32 \( \pm \) 0.06 cnts/liter/day – 0.63 ppt of \( ^{232}\text{Th} \) level

- All neutron events: alphas from internal sources
  Neutron rate < 1.8 cpd (90 % C.L.) inside the shield

- Neutron rate outside the shield
  \( 8 \times 10^{-7} \) /cm\(^2\)/s (1.5 < E neutron < 6 MeV)
  After subtracting internal background estimated from the data inside the shield
Electrostatic alpha spectroscopy: 70 liter stainless container
Use Si(Li) photodiode: 30 x 30 mm
Estimate $^{222}\text{Rn}$ amount with energy spectrum of $^{218}\text{Po}$ & $^{214}\text{Po}$.
Photodiode calibration: $^{210}\text{Po}$, $^{241}\text{Am}$
$^{222}\text{Rn}$ in air = 1 ~ 2 pCi/liter
Absolute efficiency calibration done with $^{226}\text{Ra}$
Internal background of CsI Crystal

- $^{137}$Cs (artificial)
  - serious background at low energy
- $^{134}$Cs (artificial+$^{133}$Cs(n, gamma))
- $^{87}$Rb (natural)
  - Hard to reject
  - reduction technique in material is known

Single Crystal (~10 kg) background @ ~10keV

$^{87}$Rb 1.07 cpd/1ppb
$^{137}$Cs 0.35 cpd/1mBq/kg
$^{134}$Cs 0.07 cpd/1mBq/kg

From simulation
Reduction of Internal Background

**Cs137 Reduction**
- Water is main source of Cs137
- It was reduced by using purified water

**Rb87 Reduction**
- CsI solubility in water is very high.
- Recrystallization reduces Rb87.
- 10 ppb powder $\rightarrow$ $\sim$ 1 ppb ($< 1.1$cpd)
Further reduction of internal background

New CsI powder produced with ultra pure water

2mBq/kg $\rightarrow$ 0.7 cpd internal background
Reduction of Internal Background cont’ed

Best available Crystal at Market

- 70cpd
- 20cpd
- 14cpd
- 6cpd
- 4cpd

Powder Selection

Cs137 Reduction Using Pure water

Rb87 Reduction by Re-crystallization

Ultra Pure Water Used
Data taking with CsI(Tl)

CsI(Tl) Crystal  8x8x30 cm³  (8.7 kg)
3” PMT (9269QA)
Quartz window, RbCs photo cathode
4~6 Photo-electron/keV
DAQ 500MHz Home Made FADC
5 photo-electron within 2μsec trigger condition
total 32μsec window

<table>
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<th>Name</th>
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<th>Company</th>
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<tbody>
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<tr>
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<tr>
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<tr>
<td>0605B</td>
<td>~4CPD</td>
<td>8.7 kg</td>
<td>beijing</td>
</tr>
</tbody>
</table>
Neutron calibration facility in SNU

300 mCi Am/Be source
- neutron rate $7 \times 10^5$ neutrons/sec
- a few 100 neutrons/sec hit
  3cmX3cm crystal
- Quenching factor of Recoil Energy
  Take Neutron calibration data
  PSD check – Quality factor

PSD discrimination
Mean time distribution

@Energy = 4-5 keV
137 Cs Compton
Neutron Recoil

Tag $\gamma (4.4 \text{MeV})$
to measure TOF and energy of neutrons
Extraction of nuclear recoil events

\[ N_{NR}^i f_{NR}^i(x) + N_{ER}^i f_{ER}^i(x) \]

\[ x = \log(\langle t \rangle) \]
Rate of nuclear recoil events

Log mean time distribution of background events are fitted to distributions of Compton events and neutron events

Filled circle: w/o PMT noise cut
Open square: with PMT noise cut - efficiency corrected
Open circle: fitted the number of nuclear recoil events

$^{56}$Fe energy distribution
solid line for MC and dotted points for data

Simulated energy distributions of WIMP for different masses

20 GeV, 50 GeV, 100 GeV, 1 TeV
Interaction rate of WIMP

Local WIMP density $\sim 0.3\text{GeV/cm}^3$
Maxwellian velocity distribution with $\bar{v} \sim 270\text{km/s}$
$\Rightarrow$ Local flux of WIMP $\sim 100\text{ GeV/m}_\chi x 10^5/\text{cm}^2/\text{s}$

$$\frac{dR}{dE} = \frac{\rho_x}{4v_E M_x M_{\text{red}}(M_{\text{nuc}})} \left[ \text{erf}\left(\frac{v_{\text{min}} + v_E}{v_0}\right) - \text{erf}\left(\frac{v_{\text{min}}}{v_0}\right) \right],$$

$$v_{\text{min}} = \sqrt{\frac{E M_{\text{nuc}}}{2 M_{\text{red}}}},$$

$E_{\text{recoil}}(\text{max}) = 2v_x^2 m_N \frac{m_x^2}{(m_N + m_\chi)^2}$

Recoil energy $< 100\text{ keV}$
Measured energy $< 10\text{ keV}$ due to quenching
Dark matter density at the solar system
\[ \rho_D = 0.3 \text{ GeV } c^{-2} \text{ cm}^{-3} \]
Use annual average parameters
\[ V_0 = 220 \text{ km s}^{-1}, \quad V_E = 232 \text{ km s}^{-1}, \quad V_{Esc} = 650 \text{ km s}^{-1} \]

Spin Independent Limit

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Limit (kg days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAIAD - NaI(Tl)</td>
<td>3879</td>
</tr>
<tr>
<td>KIMS - CsI(Tl)</td>
<td>237</td>
</tr>
<tr>
<td>DAMA - NaI(Tl)</td>
<td>4123</td>
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</tbody>
</table>

PLB 633(2006) 201
In Feb. 2006
Spin dependent WIMP limit only with I

Pure proton case
Form factor and spin expectation value for “I” are obtained from
“M.T.Ressel and D.J.Dean PRC 56(1997) 535

Pure neutron case
WIMP search with CsI(Tl) crystal

Summary & Prospects

• First physics result was published

• Various R&D run was done
  – About 4000 kg day data acquired
  – With and without quartz block (5cm thick)
  – 0 degree and Room temperature operation
  – Analysis is ongoing

• Successfully reduce internal backgrounds of CsI(Tl) crystals
  – 70 kg full size crystals (8x8x30cm³) are being prepared
  – Mass production stage
    • 2 Crystal/Month growing is possible

• With more than 100 kg crystals, we start to probe
  – Annual modulation
  – SD+SI interaction search
Search for Low Mass WIMP

ULE HPGe detector setup

5g 1 cpd level detector
Tested at Academia Cincia, Taiwan
and delivered to SNU in Dec, 2004.

If successful → upgrade to 1kg mass

CsI(Tl) crystal
Compton veto
→ Built by TU
→ Delivered to SNU

Collaboration with China and Taiwan
Double beta decay

\[(A, Z) \rightarrow (A, Z+2) + 2\beta + 2\nu\]

**2\nu** mode: a conventional 2\textsuperscript{nd} order process in nuclear physics

**0\nu** mode: a hypothetical process can happen only if: 
\[\bullet M_\nu \neq 0 \quad \text{Since helicity has to flip}\]
\[\bullet \nu = \bar{\nu}\]

Several new particles can take the place of the virtual \(\nu\)

But 0\nu\beta\beta decay always implies new physics

1/ \(T_{1/2}^{0\nu}\) \(\propto <m_{\beta\beta}>^2\)

\(<m_{\beta\beta}> = \left| \sum_i U_{ei}^2 m_{\nu_i} e^{i\alpha_i} \right|^2\)
Experimental search for DBD

Two approaches:

1. Source $\equiv$ Detector (calorimetric technique)
   - high energy resolution
   - 100% efficiency
   - no event topology

2. Source $\neq$ Detector
   - event shape reconstruction
   - low energy resolution
   - low efficiency

If you use the calorimetric approach:

Signature: shape of the two electron sum energy spectrum

- two neutrino DBD continuum with maximum at $\sim 1/3 \, Q$
- neutrinoless DBD peak enlarged only by the detector energy resolution

Low energy resolution:
- $2\nu$ events can mask $0\nu$ ones

Low background:
- underground operation
- shielding
- low radioactivity of materials
Double beta decay R&D

1. TMSN50% + STD Liquid scintillator
   $^{124}\text{Sn} \rightarrow ^{124}\text{Te} + 2\beta$–decay
   $T_{1/2} > 3.41 \times 10^{19}$ yr at 90% C.L.

2. $\text{CaMoO}_4$ Crystal 1.8x1.8x3.5 cm$^3$
   $^{100}\text{Mo} \rightarrow ^{100}\text{Ru} + 2\beta$–decay
   10kg Mo-100 CaMoO$_4$
   5-year running
   $T_{1/2} > 1 \times 10^{25}$ yr at 68% C.L.
   Present Best Limit >
   $4.6 \times 10^{23}$ yr @ 90% C.L.
Other activities
Summary and prospect

ULE HPGe detector for low mass WIMP search
- Compton veto detector delivered
- Prototype detector and shield is being soon

Cryogenic detector for low energy detection
- Fabrication and test of TES sensor on-going
- Need fast cycling of sample test for the TES optimization

Metal loaded liquid scintillator for $0\nu\beta\beta$ decay
- Pilot experiment with 1 liter 50% Sn loaded LS → encouraging result
- Study on internal background in progress
- Loading other element in progress

$\text{CaMoO}_4$
- Test with a 50g crystal has been done → encouraging result
- R&D for growing optimization and background reduction in progress
- 10kg crystal can be easily installed in the current WIMP search setup