Development of low background CsI(Tl) crystals and search for WIMP

1. Why CsI(Tl) crystal for drak matter search?
2. Characteristics of CsI(Tl) crystal
3. Development of ultra-low background CsI(Tl)
4. WIMP limit and Prospect

H.J.Kim (Kyungpook National Univ.)
for KIMS Collaboration

SCINT2007, Wakeforest Univ, Winston-Salem
How to detect WIMP directly?

Elastic scattering of WIMP off a nucleus in the detector

\[ \sigma(\tilde{\chi}_1^0 N \rightarrow \tilde{\chi}_1^0 N) \]

10^{-6} \sim 10^{-10} \text{ pb}

Expected event rate

\sim 1/\text{kg/day or less}

Energy loss by ionization (scintillation) and lattice vibration
CsI(Tl) for low background experiment

Advantage

- High light yield ~60,000/MeV
- Pulse shape discrimination
- Better than NaI(Tl)
- Easy fabrication and handling
- Easy to get large mass with an affordable cost

Disadvantages

- $^{137}\text{Cs}$, $^{134}\text{Cs}$, $^{87}\text{Rb}$ background issue:
  - => Background reduction needed
- Emission spectra does not match with bi-alkali PMT:
  - => RbCs green extended PMT

<table>
<thead>
<tr>
<th></th>
<th>CsI(Tl)</th>
<th>NaI(Tl)</th>
</tr>
</thead>
<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>
</tr>
<tr>
<td>Decay Time(ns)</td>
<td>~1050</td>
<td>~230</td>
</tr>
<tr>
<td>Peak emission(nm)</td>
<td>550</td>
<td>415</td>
</tr>
<tr>
<td>Hygroscopicity</td>
<td>slight</td>
<td>strong</td>
</tr>
</tbody>
</table>
KIMS Collaboration

Korean Invisible Mass Search Experiment

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CsI(Tl) Crystal and Electronics at KIMS

- **CsI(Tl) Crystal**: 8x8x30 cm³ (8.7 kg)
- **3” PMT (9269QA)**
  - Quartz window, RbCs photo cathode
- **4~6 Photo-electron/keV**
- **DAQ 500MHz, 8bit (400Mhz, 10bit new)** Home Made FADC with VME-USB2 Interface
- **2 photo-electron for each PMT within 2μsec trigger time**
  - total 32μsec window
Quenching Factor & Pulse shape discrimination

\[ \text{CsI QF} = \frac{E_{\text{measured}}}{E_{\text{recoil}}} \]

\[ K = \frac{\beta(1-\beta)}{(\alpha - \beta)^2} \]

H. Park et al., NIMA 491 (2002) 460

H. Park et al., NIMA 491 (2002) 460

SCINT2007, H.J. Kim
Calibration for Nuclear recoil

We use sample crystal to take neutron data

Same temperature condition with WIMP search data

5-7 keV

Neutron Calibration Facility at SNU

Tag γ(4.4MeV) to measure TOF and energy of neutrons

Neutron sample
Gamma sample
Full size
Gamma sample

5-7 keV

log(mean time)
Internal background

Radioisotopes in the crystal

$^{137}\text{Cs} : \tau_{1/2} = 30.07 \text{ year} \ (\text{Artificial})$

- $\beta$ decay to $^{137}\text{Ba}^*$ ($Q = 1175.6 \text{ keV}$)
- $2 \text{ min life time}$, emitting $661.6 \text{ keV}$ gamma

Hard to reject

$^{134}\text{Cs} : \tau_{1/2} = 2.065 \text{ year} : \text{Artificial} + ^{133}\text{Cs}(n, \gamma)$

- $\beta$ to $^{134}\text{Ba}^* \ (Q=2058.7 \text{ keV})$
- Prompt $\gamma$ emission

Can be rejected easily: not a problem

$^{87}\text{Rb} : \tau_{1/2} = 4.75 \times 10^{10} \text{ year} \ (27.8\% \text{ nat. abun.})$

- $\beta$ Beta decay to $^{87}\text{Sr} \ (Q=282.3 \text{ keV})$
- No $\gamma$ emission

Hard to reject

- Reduction technique in material is known

- $0.35 \text{ cpd/mBq}$
- $0.07 \text{ cpd/mBq}$
- $0.005 \text{ cpd/mBq}$
- $1.07 \text{ cpd/ppb}$
Reduction of $^{137}$Cs background
(Extensive R&D with Chemetall GmbH)

<table>
<thead>
<tr>
<th></th>
<th>$^{137}$Cs in Water (mBq/liter)</th>
<th>$^{137}$Cs in Powder (mBq/liter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processing</td>
<td>0.5–1.66</td>
<td>20.5–81.2</td>
</tr>
<tr>
<td>Pure</td>
<td>$0.052 \pm 0.01$</td>
<td>$7.41 \pm 0.7$</td>
</tr>
<tr>
<td>Ultra-pure</td>
<td>$&lt; 0.02$</td>
<td>$1.89 \pm 0.5$</td>
</tr>
</tbody>
</table>

$^{137}$Cs reduction

- Water is the main source of $^{137}$Cs
- It was reduced by using purified water

Energy Spectrum : variable bin

Csl Powder Measurements

Processing water + pure water

Pure water only

Ultrapure water

Processing water
Rb Reduction

- Solubility of CsI is lower than RbI.
- Recrystallization is done at slightly lower temperature from saturation point.
- Further reduction is observed in crystallization process (Bridgmann)
- 10 ppb powder $\rightarrow$ ~ 1 ppb ($<1.1$ cpd)
Status of the background reduction

- **Best available Crystal at Market**: 70 cpd
- **Powder Selection**: 20 cpd
- **Cs137 Reduction Using Pure water**: 14 cpd
- **Rb87 Reduction by Re-crystallization**: 6 cpd
- **Ultra Pure Water Used**: 4 cpd

Graph showing various backgrounds and their reduction methods.
Background Spectrum of S0406 crystal

Pure Water + Recrystallization

- total: $6.27 \pm 0.67$ mBq/kg
- $^{137}\text{Cs}$: $14.1 \pm 1.41$ mBq/kg
- $^{87}\text{Rb}$: $1.32 \pm 0.43$ ppb

6CPD level

Counts/(kg keV day)

Energy (keV)
Darkmatter search in Korea (KIMS experiment)

Mineral oil 30cm
Pb 15cm : 30t
OFHC Cu 10cm : 3t
Muon veto + LSC
## Installed Crystals & data

<table>
<thead>
<tr>
<th>NAME</th>
<th>Weight(kg)</th>
<th>DATA(kg day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S0406</td>
<td>6.7</td>
<td>237</td>
</tr>
<tr>
<td>S0501A</td>
<td>8.7</td>
<td>1147</td>
</tr>
<tr>
<td>S0501B</td>
<td>8.7</td>
<td>1030</td>
</tr>
<tr>
<td>B0510A</td>
<td>8.7</td>
<td>616</td>
</tr>
<tr>
<td>B0510B</td>
<td>8.7</td>
<td>616</td>
</tr>
<tr>
<td>B0511</td>
<td>8.7</td>
<td></td>
</tr>
<tr>
<td>B0601</td>
<td>8.7</td>
<td></td>
</tr>
<tr>
<td>B0605A</td>
<td>8.7</td>
<td></td>
</tr>
<tr>
<td>B0605B</td>
<td>8.7</td>
<td></td>
</tr>
<tr>
<td>B0606A</td>
<td>8.7</td>
<td></td>
</tr>
<tr>
<td>B0606B</td>
<td>8.7</td>
<td></td>
</tr>
<tr>
<td>B0607</td>
<td>8.7</td>
<td></td>
</tr>
<tr>
<td>B0609A</td>
<td>8.7</td>
<td></td>
</tr>
<tr>
<td>B0609B</td>
<td>8.7</td>
<td></td>
</tr>
</tbody>
</table>

Published

0 degree running

3409 kg day WIMP search data is available at the 0 degree

Total 102.4 kg crystals installed in May, 2007
We had a result to mostly exclude DAMA 3-sigma region in spin independent limit on WIMP-nucleon cross section. First exclusion of DAMA with crystal (I is the same).
Spin dependent limit

Pure proton

We had best result on the WIMP proton spin dependent interaction higher than 30 GeV WIMP mass

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$J$</th>
<th>$&lt;S_p&gt;$</th>
<th>$&lt;S_n&gt;$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cs</td>
<td>7/2</td>
<td>-0.370</td>
<td>0.003</td>
</tr>
<tr>
<td>I</td>
<td>5/2</td>
<td>0.309</td>
<td>0.075</td>
</tr>
</tbody>
</table>
Summay and Prospects

• So far done
  – Background reduction successful: 6 cpd level
  – Mostly exclude DAMA 3-sigma region in spin independent limit
  – World best result on the WIMP proton spin dependent interaction

• 100kg CsI(Tl) just installed ...
  – 12 full size crystals (8x8x30cm³) with total 100 kg were installed on May, 2007 (4 cpd expected)
  – SD+SI interaction search by PSD method
  – Annual modulation
  – PSD + Annual modulation combined

• Long term future ..... 
  – Background less than 2 cpd
  – 250 kg CsI(tl) crystals
Thank you
Production of CsI powder in Chemetall Company (Germany)

Pollucite
Digestion
Purification of Cs salt solution
Conversion to CsOH solution
Evaporation
CsOH solution 50%
Purification
Conversion with HI
High purity CsI

70 liters/1kg of CsI

Power plant
Processing water
River water
Pure water ~ 0.5 MΩ

Cartridge Polisher

SK-water purification system

Rubidium reduction is possible in the purification steps
Quenching factor

- Birks’ formula

\[
\frac{dL}{dx} = \frac{S \frac{dE}{dx}}{1 + kB \frac{dE}{dx}}
\]

Definition of Quenching Factor

\[QF = \frac{E_{ee}}{E_R}\]

\[E_{ee} \propto L\]

Quenching factor of CsI(Tl) crystal
Event Selection to reject PMT related backgrounds

<table>
<thead>
<tr>
<th>Gamma Calibration Data</th>
<th>PMT Only Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>The biggest cluster charge (PE)</td>
<td></td>
</tr>
<tr>
<td>Energy (keV)</td>
<td></td>
</tr>
<tr>
<td>Mean charge of cluster (PE)</td>
<td></td>
</tr>
<tr>
<td>Energy (keV)</td>
<td></td>
</tr>
</tbody>
</table>

- Gamma Calibration Data: Equivalent to ~167 kg days underground data.
- PMT Only Data: ~less than 0.01CPD.
Systematic errors contribute to limit in the WIMP Mass 50 GeV.

<table>
<thead>
<tr>
<th>Contents</th>
<th>Contribution to</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>0.3%</td>
</tr>
<tr>
<td>Fit systematic</td>
<td>5.1%</td>
</tr>
<tr>
<td>Quenching factor</td>
<td>12.4%</td>
</tr>
<tr>
<td>Energy resolution</td>
<td>1.1%</td>
</tr>
<tr>
<td>Energy calibration</td>
<td>1.5%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>14%</strong></td>
</tr>
</tbody>
</table>
WIMP Proton Cross Section

- WIMP Nucleus Scattering

\[
\frac{dR}{dE} = \frac{\rho_x}{4v_E M_x M_{\text{red}}^2(M_{\text{nuc}})} \left[ \text{erf} \left( \frac{u_{\text{min}} + v_E}{v_0} \right) - \text{erf} \left( \frac{u_{\text{min}} + v_E}{v_0} \right) \right],
\]

where \( \rho_x = \) galactic halo density, \( v_E = \) earth velocity in galactic frame, and \( v_0 = \) sun velocity in galactic frame.

- Spin Independent
- Spin Dependent

\[
\sigma_{\chi N}^{SI} = \frac{M_{\text{red}}^2(M_{\text{nuc}})}{M_{\text{red}}^2(M_p)} \left[ Z + (A - Z) \frac{f_n}{f_p} \right]^2 \sigma_{\chi p}^{SI},
\]

\[
\sigma_{\chi N}^{SD} = \frac{M_{\text{red}}^2(M_{\text{nuc}})}{M_{\text{red}}^2(M_p)} \frac{4(J+1)}{3J} \left[ \langle S_p \rangle + \langle S_n \rangle \frac{a_n}{a_p} \right]^2 \sigma_{\chi p}^{SD}.
\]
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 $\sim 100 \text{ GeV/m}_\chi \times 10^5/\text{cm}^2/\text{s}$

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

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

$$E_{\text{recoil}}(\text{max}) = 2v_x^2 m_N \frac{m_\chi^2}{(m_N + m_\chi)^2}.$$
$a_p - a_n$ plane

KI MS 3409 kg
day
NAI AD 12523 kg
day
CDMS (2005)