Dark Matter search with ELEGANT VI CaF$_2$ detector

Introduction
ELEGANT VI detector
Present results
Improvements
Summary

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The tunnel which is originally constructed for the railway is 5 km long, and its maximum depth is about 470 m. Because of the natural ventilation due to the relatively strong wind inside the tunnel, the radon concentration is two or three orders of magnitude lower than the Kamioka underground laboratory.

- Cosmic ray: $4.0 \times 10^{-7}$ cm$^{-2}$sec$^{-1}$
- Neutron flux: $4.0 \times 10^{-5}$ cm$^{-2}$sec$^{-1}$
- Rn concentration: 10 Bqm$^{-3}$

Oto Cosmo Observatory

ELEGANT VI detector
CaF$_2$ scintillator array
Spin-coupled DM search
$^{48}$Ca double beta decay search
CaF$_2$ scintillation Detector

**$^{19}$F :** Search for *spin coupled* Dark Matters
- large $\sigma$
- small ambiguity between the models

- **$^{48}$Ca :** Search for $0\nu\beta\beta$ decay
  - highest Q-value
  - least BG expected

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$^{48}$Ca</th>
<th>$^{76}$Ge</th>
<th>$^{82}$Se</th>
<th>$^{100}$Mo</th>
<th>$^{116}$Cd</th>
<th>$^{136}$Xe</th>
<th>$^{150}$Nd</th>
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</thead>
<tbody>
<tr>
<td>Q-value (MeV)</td>
<td>4.27</td>
<td>2.04</td>
<td>3.00</td>
<td>3.03</td>
<td>2.80</td>
<td>2.48</td>
<td>3.37</td>
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<tr>
<td>$G_{0\nu} \times 10^{-25}$ (year$^{-1}$eV$^{-2}$)</td>
<td>2.44</td>
<td>0.244</td>
<td>1.08</td>
<td>1.75</td>
<td>1.89</td>
<td>1.81</td>
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Natural abundance 0.187%
ELEGANT VI

- large mass scintillator
  ~3.5 kg $^{19}$F
  ~7.7 g $^{48}$Ca

- low background
  - high purity crystal
  - least material: non hygroscopic
  - 4π active shield
    - CaF$_2$(Eu)+CaF$_2$(pure)
    - roll-off ratio
    - segmentation
    - CsI(Tl) veto detector
  - passive shield
    - OFHC Cu(t:5 cm), Pb(t:10 cm)
    - air-tight box + N$_2$ gas purge
    - Rn in the air
    - LiH + paraffin(t:15 mm), Cd sheet(t:0.6 mm), and H$_3$BO$_3$+H$_2$O tank

Surrounded by H$_3$BO$_3$ loaded-water tank
CaF$_2$(Eu) & CaF$_2$(pure)

CaF$_2$(pure) as light guide
active shield against PMT

CaF$_2$(Eu) is not transparent for U.V. light

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**Scintillation emission spectra of CaF$_2$ crystal**

- CaF$_2$(Eu): from BICRON catalogue
- CaF$_2$(pure): measured value
Roll-off ratio

\[ R = \frac{V_R - V_L}{V_R + V_L} \]

- \( V_L \approx V_R \)
- \( V_L > V_R \)

CaF\(_2\) (pure) \( n = 1.44 \)
CaF\(_2\) (Eu) \( n = 1.47 \)

Quartz window

Visible light

U.V. light

\( V_L, V_R \): ADC channel from left & right PMT

9 June '03

Neutrinos and Dark Matter in Nuclear Physics (NDM03)
Recoil response calibration ($f$-value)

- Calibration for our crystal

$^{19}$F$(n, n)$ elastic scattering

3.2 MV Pelletron (~2 $\mu$A at 2 MHz)

Result

(R. Hazama, et al., NIM A482 (2002) 297)
Contamination measurement

- **U-series**
  - hardware (second) trigger
  - time window : 9 – 499 $\mu$sec.

- **Ac-series**

- **Th-series**
  - software cut
  - time window : 0.05 – 1.0 (0.5) sec.

\[
\begin{align*}
\text{214 Bi} & \quad E_\beta = 3270 \quad \rightarrow \quad \text{214 Po} \quad E_\alpha = 7687 \quad \rightarrow \quad \text{210 Pb} \\
& \quad (164.3 \ \mu\text{sec})
\end{align*}
\]

\[
\begin{align*}
\text{219 Rn} & \quad E_\alpha = 6819 \quad \rightarrow \quad \text{215 Po} \quad E_\alpha = 7386 \quad \rightarrow \quad \text{211 Pb} \\
& \quad (1.781 \ \text{msec})
\end{align*}
\]

\[
\begin{align*}
\text{220 Rn} & \quad E_\alpha = 6288 \quad \rightarrow \quad \text{216 Po} \quad E_\alpha = 6779 \quad \rightarrow \quad \text{208 Pb} \\
& \quad (0.145 \ \text{sec})
\end{align*}
\]
Contamination measurement

$^{214}\text{Bi} \xrightarrow{\beta} ^{214}\text{Po}$  $^{219}\text{Rn} \xrightarrow{\alpha} ^{215}\text{Po}$  $^{220}\text{Rn} \xrightarrow{\alpha} ^{216}\text{Po}$  time window : 0.05-1.0 sec

Energy (keV)

Counts (20keV)
### Contamination inside crystals

**×10^5 Bq/kg**

<table>
<thead>
<tr>
<th>CaF&lt;sub&gt;2&lt;/sub&gt; #1 &amp; #25</th>
<th>U-series (214Bi)</th>
<th>Ac-series (219Rn)</th>
<th>Th-series (220Rn)</th>
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**CaF<sub>2</sub> #1 & #25**

High contamination

**Average contamination**

( #2 - #24 )

- U-series (214Bi): 1.11 × 10^-3 Bq/kg
- Ac-series (219Rn): 3.84 × 10^-4 Bq/kg
- Th-series (220Rn): 9.81 × 10^-5 Bq/kg

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Low energy signal by CaF₂ scintillator

- CaF₂(Eu) long falling time (~ 1 µsec)
  ~0.4 keV/photoelectron

ex.) 4 keV signal

4 µsec gate width

ADC

- baseline fluctuation
- one photoelectron signal fluctuation
- noise
- etc….
**Flash Scaler**

- **Flash scaler** \( \leq 30 \text{ keV} \)
  - like multichannel scaler (MCS)
    - dwell time: 50 – 100 nsec
    - each channel: 8 bits scaler

![Diagram of a flash scaler system with signal from PMT, discriminator output, clock signal, and flash scaler output.](image)
Single photon counting in low energy region

- Improvement in energy resolution
  - free from baseline fluctuations
  - free from single photoelectron fluctuations

- Reject the backgrounds fired at CaF$_2$(pure) crystals

\[ N_{\text{cut}} = A \times N_{\text{Eu}} + B \times N_{\text{pure}} \]

Fitting by simple binominal function

- \( P \): probability counted by left (right) PMT
- \( N \): total photon number counted
Roll-off ratio by single photon counting

- **Fitting by Binominal functions for each** $N_{\text{tot}}$

  \[ N_{l,r} : \text{number of photoelectrons counted by left/right PMT} \]

  \[ N_{\text{tot}} = N_l + N_r \]

  \[ r = \frac{N_r - N_l}{N_{\text{tot}}} : \text{roll-off ratio} \]

  \[ F(N_{\text{tot}}, r) = n_{\text{left}} B^*(N_{\text{tot}}, P_{\text{left}}, r) + n_{\text{Eu}} B^*(N_{\text{tot}}, P_{\text{Eu}}, r) + n_{\text{right}} B^*(N_{\text{tot}}, P_{\text{right}}, r) \]

  \[ B^*(N, P, r) = \frac{B(N, P, r)}{\sum_{i=\frac{N-N+1}{2}}^{\frac{N}{2}} B(N, P, r_i)} : \text{modified binominal function} \]

  \[ B(N, P, r) = \text{(coincidence trigger)} \]

  \[ P_{\text{Eu}} : \text{determined by calibration run} \]

  \[ n_{\text{left}}, n_{\text{Eu}}, n_{\text{right}}, P_{\text{left}}, P_{\text{right}} : \text{fitting parameter} \]
Analysis

- Flash scaler test module was introduced for 1 crystal (#12)
  - Live time 71.12 days
Preliminary

- Single crystal, 71.12 days

Exclusion Plot (Spin dependent)

Energy (keV) vs Rate (dru)

WIMP-proton cross section (pb) vs WIMP mass (GeV)

(live time: 71.12 days)
Improvements

- Introduce Flash scalers for central 9 crystals
  - Crystals (CaF$_2$(Eu), CaF$_2$(pure)) with lower contaminations are gathered in the central region of the detector.

- New trigger logic module
  old: \(((\text{left PMT}) \text{ and } (\text{right PMT})) \text{ and } (\text{sum})\)

  new: at least 2 p.e from left and/or right PMTs
  (using FPGA chip)
  more statistics, take data with $r = \pm 1.0$

- PSD using time distribution of photoelectrons
Pulse shape discrimination

- Time distribution of p.e. measured by F.S.
  Test measurement was done for single crystal
  CaF$_2$(Eu), CaF$_2$(pure)

\[
\tau = \frac{\sum n_i t_i}{N_{\text{tot}} - 1}
\]

\[\sum n_i = N_{\text{tot}}\]

- $n_i$ : number of counts for $i$th bin
- $t_i$ : mean time of $i$th bin
- width of each bin : 100 nsec.
- number of bins : 70 (7 $\mu$sec)

$^{60}$Co : $\gamma$ source

$^{252}$Cf : neutron source

PMTs (Hamamatsu H3178MOD)

CaF$_2$(Eu), CaF$_2$(pure) : crystal

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Pulse shape measurement by Flash scaler

\[ ex.) \quad N_{\text{tot}} = 20 \text{ p.e.} \]

\[ t = 0 : \text{determined by first event} \]

CaF\(_2\)(pure)
- Black: \(^{60}\text{Co}\), Red: \(^{252}\text{Cf}\)

CaF\(_2\)(Eu)
- Black: \(^{60}\text{Co}\), Red: \(^{252}\text{Cf}\)
Mean $\tau$ distribution

CaF$_2$(pure)
Black: $^{60}$Co, Red: $^{252}$Cf

CaF$_2$(Eu)
Black: $^{60}$Co, Red: $^{252}$Cf

‘Energy’ means electron equivalent energy

>50 keV not valid
Failed to count because of series of pulses

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CaF$_2$(pure) scintillator

- **log-normal distribution fit**

  $\gamma$ distribution parameter $\rightarrow$ $^{60}$Co

  $P(x) = \frac{1}{x\sqrt{2\pi\sigma^2}}\exp\left(-\frac{(\ln x - \mu)^2}{2\sigma^2}\right)$

  $\gamma$ only
  $N=30$ p.e.

  $\gamma +$ neutron
  $^{252}$Cf

  neutron

  $^{60}$Co

  N=30 p.e.
Decay time for $n/\gamma$

- **Decay time vs. energy**
- **Cut efficiency**: $\frac{\text{number of events less than cut point}}{\text{total number of events}}$

![Graph showing decay time vs. energy and cut efficiency](image)

- Black - $\gamma$, Red - neutron
- Cut point (nsec) about 200 nsec difference
- Black--neutron, Green--gamma

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Q-value

$S$: nuclear recoil events

$B$: $\gamma$ events

$N_{\text{pass}}$: number of events below cut point

$N_{\text{fail}}$: number of events above cut point

$\alpha$: cut efficiency for neutron

$\beta$: cut efficiency for $\gamma$

\[
N_{\text{pass}} = (\alpha S + \beta B)MT
\]

\[
N_{\text{fail}} = ((1 - \alpha)S + (1 - \beta)B)MT
\]

\[
S = \frac{(1 - \beta)N_{\text{pass}} - \beta N_{\text{fail}}}{(\alpha - \beta)MT}
\]

\[
\delta S^2 = \frac{BQ}{MT}; \quad Q = \frac{\beta(1 - \beta)}{(\alpha - \beta)^2}
\]

cf ) $Q = 0.15$ at 22 keV for NaI(Tl)

**Cut point and Q-value**

- **CaF$_2$(Pure)**

  Q-value (N = 30 p.e.)

  ![Graph showing cut point and Q-value for CaF$_2$(Pure).]

  *Minimum: $\sim$1 $\mu$sec*

  Data obtained with normal PMTs

  PMTs with UV sensitive cathode → more efficient PSD ???
CaF₂(Eu) scintillator

- Small difference (??) in decay time

need more study

UKDMC group reported no difference
Summary and Prospects

- ELEGANT VI has been operated at Oto Cosmo Observatory for the study of double beta decay of $^{48}\text{Ca}$ and search for WIMPs.
- Single photoelectron counting by means of Flash scaler was successfully done for 1 crystal. We can reject the background fired at CaF$_2$(pure) crystals.
- We will introduce Flash scalers for central 9 crystals and new trigger system for further run.
- We found a potential of pulse shape discrimination ($n/\gamma$) in CaF$_2$(pure) scintillator by using the Flash scaler.

\[ Q < 1.0 \text{ in low energy region} \]

WIMPs search by CaF$_2$(pure) scintillator

(CANDLES : S. Umehara)