新学術領域研究「ニュートリノフロンティア」公募研究

Development of new measurement technique of ^{48}Ca β decay background for the study of ββ decay of ^{48}Ca

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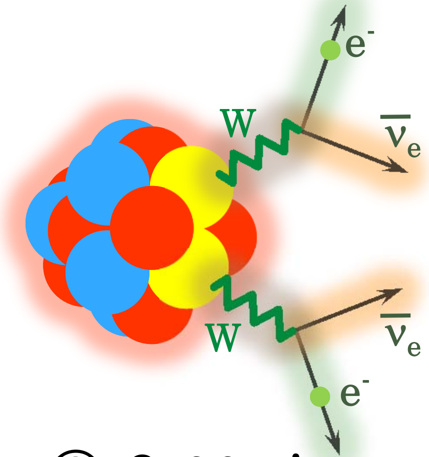
Introduction of ββ Decay

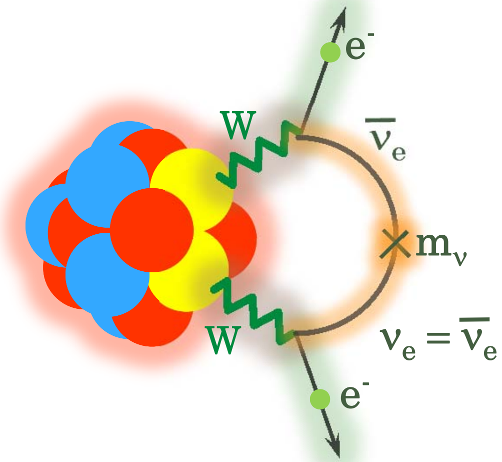
- Two decay modes are usually discussed for ββ decay:

① 2νββ decay : $(A,Z) \rightarrow (A,Z+2) + 2e^{-} + 2\bar{\nu}_e$



- allowed by the Standard Model.
- already observed in more than 10 isotopes.
- Lifetimes ; $\tau = 10^{18} \sim 10^{20}$ yr

② 0νββ decay : $(A,Z) \rightarrow (A,Z+2) + 2e^{-}$



- process beyond the Standard Model.
  - Lepton number violation
  - non-zero neutrino mass
  - Majorana particle
- not observed yet.

  except for the KKDC claim, still alive ?
- predicted lifetimes ; $\tau > 10^{26}$ yr

Physics of 0νββ Decay

- 0νββ search is the useful tools to explore unknown neutrino properties,
  - Origin of neutrino mass, <u>**Dirac or Majorana ?**</u>

    If neutrino is Majorana, 0νββ will be observed !
  - Absolute mass scale ?

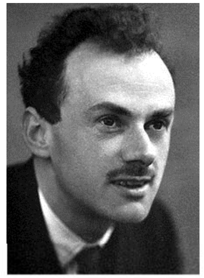
    The effective Majorana mass is calculated by

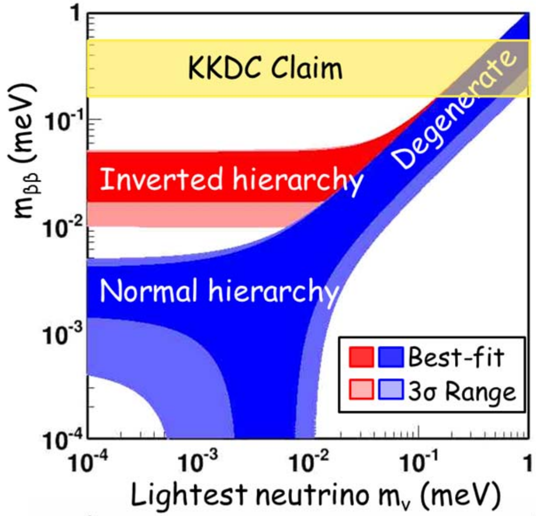
    $T_{0\nu}^{-1} = G_{0\nu}(Q_{\beta\beta},Z)\ |M_{0\nu}|^2\ \langle m_\nu\rangle^2$ (mass term),

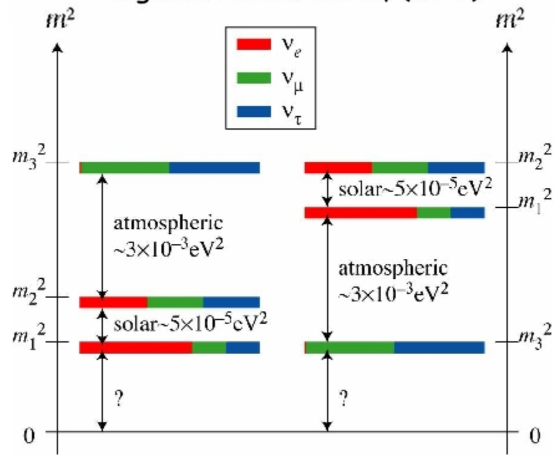
    $\langle m_\nu \rangle = |\sum U_{ei}^2\ m_i|$
  - Mass hierarchy

    (normal, inverted or degenerate) ?
  - CP Phase in the neutrino mixing matrix ?
  - Sterile neutrino ?
  - ……

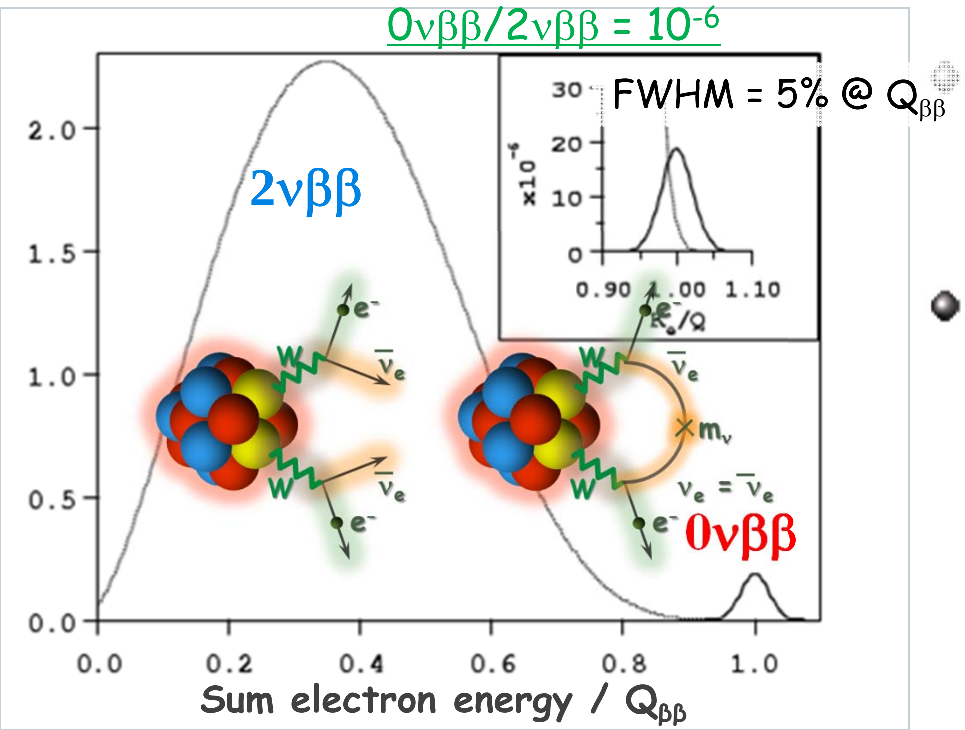
- Neutrino is Majorana particle, ➔
  - ΔL ≠ 0 (Lepton number violation) → Leptogenesis ?
  - See-Saw mechanism ?
    - can explain tiny neutrino masses







Signature of $0\nu\beta\beta$



S.R.Elliot and P.Vogel, Ann. Rev.Nucl.Part.Sci.52(2002)115.

- $0\nu\beta\beta$ decay ;
  - **peak at $Q_{\beta\beta}$**
- $2\nu\beta\beta$;
  - **continuum to $Q_{\beta\beta}$ end point**
  - two electrons from vertex
  - production of daughter isotope

- The shape of the two electron sum energy spectrum enables to distinguish the two different decay modes. ← **Good energy resolution**.
- The predicted $T_{1/2}$ is long (~ 10^{26}yr) . ← **Low BG condition**

CANDLES

@Kamioka Observatory

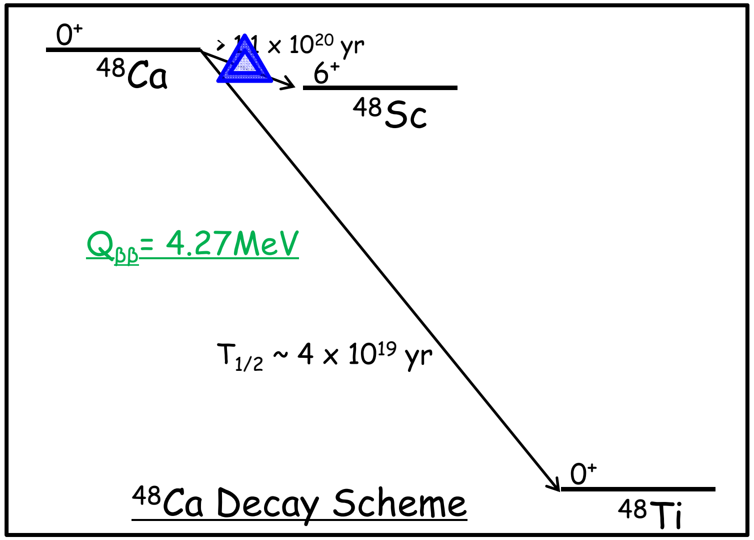
- **CANDLES is the project to search for 0νββ decay of ^{48}Ca.**
- **Detector (CANDLES-III)**
  - Main detector : CaF_2 scintillators(~300kg)
  - Liquid Scintillator : Active Veto (~ 2.1 m^3/1.7 tons)
  - PMTs : 13inch x 48 & 20inch x 14
  - Installed in $3m^{\phi} \times 4m^{h}$ (Water tank)
- **Site: Kamioka** (~1000 m depth)

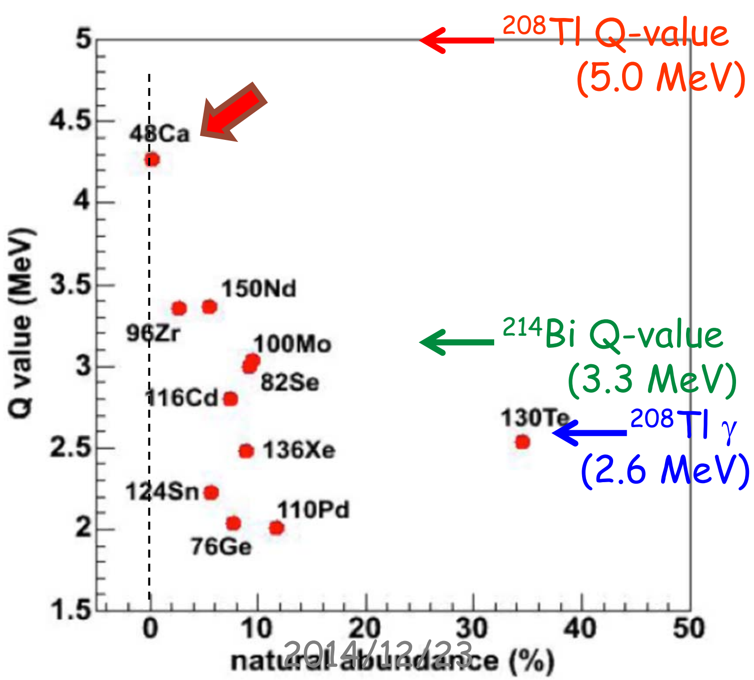
^{48}Ca for ββ Isotope

- ^{48}Ca isotope
  - Highest Q-value (4.27MeV)
    - ➔ Large phase space factor
    - ➔ Low background
      - γ-ray ; 2.6 MeV (^{208}Tl)
      - β-ray ; 3.3 MeV (^{214}Bi)
  - Chance to realize the Background Free Measurement !

$$\langle m_\nu \rangle \propto T_{0\nu}^{-1/2} \propto (1/\ M \cdot T_{live})^{1/2}$$

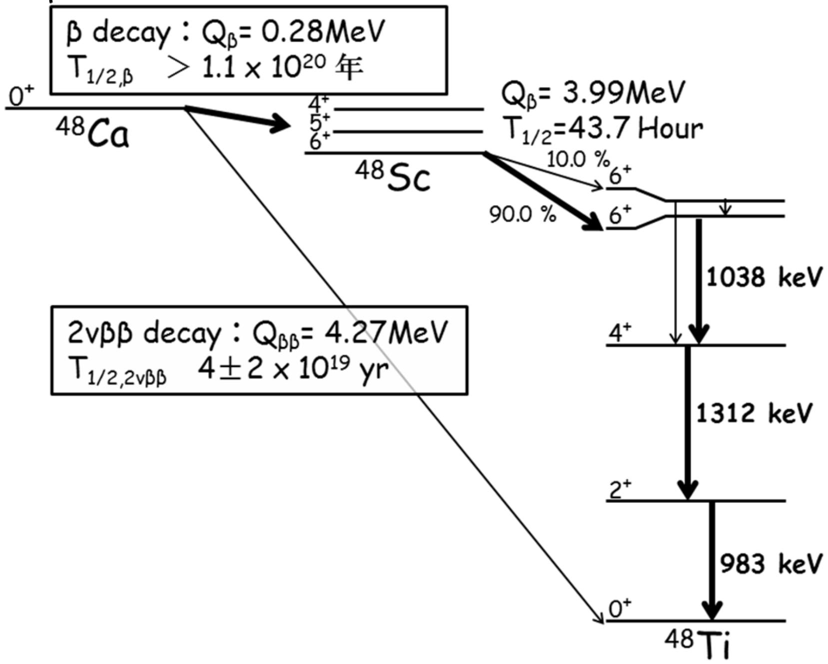
  - Small natural abundance (0.187 %)
    - Chance to improve the sensitivity by the enrichment without scale-up.
    - Enrichment has low risk to increase BG origins
  - Usually, β-decays of ββ isotopes are energetically forbidden, β-decay of ^{48}Ca is strongly suppressed by spin transition law, not forbidden.

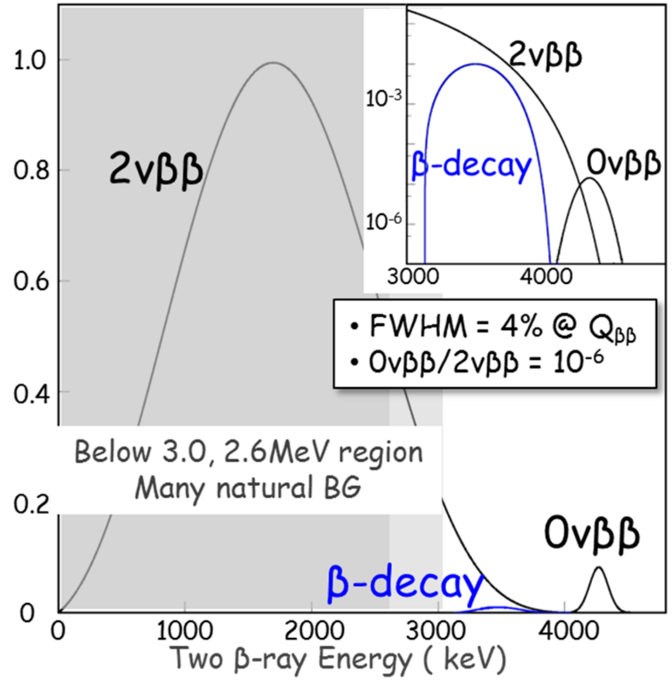




Importance to measure β-decay rate

- To search 0νββ decay, it is important to estimate BG at $Q_{\beta\beta}$-value, especially BG from high energy tail of 2νββ spectrum.
- We also have to measure β-decay rate of ^{48}Ca, precisely, to estimate 2νββ decay rate. The event rate below 3 MeV, there might be large amount of BG due to natural radioactivities, ^{214}Bi (Q=3.0MeV), ^{208}Tl (E_γ=2.6MeV).

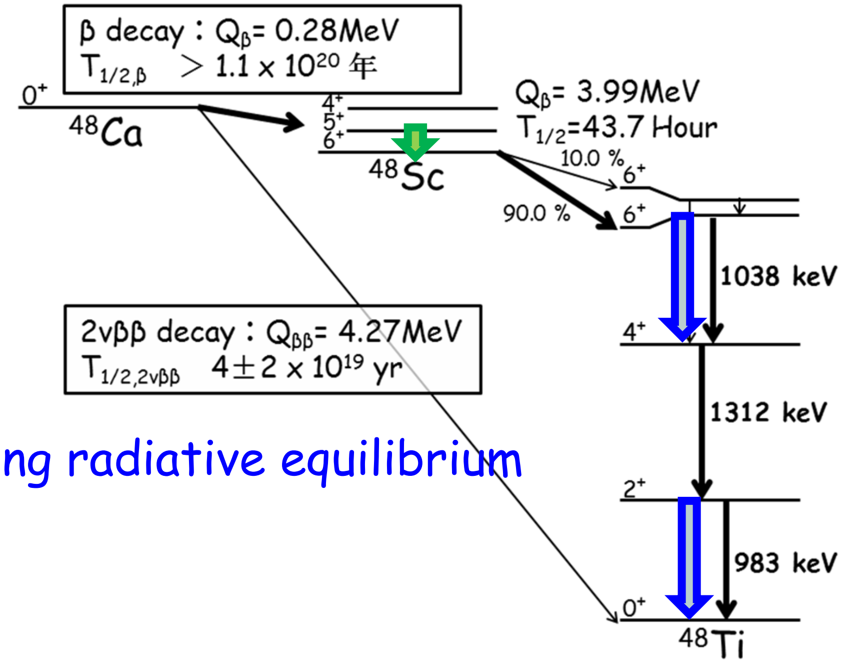




- The lower limit of β-decay half life (1.1×10^{20} yr) was obtained for ^{48}Ca so far.
- Theoretical calc. ; 7.6×10^{20} [1] ~ 1.1×10^{21}[2] yr

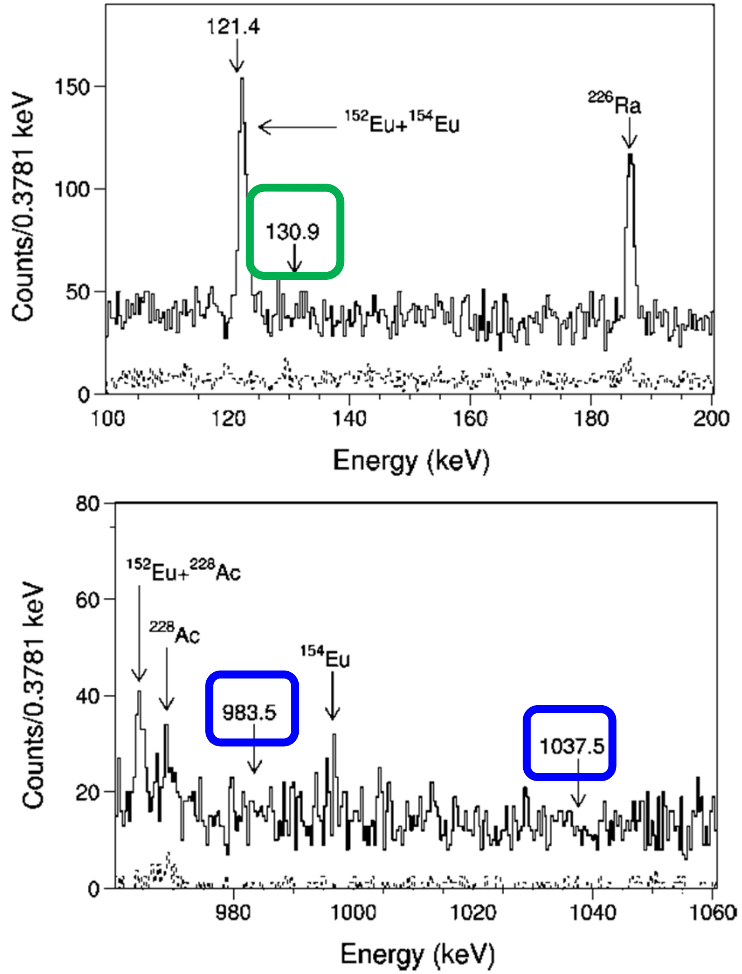
Measurement of β-decay rate

- An **enriched $^{48}CaCO_3$ powder** (^{48}Ca; 20.18 g) was measured for 797 hours with **400 cc low-background HPGe detector**.
- For single β transitions to ^{48}Sc,
  - 0.71×10^{20} y (6+, G.S.)
  - 1.1×10^{20} y (5+)
  - 0.82×10^{20} y (4+)



using radiative equilibrium

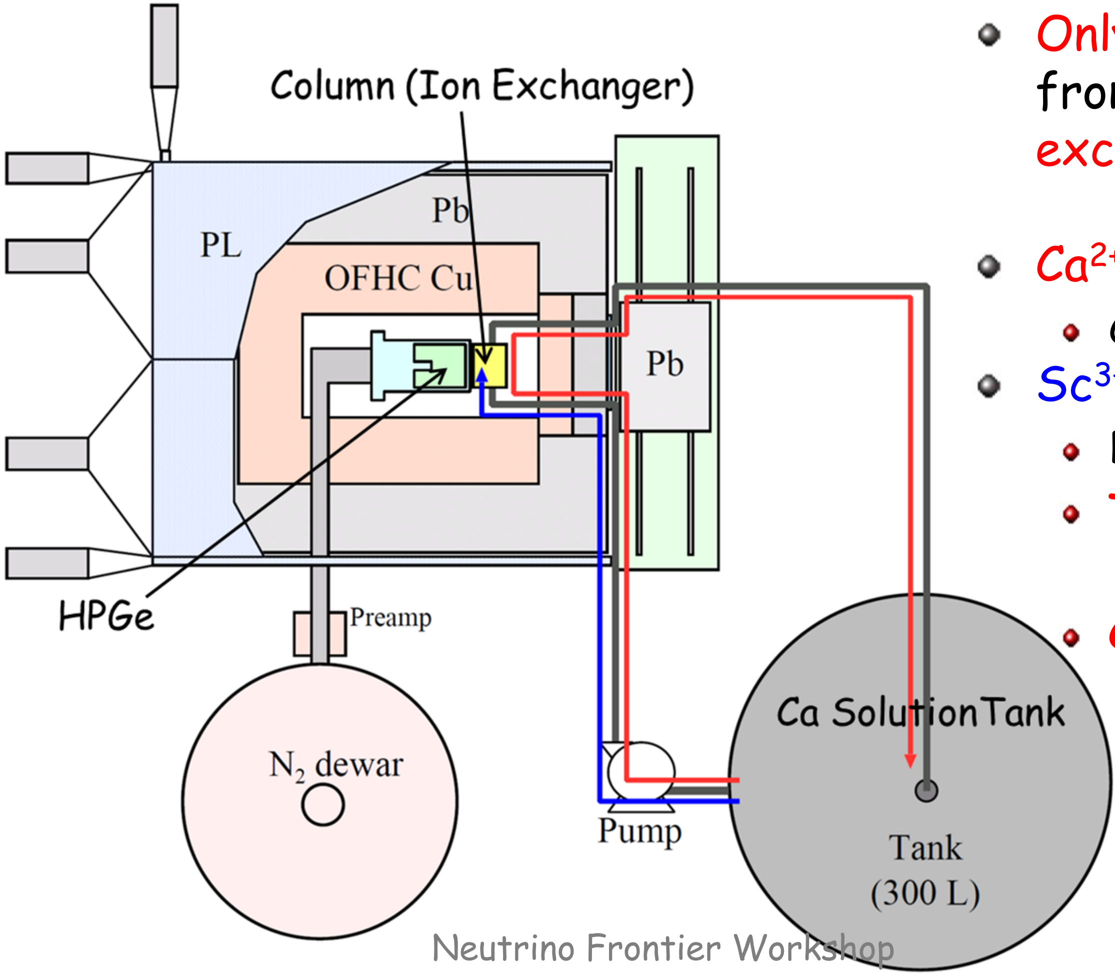
A. Bakalyarov *et al.*
Nucl. Phys. A 700 (2002)17-24



- It is not realistic to increase enriched ^{48}Ca, because it is so expensive, and not available. ➔ **We propose new measuring technique.**

New Method for β-decay Measurement

- Using radiative equilibrium of $^{48}Ca \rightarrow {}^{48}Sc \rightarrow {}^{48}Ti$.
- Count γ-rays from $^{48}Ti^*$ by low background HPGe detector.
  - It is available at sea level lab.@ Osaka Univ.
- Using large amount of $^{nat.}Ca$ source (~ 100 kg)



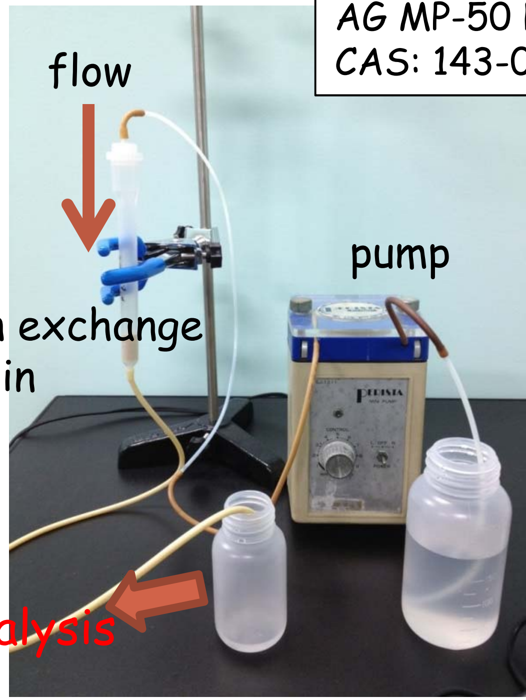
- Only Sc^{3+} ions are concentrated in front of HPGe detector by using ion exchange resin.

- Ca^{2+} solution ; Ca^{2+} path →
  - Circulated with constant flow rate
- Sc^{3+} ion ; Sc^{3+}Path →
  - Decay product of ^{48}Ca β-decay
  - **Trapped in the resin column** (replacing $Ca^{2+} \Leftrightarrow Sc^{3+}$)
  - **Concentrated** at counting site

Test of measuring technique

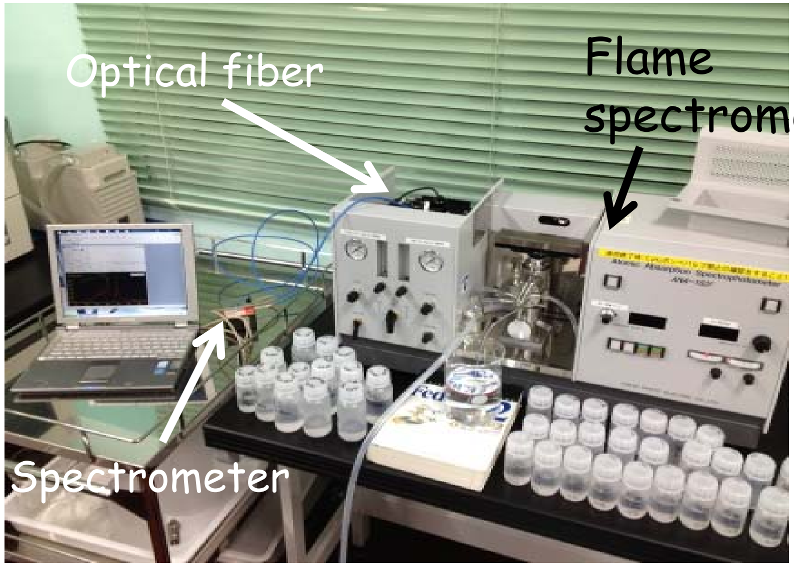
- Requirements for ion+ exchange resin,
  - Trap Sc^{3+} ion efficiently, more than Ca^{2+}
  - Keep trapping Sc^{3+} in the resin longer than $T_{1/2}$ of ^{48}Sc (44 hours)
  - To increase the ^{48}Ca source,
    - Increase flow rate of circulation
    - Increase concentration of Ca solution
    (Solubility of $CaCl_2$: 74.5 g/100mL @20 ℃)

- Trial measurement (Toy level)
  - Firstly, flow the Ca^{2+} solution. Ca ions are trapped in the resin.
  - After the resin is saturated by trapped Ca ions, flow Sc^{3+} solution.
  - Measure the Ca, Sc amount in the output flow by the flame spectrometer.

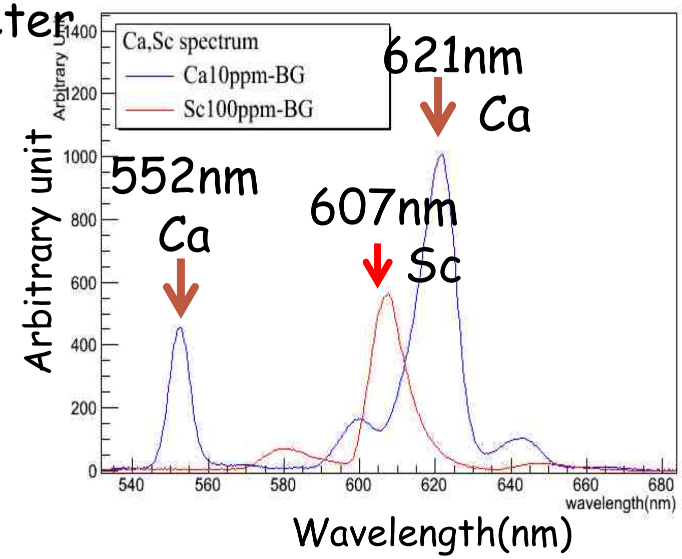


Measuring Ca, Sc concentration

- Measure Ca & Sc concentration with flame spectrometer （炎光分析器）



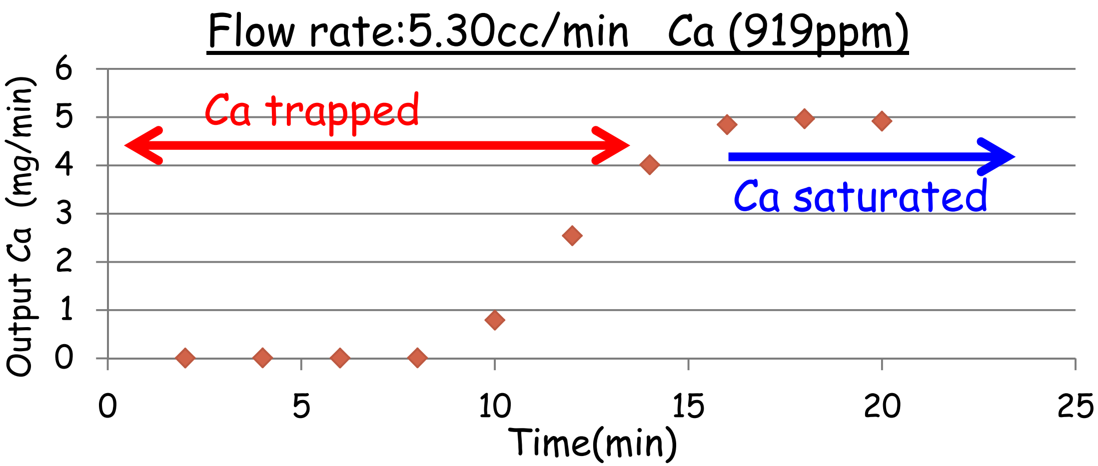
Ca, Sc spectrum



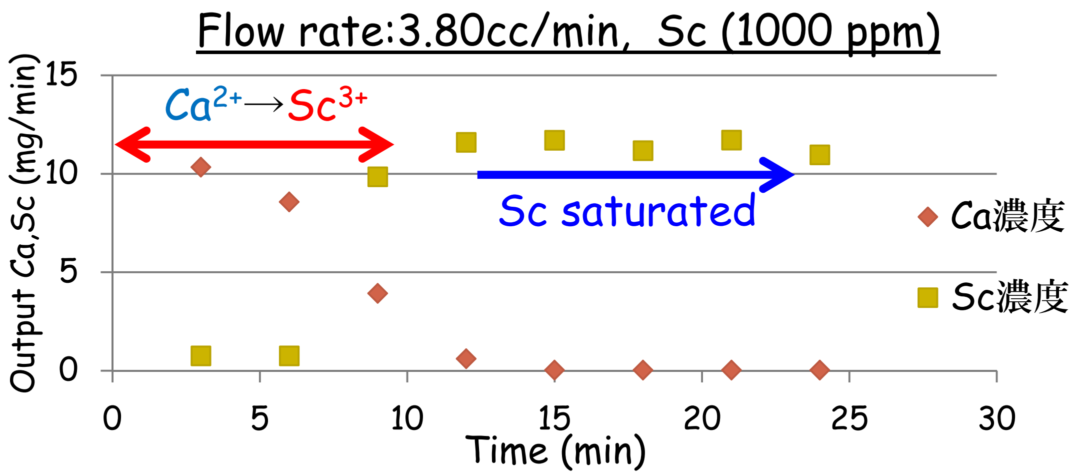
- Measure Ca, Sc concentration from peak intensities.
- Sensitivity of flame analysis
  - Ca ; ~ 0.1 ppm
  - Sc ; ~ 10 ppm
- Difficult to measure Sc concentration in dense Ca solution since the Ca flame spectrum overlaid on the Sc flame peak.

➔ Overcome , later

Test result for concept



Ca trapped amount : 53.4 mg
(per resin = 1.0 g)

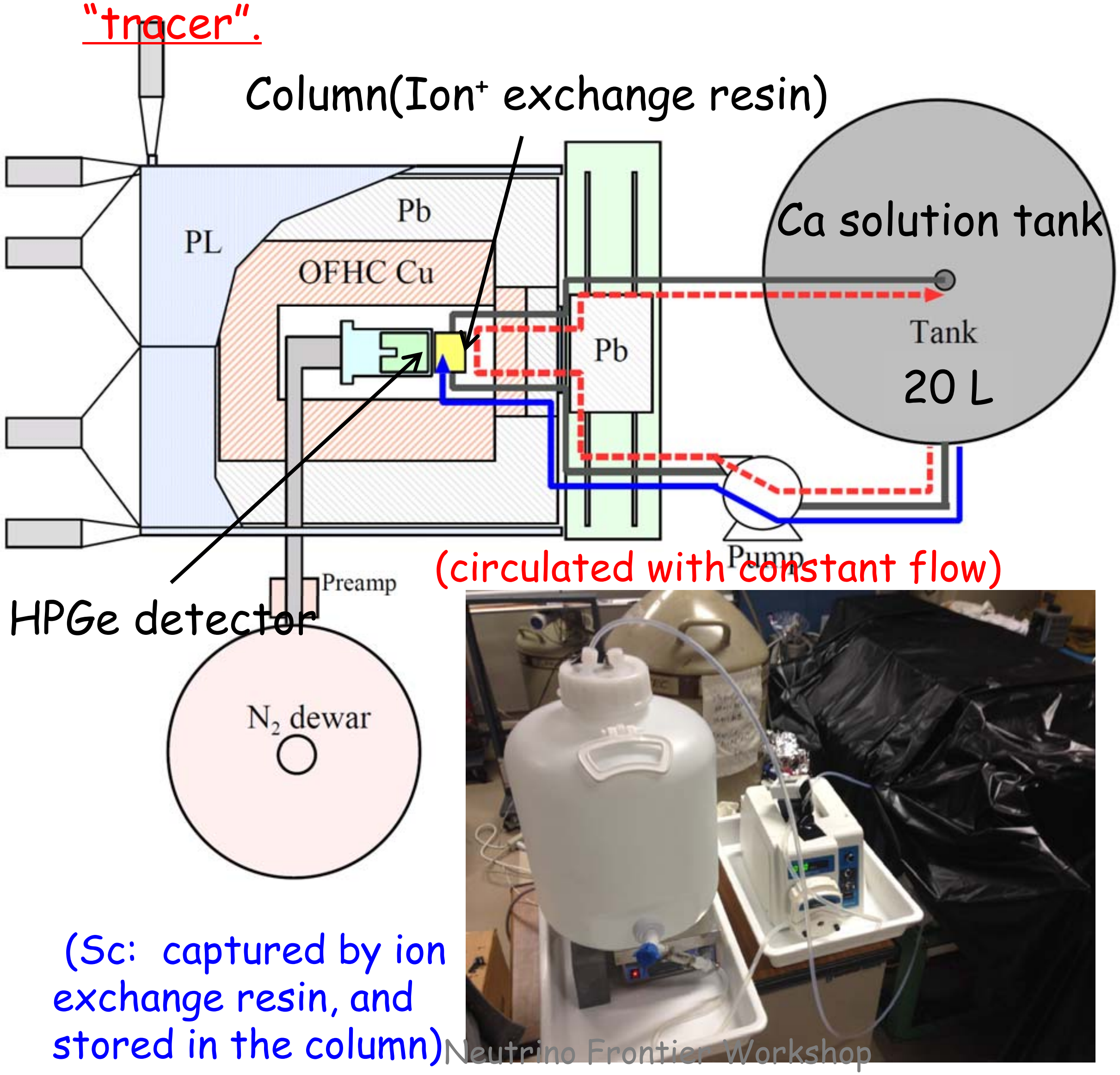


Sc trapped (replaced) amount :
21.9 mg (per resin = 1.0 g)

- Sc^{3+} can be replaced with Ca^{2+} in the ion exchange resin, thus the principle of the technique is O.K.
- Next question ; Same for "small" amount of Sc in the "dense" Ca solution ?

Trial Experiment

- To confirm trapping Sc^{3+} one by one, we produced radioactive ^{46}Sc, as a "tracer".



(circulated with constant flow)

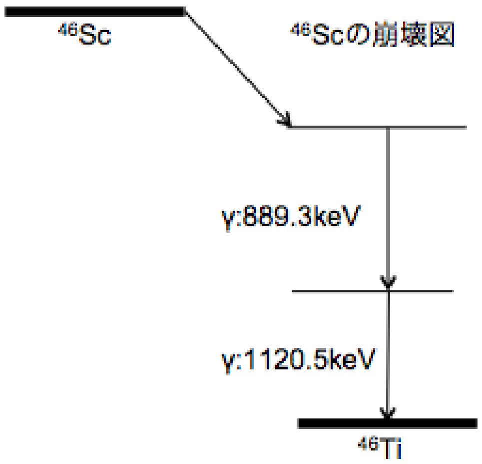
(Sc: captured by ion exchange resin, and stored in the column)

Procedure

- Circulate Ca^{2+} solution (~2 L)
- Mix tiny amount of ^{46}Sc (~a few Bq, 10μg of Sc)
- Counting γ-rays from ^{46}Sc trapped in the resin
- Estimate Efficiency
  - Dependence on Ca concentration
  - Dependence on resin amount

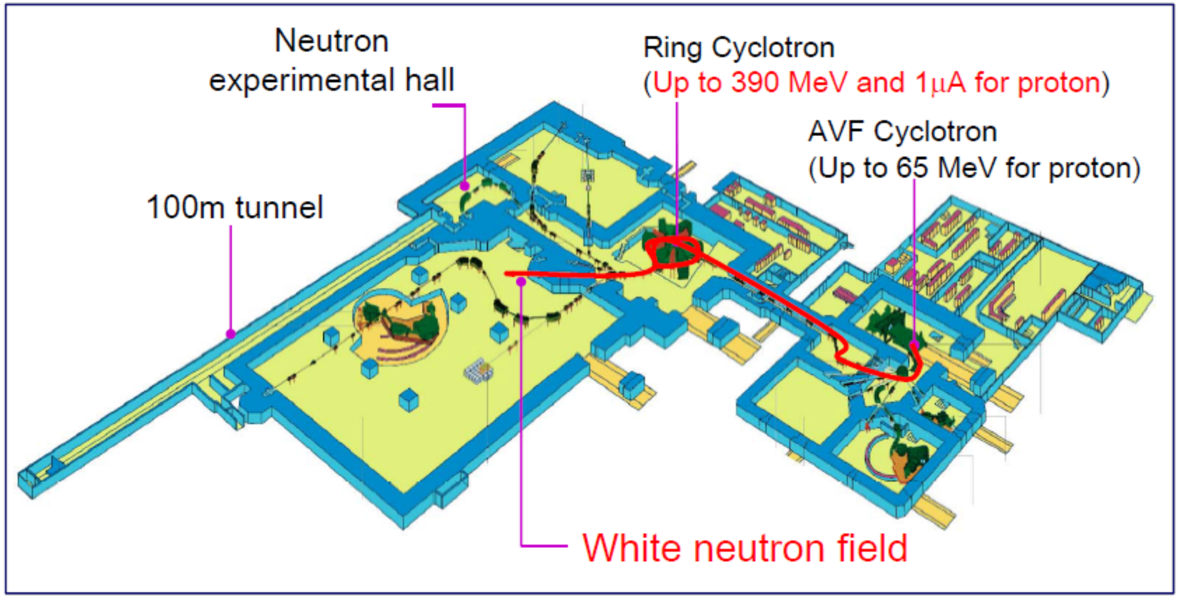
Production of ^{46}Sc Tracer

- ^{46}Sc radioactivity was produced by neutron irradiation $^{45}Sc(n, \gamma)^{46}Sc$.
- Neutron irradiation line @ RCNP, Osaka University
  - Proton beam is bombarded on W target.
  - x 10^8 neutron flux, comparing the one at ground surface



put Sc solution sample far from the beam

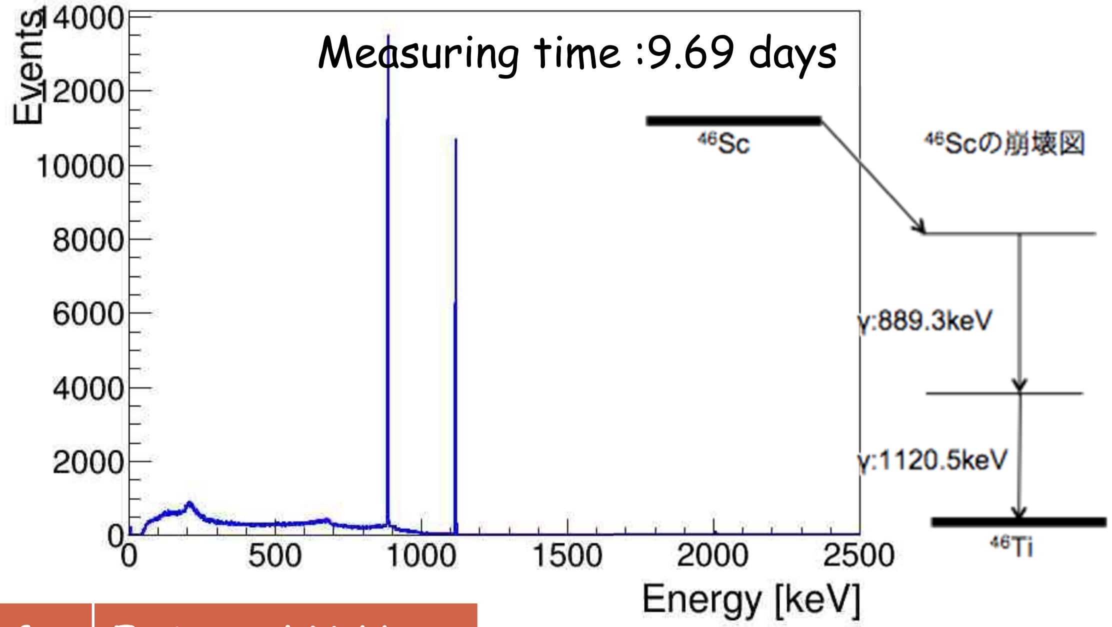
<u>RCNP cyclotron facility, Osaka University</u>



^{46}Sc Activity Estimation

- Produced ^{46}Sc activity was estimated by conventional method, γ-ray counting with HPGe detector

Measurement with HPGe detector



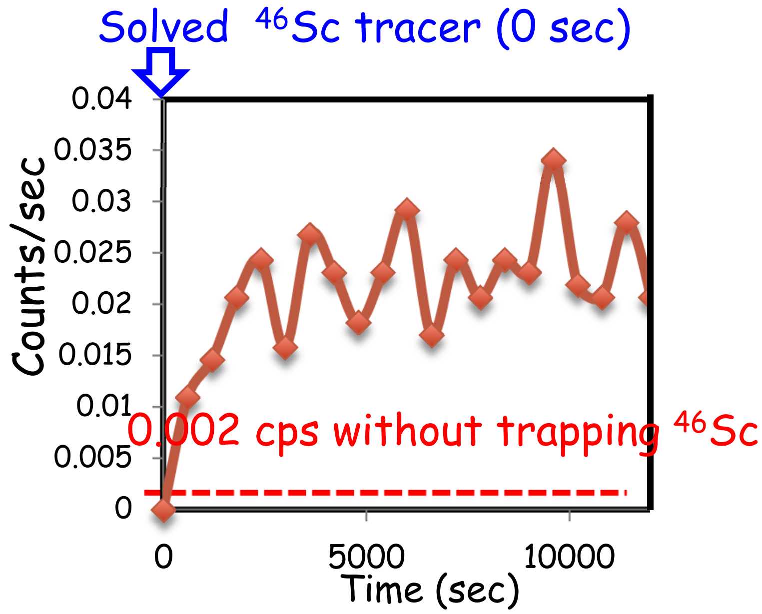
Number of observed events	Detection eff. of γ-rays	Estimated Nubber of ^{46}Sc nuclei
207652	6.29×10^{-3}	3.9×10^{8}

➔ 32 Bq/100cc

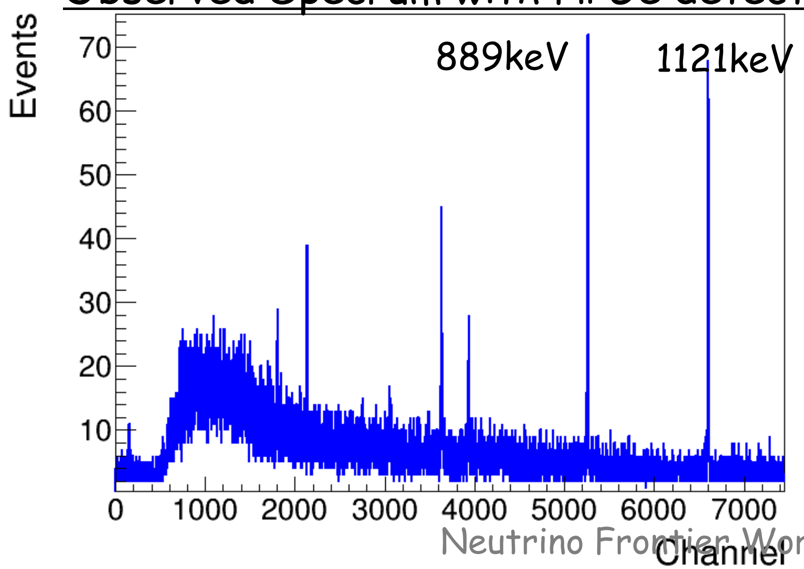
- HPGe detector can measure an order of 10mBq. Enough activity to test the principle of Sc^{3+} trapping/concentrating method.

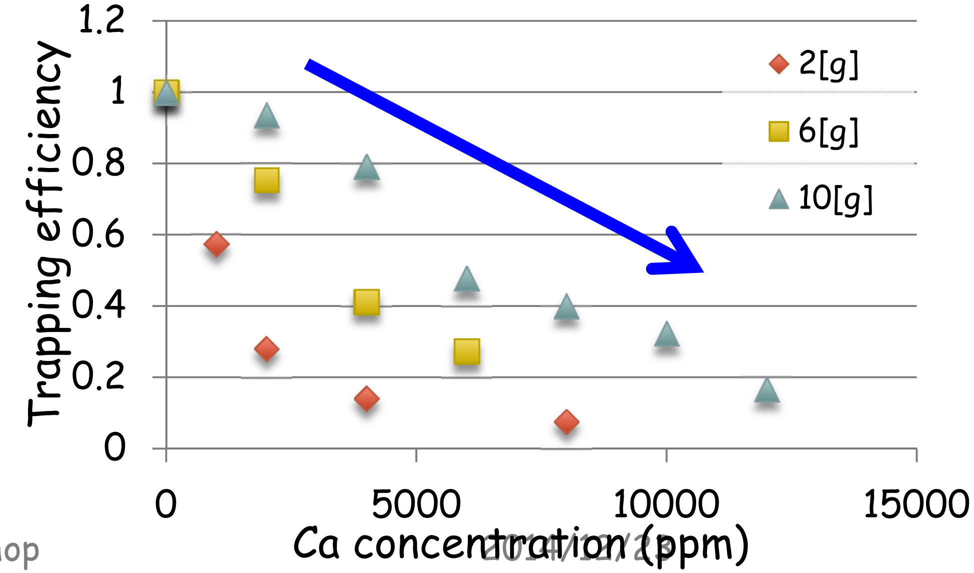
Trial Measurements

- Most of Sc^{3+} ion was trapped in the resin by 30 min., as expected.
- Counting rates corresponds trapping efficiency of Sc.
- Observed Rn peaks in Ge spectrum,
  - Rn gas was solved in the water during solving $CaCl_2$ compound in the pure water
- Measuring concept was O.K., however eff. is getting worse, as Ca amount is increasing.



Observed Specrum with HPGe detector

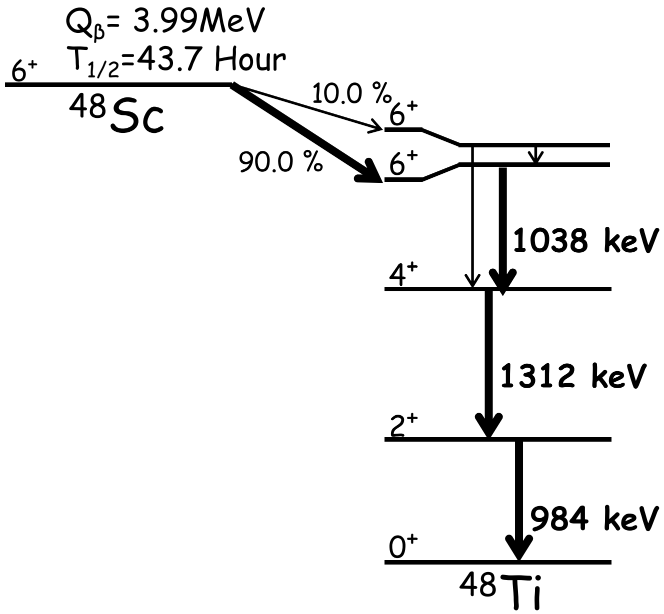




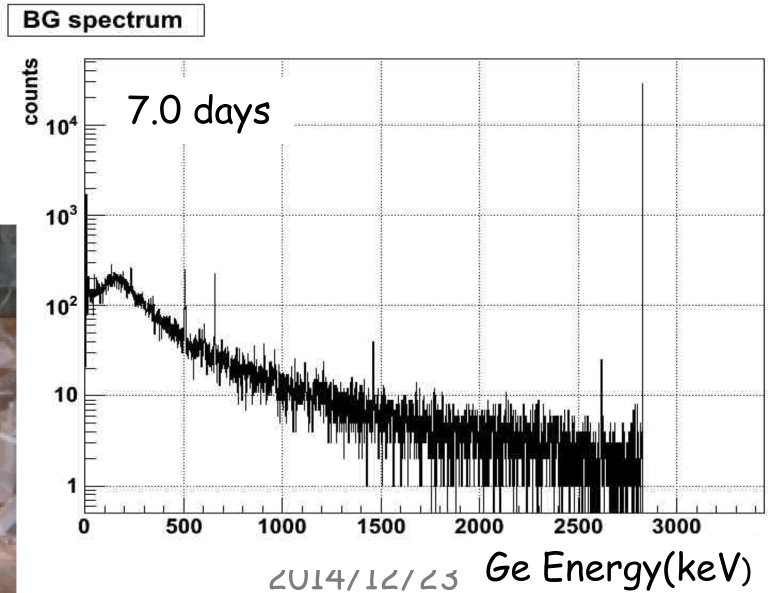
Another Things for Designing Exp.

- The detection eff. of HPGe detector
  - Monte Carlo code is well tuned for the use of material screening of purity.

Peak Energy (kev)	Efficiency (%)
984	1.26
1038	1.21
1312	0.97
979 + 1038	2.05×10^{-2}
983.5 + 1312	1.67×10^{-2}
1038 + 1312	1.60×10^{-2}



- Radio purity of ion exchange resin
  - Already measured, no problems



Summary and Plan

- $0\nu\beta\beta$ decay is also the key process to explore unknown neutrino properties.
- We are promoting CANDLES project, which is $0\nu\beta\beta$ search program by sing ^{48}Ca isotope.
- To estimate the BG in the Q-value, it is important to measure $2\nu\beta\beta$ decay rate to estimate BG from high energy tail of the $2\nu\beta\beta$ spectrum.
- As for ^{48}Ca as $\beta\beta$ isotope,
  - Highest Q-value ; chance to realize BG free measurement
  - Low natural abundance ; thought as disadvantage, but chance to improve the sensitivity much.
  - Not completely forbidden β-decay to ^{48}Sc.
- Q-value of ^{48}Sc is high enough 4.0 MeV, it will affect the estimation of $2\nu\beta\beta$ decay rate of ^{48}Ca.
- We proposed/develop new measuring technique of β-decay rate of ^{48}Ca.
- The concept of measurement is well confirmed.
- Currently, we are trying to increase Ca concentration of solution without deteriorating the detection efficiency. We have some ideas such as,
  - producing resin cartridge with many tiny pores, like activated charcoals, functional filters, to increase active surface of ion exchange resin.
  - using functional films which Sc ion can penetrate, but Ca cannot.
- Acknowledge the support by 新学術"Neutrino Frontier".