Neutron lifetime measurement with pulsed neutron beam at J-PARC

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On behalf of the NOP collaboration

Next generation Experiments to Measure the Neutron lifetime
9th.Nov.2012, Santa Fe

Outline

- Other experiments
- Principle of this experiment
  - In flight β-decay, $^{3}He(n,p)^{3}H$ reaction, Cal lifetime
- Neutron source
  - J-PARC, MLF, BL05, Spin Flip Chopper
- TPC
  - High efficiency
    - Define fiducial-volume, Detect low energy β-decay
  - Low background
    - PEEK, ^{6}LiF board, Pb&Fe shielding, Cosmic ray veto
- Background subtraction
  - Time-constant, gas scatter
- Other uncertainties
  - Number density of 3He, Cross section of $^{3}He(n,p)^{3}H$, Temperature
- Schedule
- Summary

Experiments for neutron lifetime

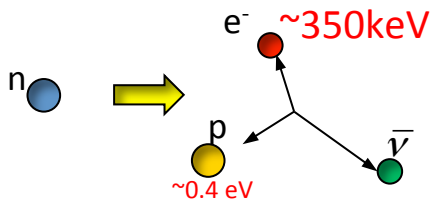
Method	Beam	Penning trap	Gravitational trap	Magnetic trap
Neutron source	reactor	reactor	reactor	reactor
Energy	Cold neutron	Cold neutron	UCN	UCN
Detection particle	**Electron**	Proton	Neutron	Neutron
Challenge	high background	flux monitor	wall effect	depolarization
Result	878 ± 27 ± 14 (1989)	886.6 ± 1.2 ± 3.2 (2005)	878.5 ± 0.7 ± 0.3 (2008)	878 ± 1.9 (2009)

Neutron lifetime is measured by in-beam and storage methods.
Our experiment is in-beam method.
We are using pulsed neutrons from separation neutron source.

We are trying for O(0.1%) with beam method.

In flight β-decay

Beta decay



$$N_e = \frac{\varepsilon_e t \rho_n}{\tau_n}$$

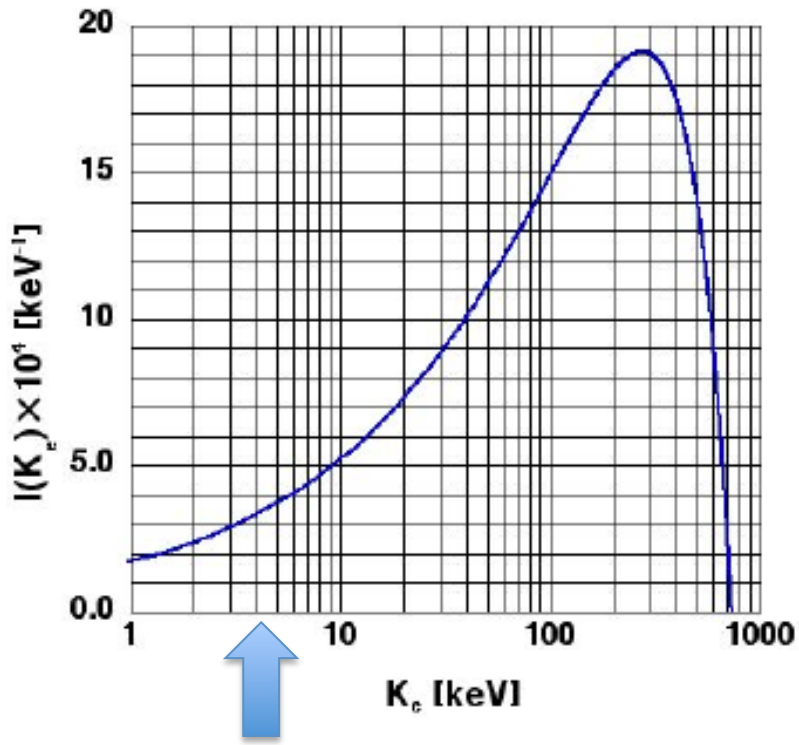
~10^{-6} decay in 1m
for cold neutron (1100m/s)

Neutron decays into electron, proton and neutrino.

β-decay is 3-body decay, so energy spectrum has a low energy tail.

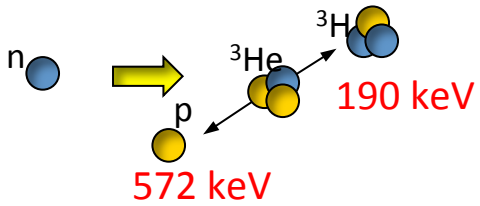
99.9% of β-decay electrons have >4 keV energy.

Energy spectrum of electron



Neutron flux

^{3}He(n,p)^{3}H



$$N_p = \varepsilon_p t \rho_n \rho_{^3He} \sigma_{^3He}(v_n)$$

$$\sigma_{3He}(v_n)\, v_n = \sigma_{3He}(v_0)\, v_0$$

Reaction rate is proportional to 1/*v*

β decay ~3.6mPa ^{3}He

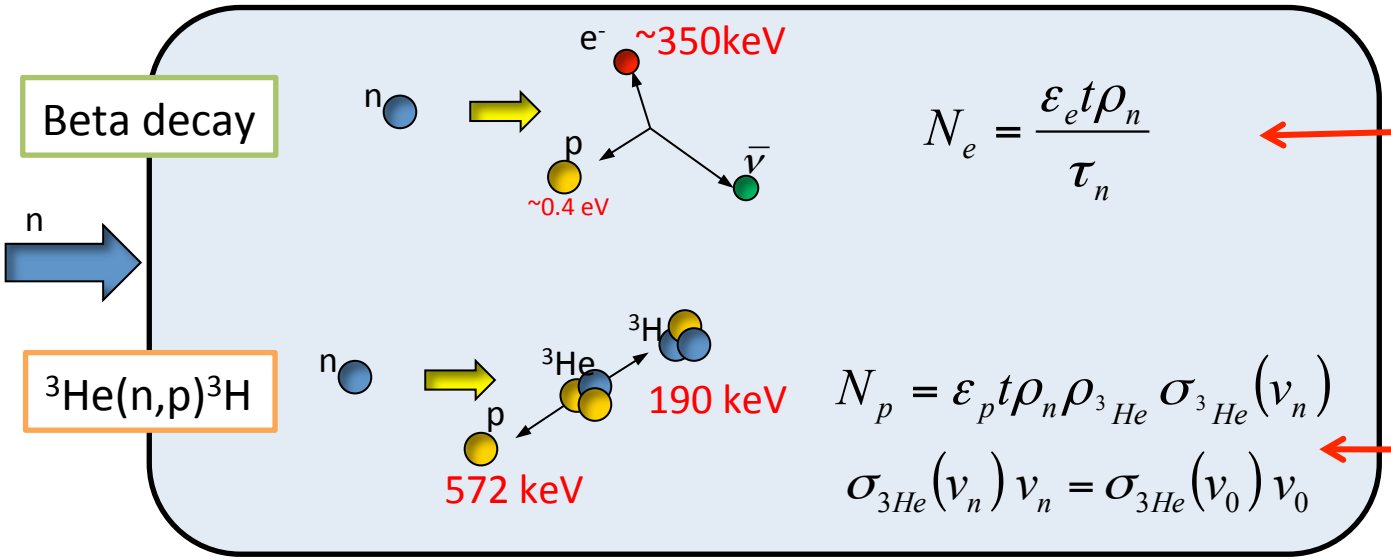
The difficulty of in-beam method is determination of the beam flux.

By adding a small amount of ^{3}He, we can measure the neutron flux via the 3He(n,p)3H reaction.

4mPa of ^{3}He gives same event rate with beta decay.

Both of the event rates are proportional to 1/v, so the velocity dependence is canceled by taking the ratio.

Principle of our experiment



$$N_e = \frac{\varepsilon_e t \rho_n}{\tau_n}$$

10^{-6} decay in 1m

$$N_p = \varepsilon_p t \rho_n \rho_{^3He} \sigma_{^3He}(v_n)$$

$$\sigma_{3He}(v_n)\, v_n = \sigma_{3He}(v_0)\, v_0$$

Reaction rate is proportional to 1/*v*

β decay ~3.6mPa ^{3}He

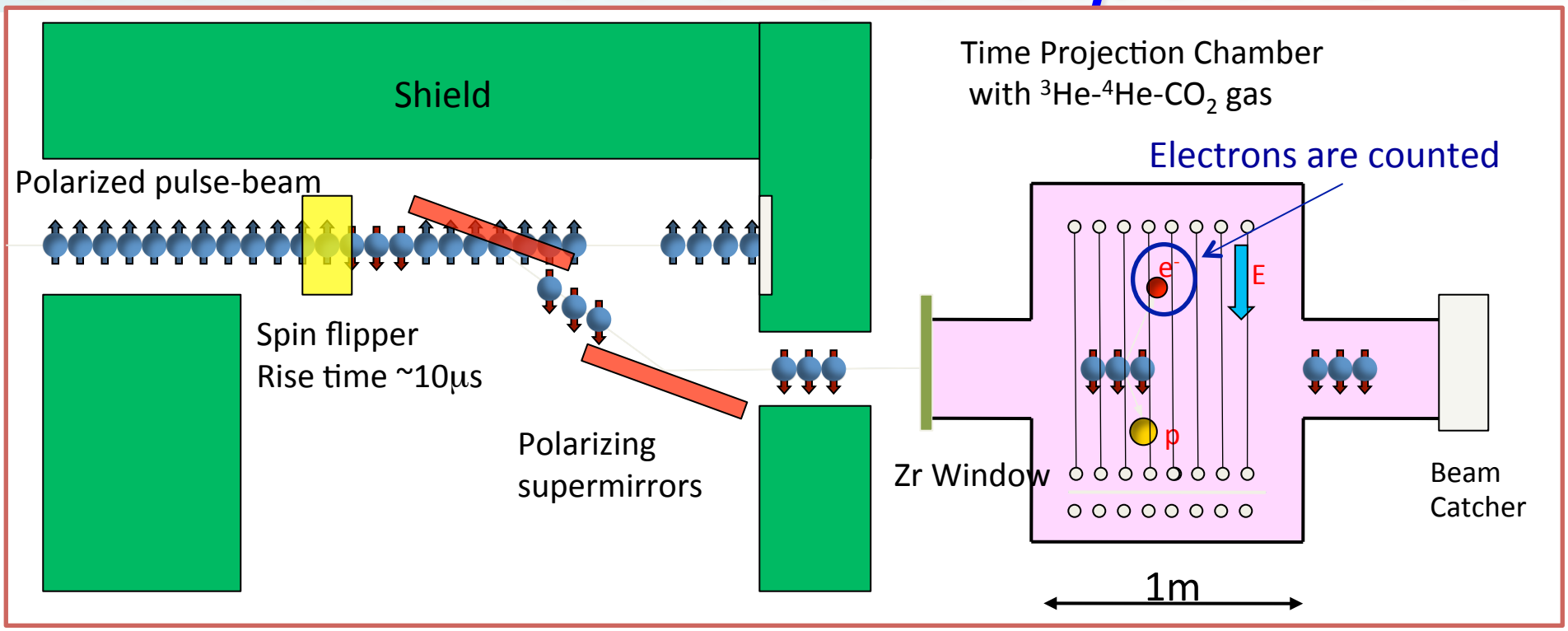
Neutron Lifetime is given as

$$\tau_n^{-1} = \frac{N_e/\varepsilon_e}{N_p/\varepsilon_p} \rho_{^3He} \sigma_{^3He}(v_0)\, v_0$$

N_e, N_p : Electron and proton counts
ε_e, ε_p : Detection efficiencies
ρ_{3He} : Atom density of ^{3}He
v_0 : 2200 m/s
$\sigma_{3He}(v_0)$: Cross section of ^{3}He(n,p)^{3}H at 2200m/s

We use a TPC to detect the electron from the neutron decay and the proton from the ^{3}He(n,p)^{3}H reaction, **simultaneously in a same detector**.
The ratio of counting rate of electron and proton gives the neutron lifetime.
Comparing with UCN experiment,
There are no systematic uncertainties due to wall interaction or depolarization.

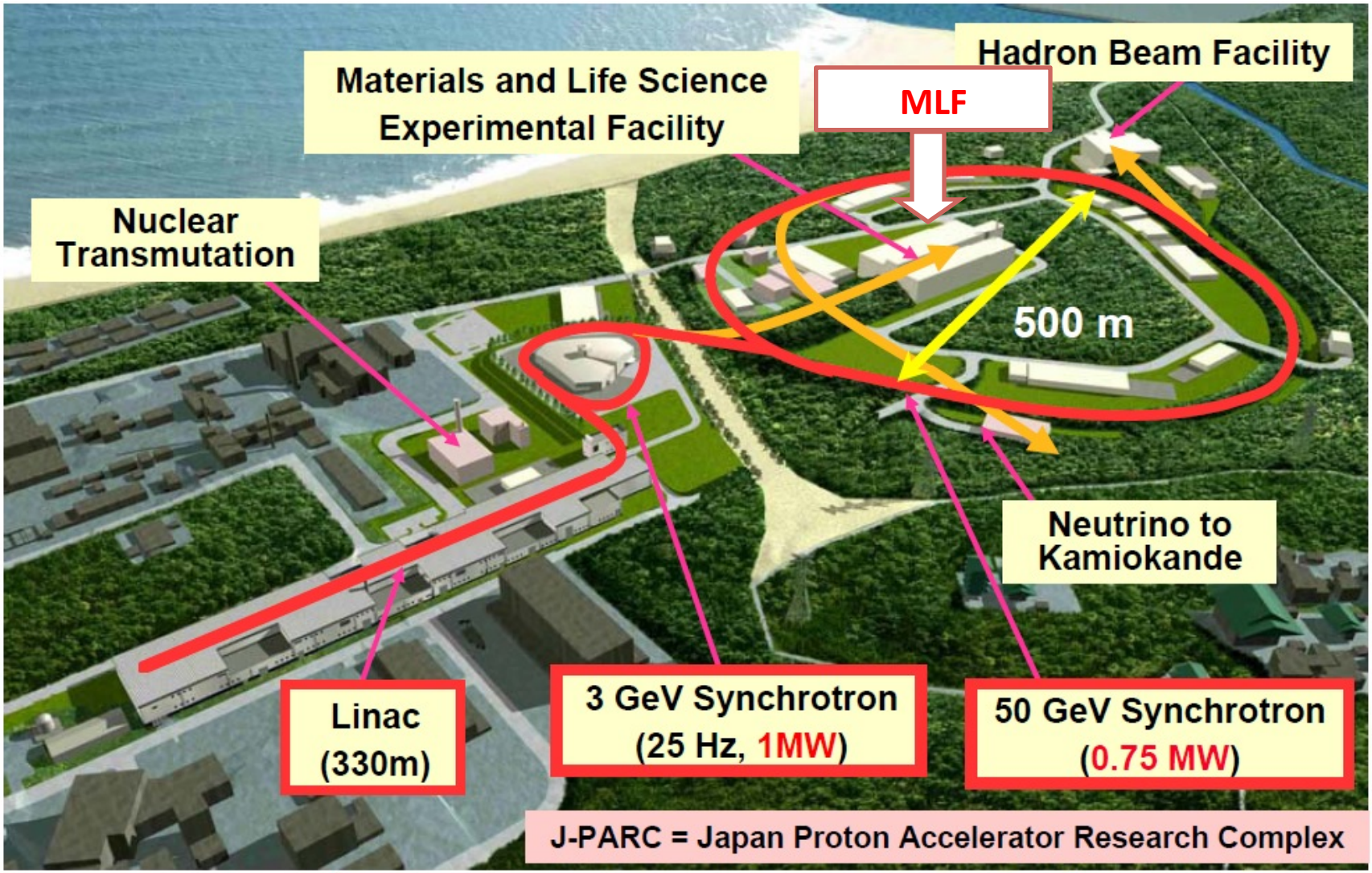
Schematic view of this experiment



- Electrons by beta decay are measured by a gas detector of 1m length.
- Neutrons are transported into the detector with a bunch length of 40 cm.

Good efficiency: All neutrons are inside of detector in a certain time region.
Low background : Background from windows, beam catcher, and chopper can be separated by TOF.

J-PARC at Tokai, Japan



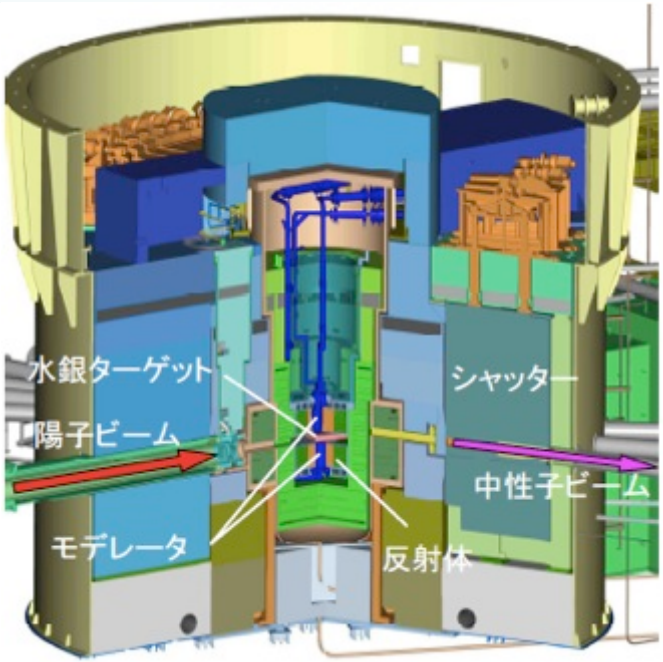
Joint Project between KEK and JAEA

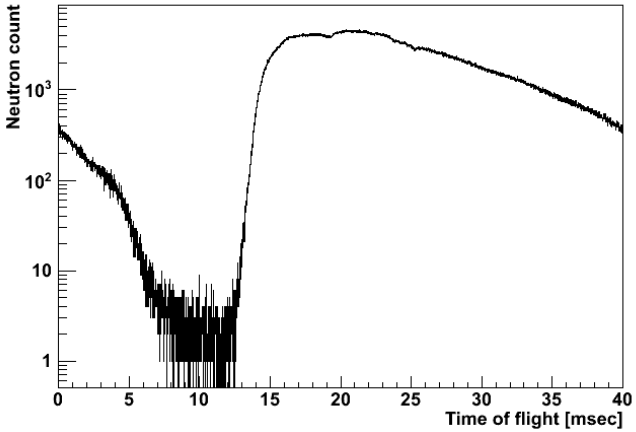
J-PARC Pulsed Neutron source

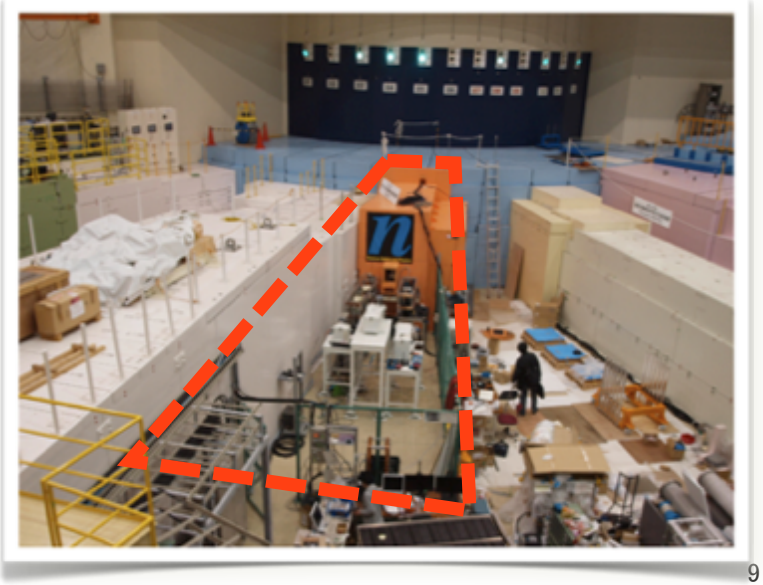
BL05, Polarization beam branch

Repetition rate	25Hz
Moderator	Coupled（20 K）
Beam size	10 cm x 4 cm
Flux	8.6 x 10^6 s-1 cm-2 (1MW)
Polarization	96%
Energy	1 ～ 20 meV
wavelength	0.2 ～ 1 nm
Velocity	500 ～ 2000 m/s

→ Experimental apparatus is installed at 20 m distance



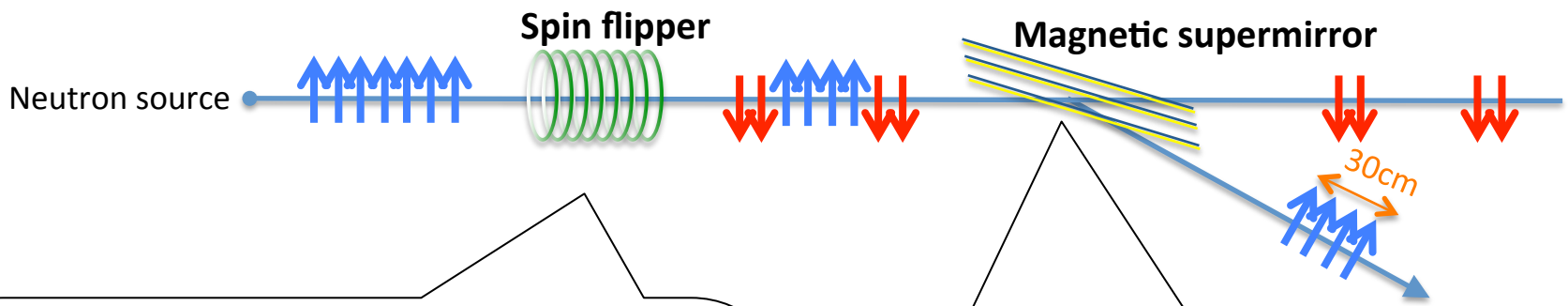




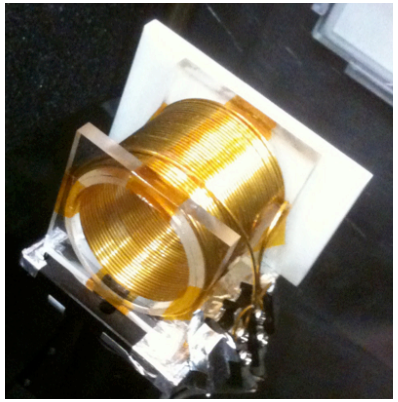
Spin Flip Chopper(SFC)

Resonance flippers flip the neutron spin.

Magnetic supermirror reflects only non-flipped neutrons.



Guide field B_y and oscillating field $B_z \sin(\omega t)$



Diameter	50 mm
Length	40 mm
RF frequency	29 kHz
RF field B_z	0.3 mT
Guiding field B_y	1 mT

$$P = \frac{B_z^2}{B_z^2 + (B_y - \frac{\hbar}{2|\mu_n|}\omega)^2} \sin^2\left(\sqrt{B_z^2 + \left(B_y - \frac{\hbar}{2|\mu_n|}\omega\right)^2}\, t\right)$$

Multilayer of Ferromagnetic and Paramagnetic materials

Ferromagnetic	Fe
Paramagnetic	$SiGe_3$
Magnetizing field	35 mT
Length	140 mm
Height	35 mm
number of mirrors	5
Critical angle	m=5

Neutron of 1300m/s can reflect with 1.5°

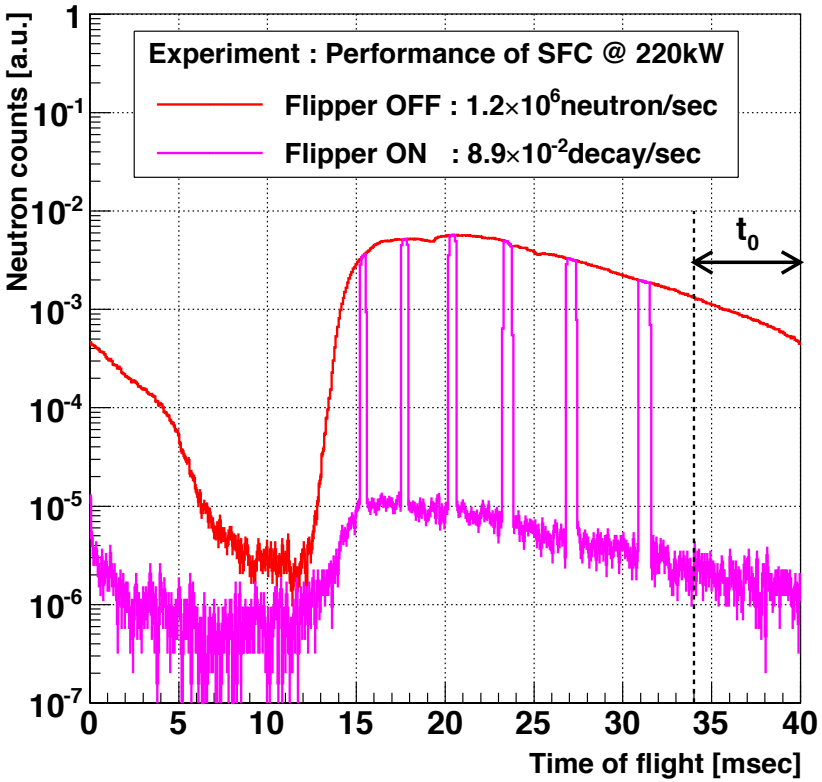
Depolarization makes the contrast worse.

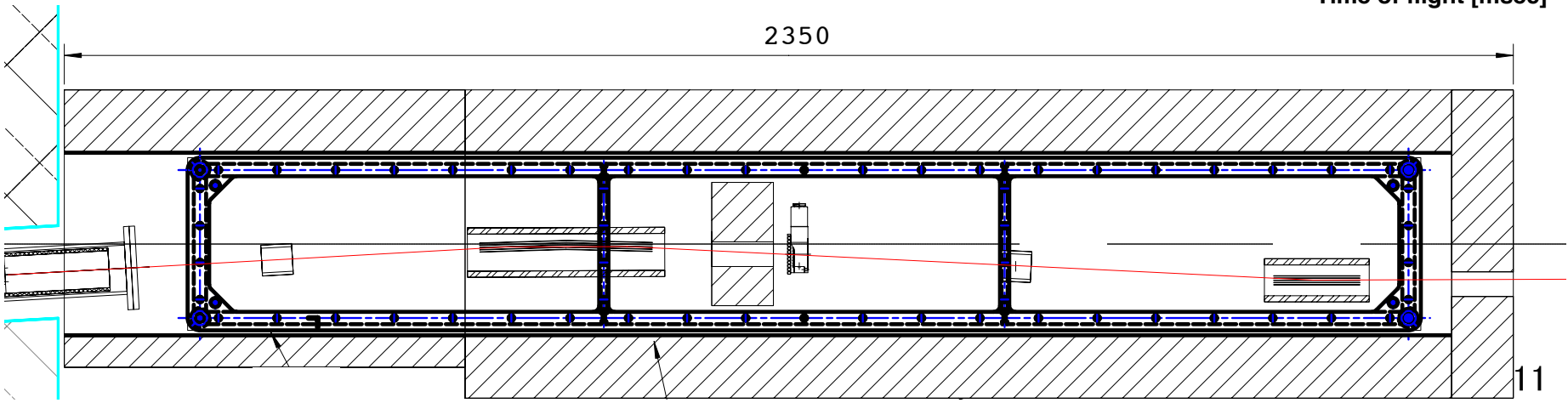
SFC performance

With 2 flipper and 3 mirror sets

– Optimized to give good contrast

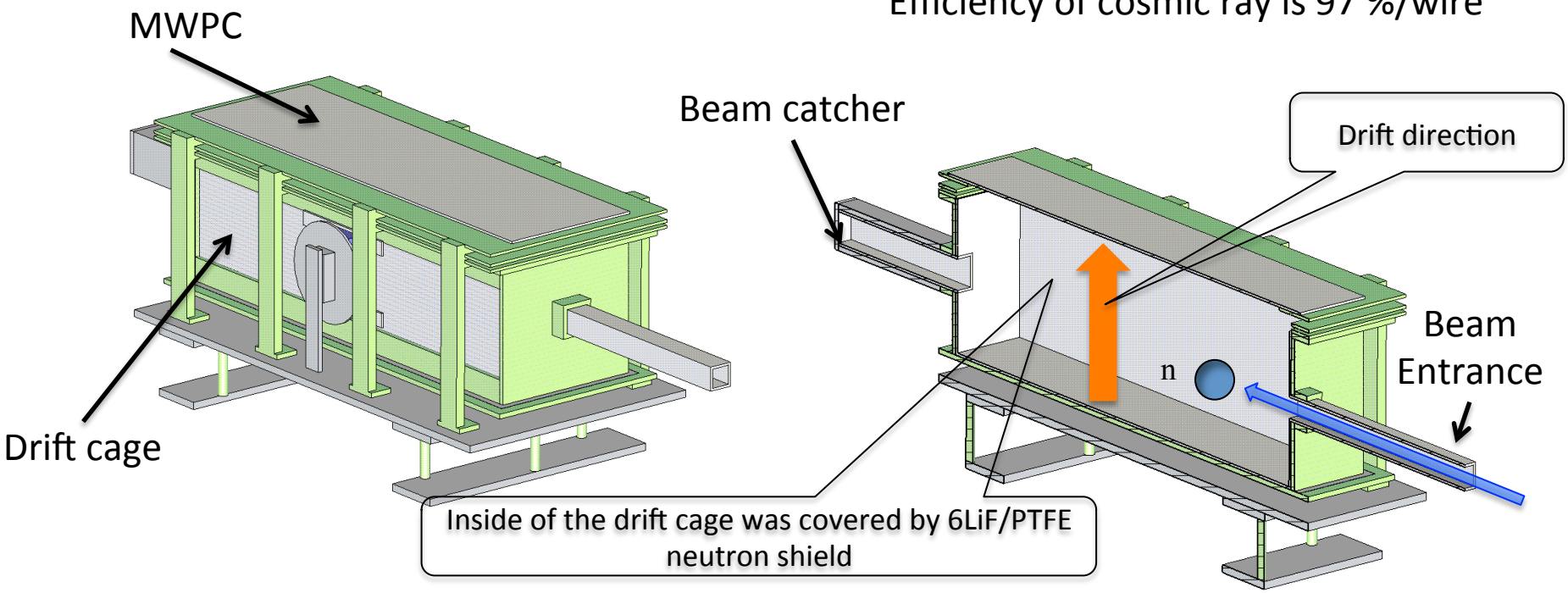
Beam size	3 cm x 2 cm
Minimum bunch length	15 cm
Rising length	5 cm
Flux (flipper on)	1.2 x 10^6 neutron/sec
Flux (flipper off)	0.3 x 10^4 neutron/sec
Contrast	400
Flux with 5 bunches	1.7 x 10^5 neutron/sec
Decay rate	0.1 decay/sec
Fiducial Time	2.8 ms / beam cycle



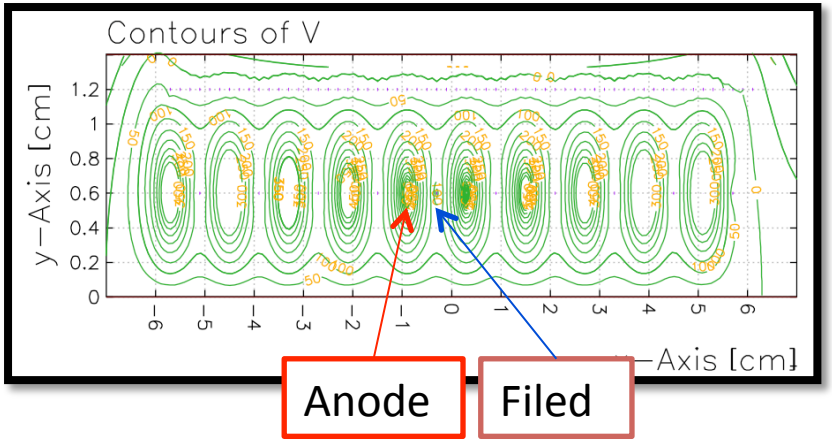


Time Projection Chamber

Efficiency of cosmic ray is 97 %/wire



Voltage of MWPC (12 mm pitch)



Anode wire	29 of W-Au wires(+1780V)
Field wire	28 of Be-Cu (0V)
Cathode wire	120 of Be-Cu (0V)
Drift length	30 cm (-9000V)
Gas mixture	He:CO2=85kPa:15kPa
TPC size(mm)	300,300,970

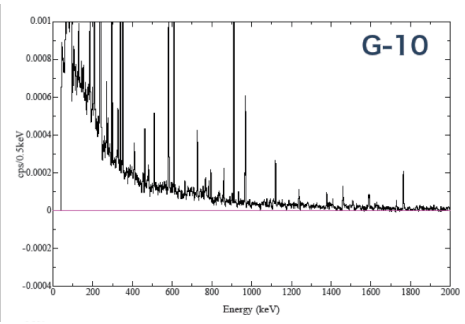
Low background TPC (inside)

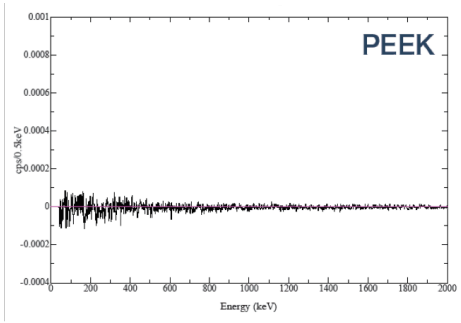
PEEK (Poly-Ether-Ether-Ketone) : used in gas detector for the first time

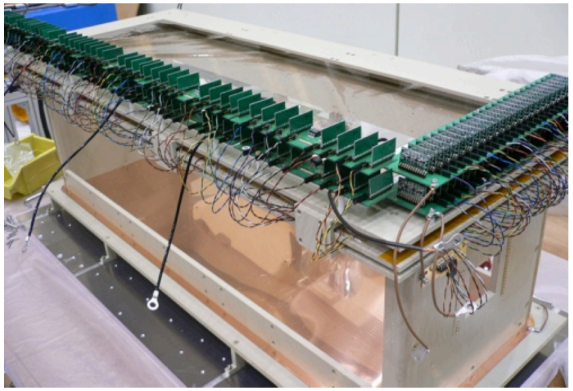
Feature : Chemically made from organic materials → small impurity

Pros : easily machinable, weldable,
1m material can be made to accuracy of 100μm

Cons : Small elasticity, need pre-tention to set up wires

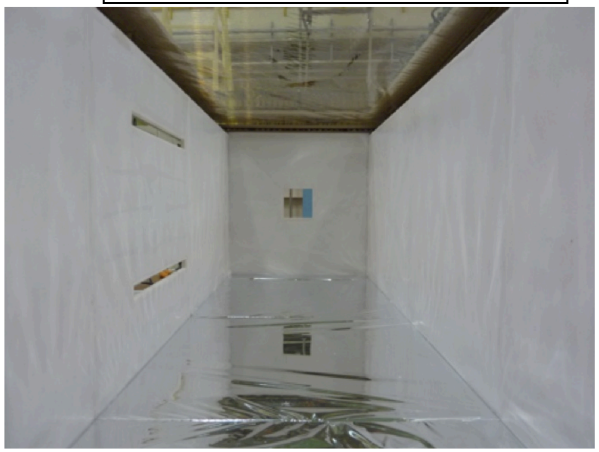






Backgrounds caused by prompt γ rays
from capture reactions of scattered neutrons by gas

^{6}Li + neutron → α + ^{3}H
Absorption length is 500μm



^{6}LiF board: sintered 95% enriched ^{6}LiF and PTFE
(LiF : PTFE=30wt% : 70wt%)

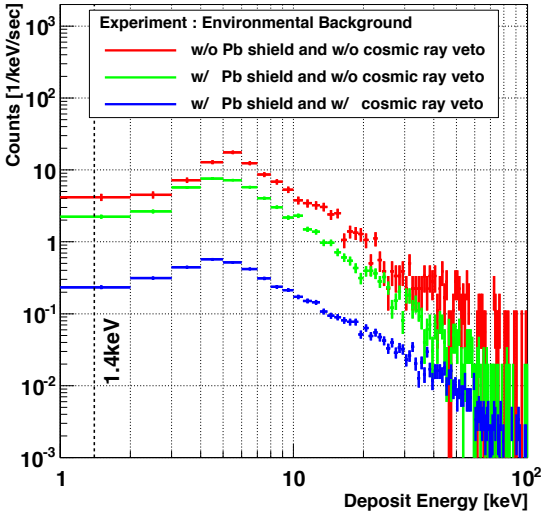
All inner surface covered with ^{6}LiF board

- Relative permittivity is ϵ=3.0
- Position of electrodes were optimized by simulation.
- Uniformity of the drift velocities was less than1%

Low background TPC (outside)

- *Lead shielding and Cosmic ray Veto*

Energy cut



- *Event Selection*
  - Energy cut : Energy deposit over 1.4keV
  - Fiducial cut : Hit on Beam region

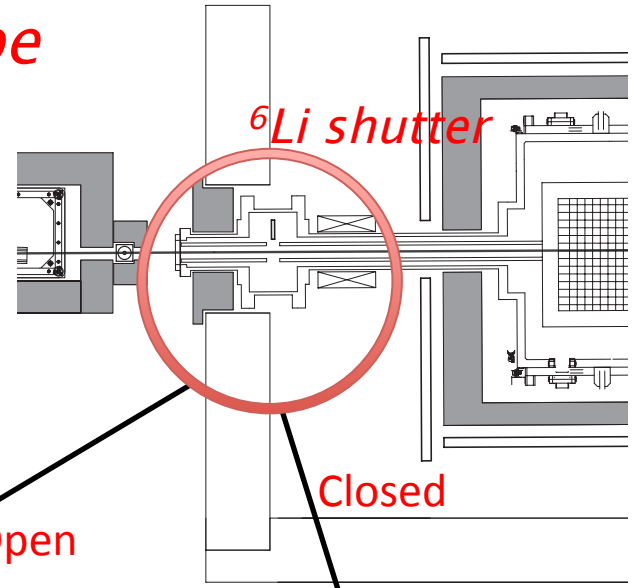
	Total count [cps]	With Energy cut [cps]	With Fiducial cut [cps]
No shielding or veto	123.7	100.1	30.7
+With Lead	58.4	44.2	13.9
+With Veto	7.7	4.3	1.4

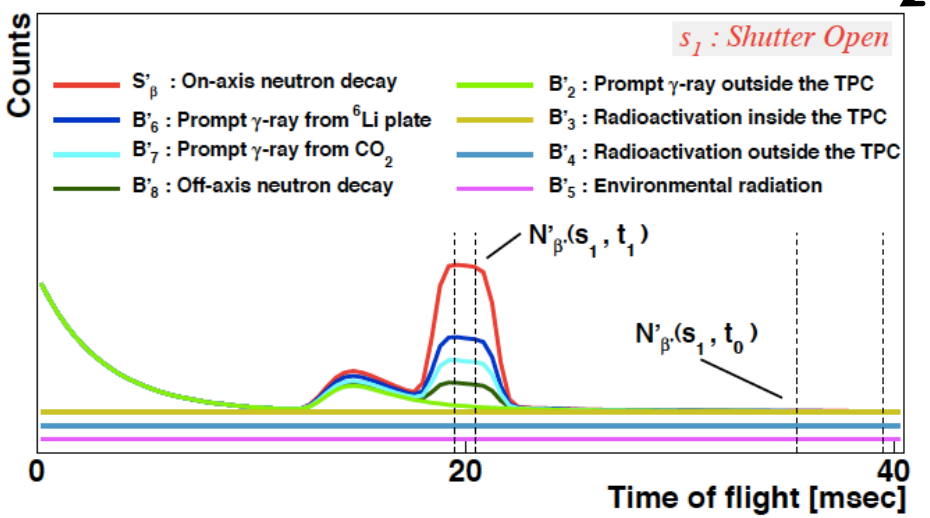
Environmental radiation : 0.8 cps
Cosmic ray : 0.5 cps
Radioactives in TPC : 0.1 cps

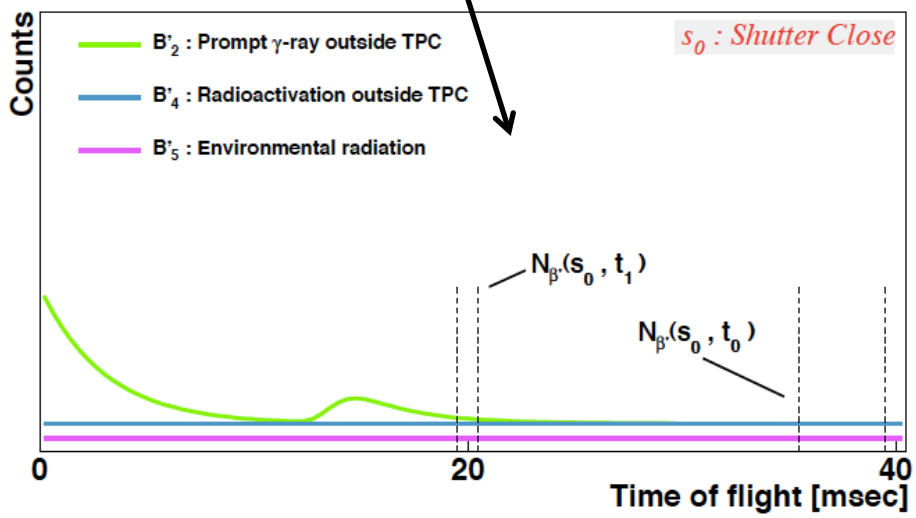
S/N achieved to 0.9

Background subtraction
Time-constant /outside of TPC

- *Time constant background can be subtracted by TOF*
  - Environmental background
  - Cosmic rays
  - Radiation inside/outside of TPC
- *Open/Closed of ^{6}Li shutter*
  - Prompt-γ from outside of TPC







⇨ Only remaining background is from TPC gas

Background subtraction
Scattered neutron by TPC gas

Scattered neutron are

1) captured by TPC gas → prompt-γ

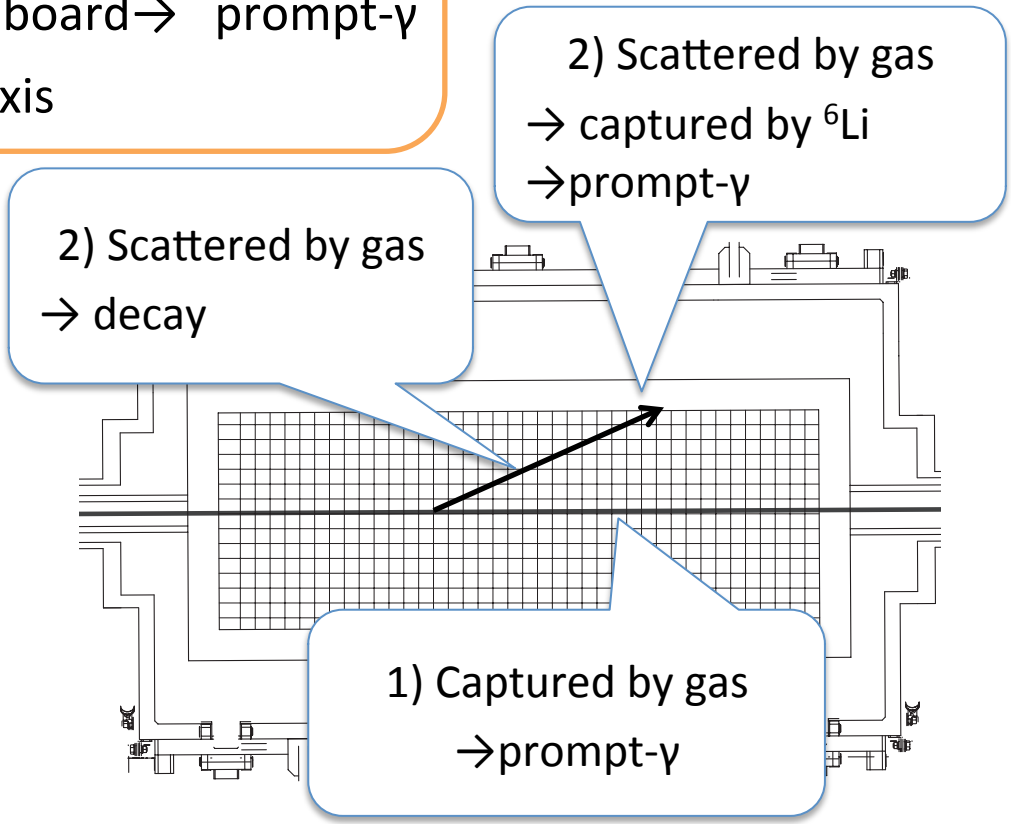
2) Scattered by gas →captured by ^{6}Li board→ prompt-γ

3) Scattered by gas → decay on off-axis

BG rate
~1% of beta decay

These BGs are proportional to the TPC gas pressure

Measurements with different gas pressure can evaluate the BGs



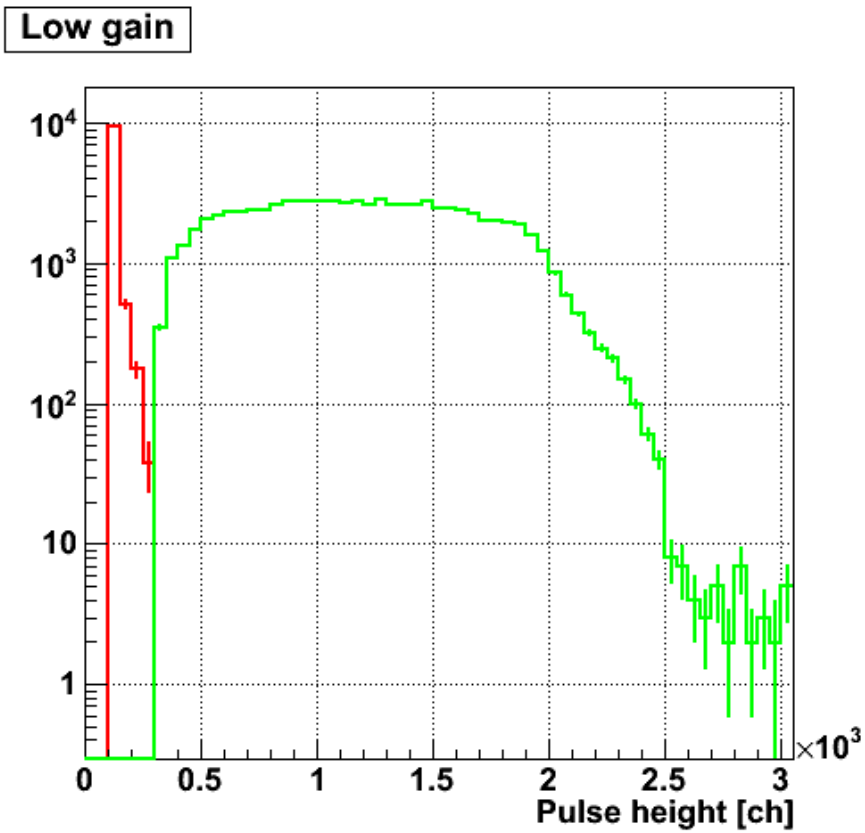
We can subtract all BGs by data-driven method.

Energy spectrum (Experiment)

- Define $^3He(n,p)^3H$ reaction as a High energy event at low gain spectrum for primitive event selection.

- Compare between turning beam on/off by Front Shutter's Open/Close, to extract neutron signal.

Red : All event (Beta + ^3He)
Green : High energy event (^3He)

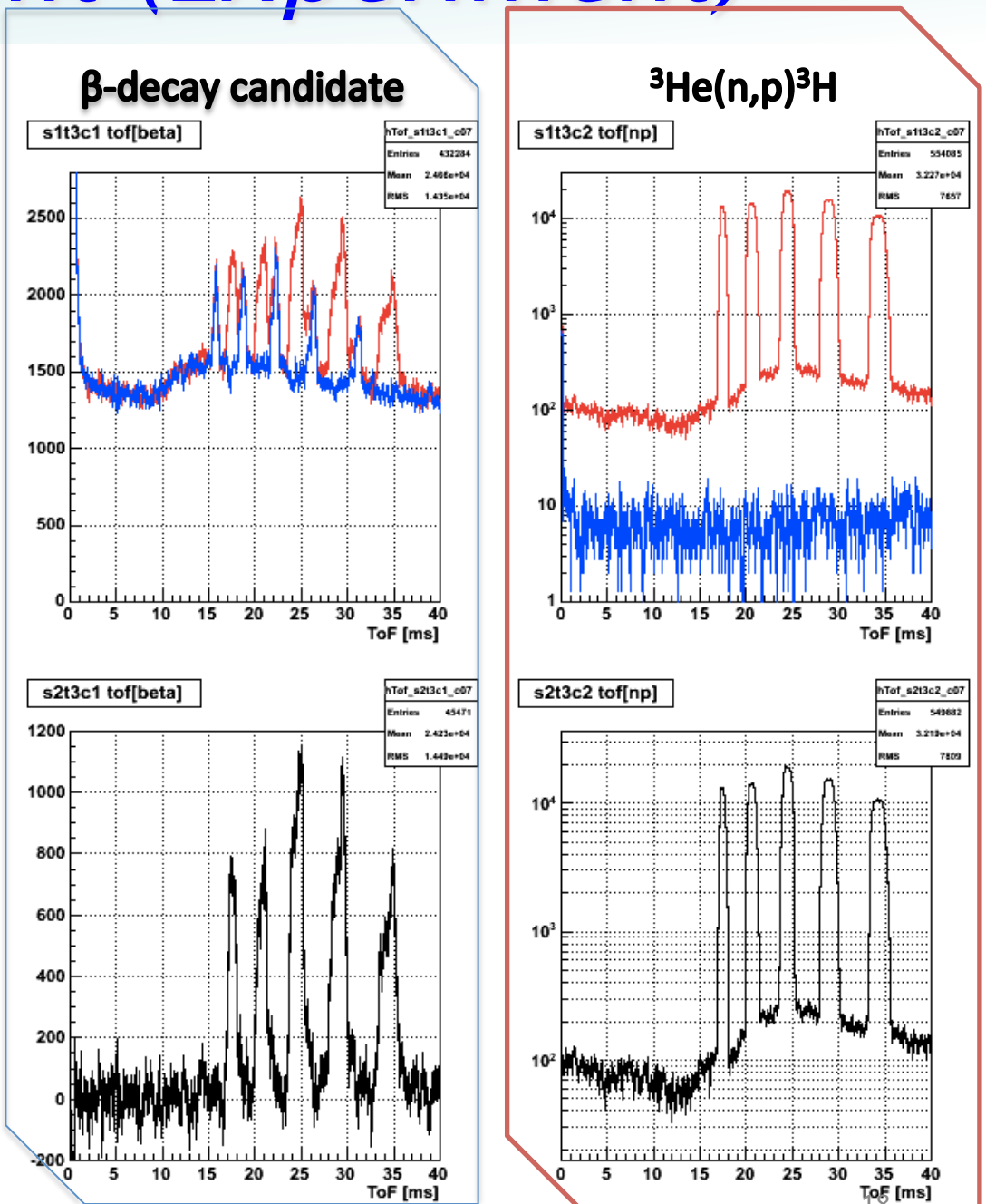


Time of Flight (Experiment)

- Plot of background estimate which compares beam on/off.

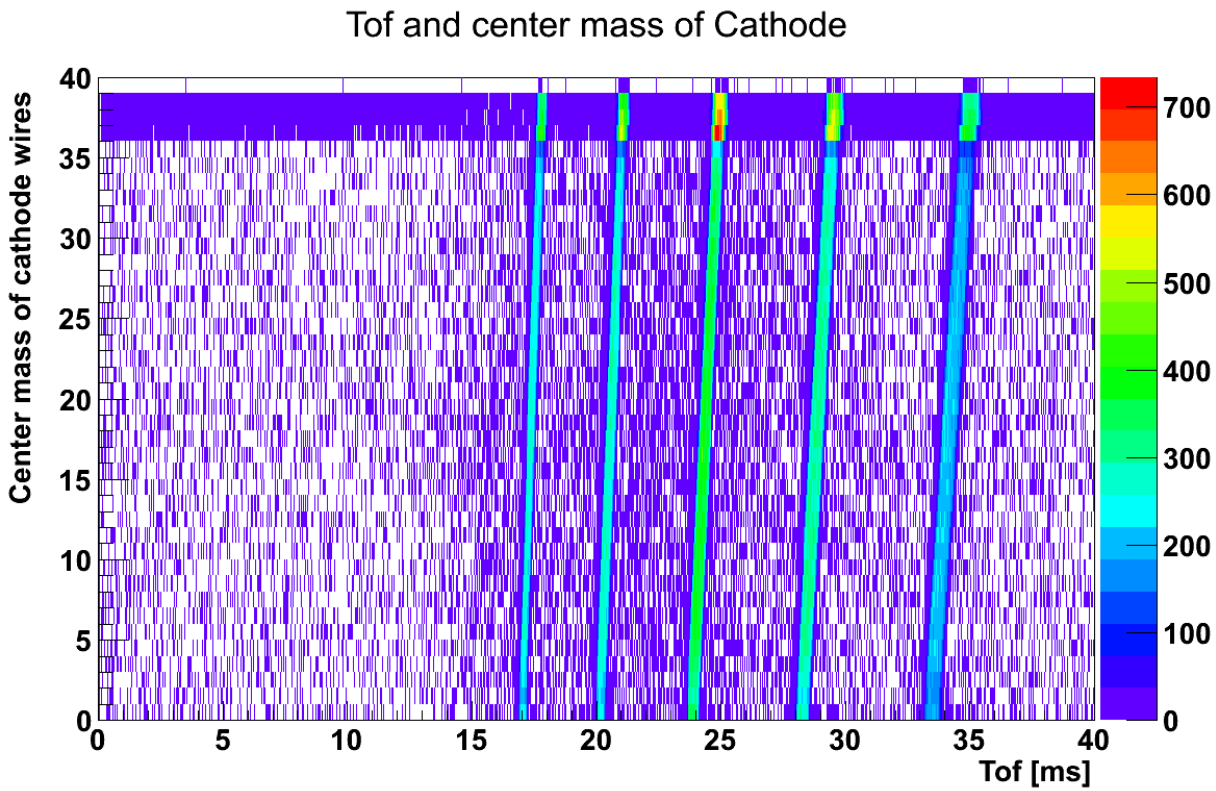
  Red : beam on
  Blue : beam off
  Black : Red – Blue

- The subtraction seems working for β-decay candidates, but not ^{3}He events.



Time of Flight (Experiment)

- The reaction points on z-axis of TPC and ToF for $^{3}He(n,p)^{3}H$ reaction.
- Reaction points move to downstream as time. The slope corresponds to neutron velocity. Later bunches are slower.
- Velocities can be determined with O(1%) uncertainty by the slopes. This results are consistent with Flipper timing.

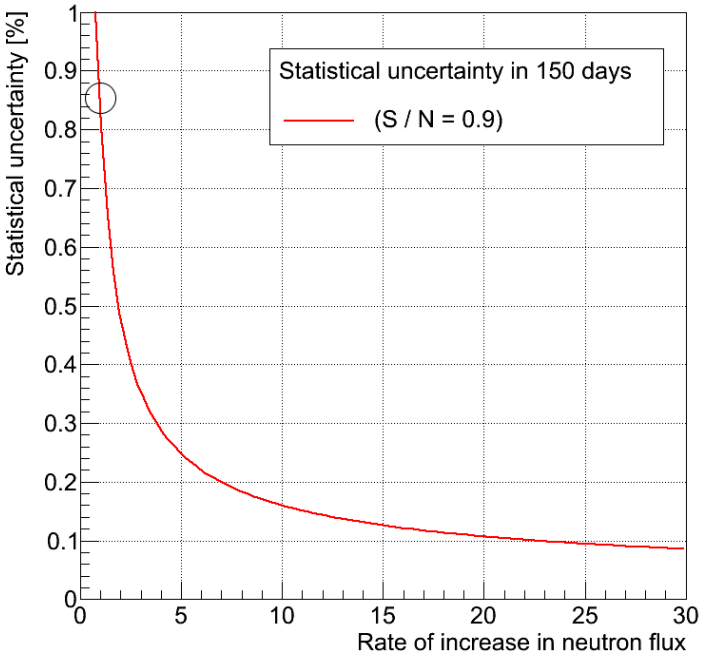


Estimation of statistical error

The decay rate is 0.1cps for beam power of 220 kW.
S/N of 0.9 achieved in present condition.

- J-PARC beam power
  will be 400 kW (about twice) at 2014

- Spin flip chopper
  - The intensity is limited by mirror size.
  - Present beam size is 3 x 2 cm.
  - Large mirrors make the beam size to 10 x 4 cm.
  - Beam Intensity will be 16 times



Beam intensity will be 32 times at 2014.
Statistical error is estimated to achieve 0.1 % in 150 days.

Uncertainties

$$\tau_n^{-1} = \frac{N_e / \varepsilon_e}{N_p / \varepsilon_p} \rho_{^3He} \sigma_{np}(v_0) v_0$$

- Statistical uncertainty: ~0.1% by measurement of 150 days.
- Determination of N_e and N_p : ε_ε > 99.9%(4keV), ε_p=100%

  Background of

  ~1% of simultaneous background

  ~35% of time dependent background (Comparing β events)

  ~110% of time independent background

  Should be subtracted correctly.

- **Density of ^{3}He atoms**
- **^{3}He(n,p)^{3}H cross section**

Number density of ^{3}He atoms

TPC gas is prepared by mixing natural He and ^{3}He(>99.9%)

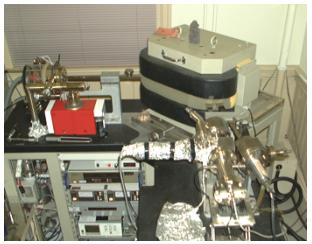
We determine

1) Absolute pressure of mixed He ~80 kPa
2) ^{3}He/^{4}He for abundance of 10^{-6} with accuracy of 10^{-3}

- Pressure can be measured to 10^{-4} precision at 100 kPa with a piezo-drive transducer.

- Partical pressure of ^{3}He dopant is controlled by a baratron gauge and volume expansion method.
  It provide $\Delta P(^3He)/P \sim 0.2\%$.

- Temperature can be measured with $\Delta T \sim 0.1$ K.



- Natural He contents ^{3}He of ~0.1 ppm. It will be determined by a mass spectroscopy. Present limit is 1%.

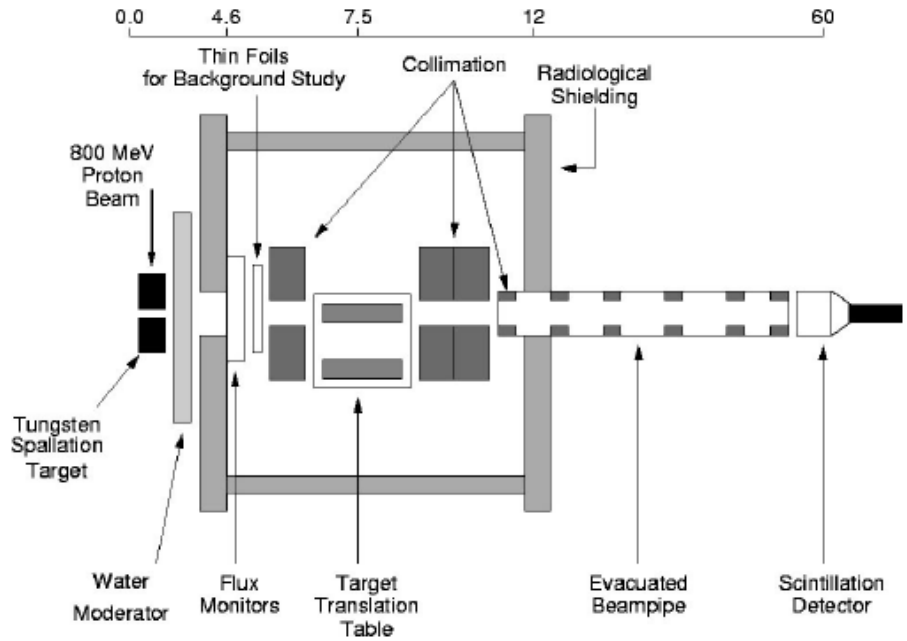
Present uncertainty of ^{3}He density is ~0.2%

Cross section of $^3He(n,p)^3H$

Transmission of ^{3}He was measured.

Present σ_{np} is 5333 ± 7 barn (0.13%)

C. D. KEITH *et al.* PHYSICAL REVIEW C 69, 034005 (2004)



More precise measurement can be done at J-PARC (e.g. 100m beamline).

Uncertainties

$$\tau_n^{-1} = \frac{N_e / \varepsilon_e}{N_p / \varepsilon_p} \rho_{^3He} \sigma_{np}(v_0) v_0$$

- Statistical uncertainty: ~0.1% by measurement of 150 days.
- Determination of N_e and N_p : ε_β > 99.9%(4keV), ε_p=100%

  Background of

  ~1% of simultaneous background

  ~35% of time dependent background

  ~110% of time independent background

  Should be subtracted correctly.
- Density of 3He atoms → ~0.2%
- 3He(n,p)3H cross section → 0.13%.

Timeline of this experiment

Year	2012										2013												2014			
Month	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4
J-PARC Beam operation	200kW							300kW																400kW		
Measure ments	Commissioning						Systematic study						Physics run											Physics run (High statistics)		
SFC											Increasing size of SFC (16 times)															
TPC													Increasing size of aperture of TPC													

Summary

- We aim to measure the neutron lifetime to O(0.1%)

- Features of our experiment are
  - We use pulsed neutron from J-PARC (BL05).
  - Neutron bunches by Spin Flip choppers.
  - Electrons are detected by TPC.
  - Neutron flux is measured by $^{3}He(n,p)^{3}H$

- The physics run will start from the next year.