Neutrinos and Dark Matter in Nuclear Physics 2015 (NDM15)
June 1-5, 2015, Jyväskylä, Finland

Nuclear Weak Processes in Astrophysics studied with Secondary Particle Beams

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- Neutrino-induced nuclear reactions
- μ-capture
- Neutron β-decay
- Summary

1. Neutrino-induced nuclear reactions

- Neutrino-heating in core-collapse supernovae;
  target; n, p, ^{4}He, ^{3}He, ^{3}H, ...

- Neutrino-process;
  post-processing on r-isotopes (heavy nuclei)
  production of ^{7}Li, ^{11}B

- Detection efficiencies of neutrino detectors;
  d, ^{12}C, ^{16,18}O, ^{37}Cl, ^{71}Ga, ^{100}Mo, ^{176}Yb, etc.

Accuracy of ~10% is required for ν-A reaction data.

How to determine ν-A reaction rates ?

- Direct method → absolute, integrated σ

  Neutrino beam experiment; absolute, $J^{\pi} \leq 4^{\pm}$

  Beta decay (inverse reaction); up to $E_{ex} < Q_{\beta}$

  Muon capture (inverse reaction); $|q| \sim 100$MeV

- Indirect method → spectroscopic, applicable to RI

  Photobreakup, Coulomb dissociation, (e,e′), (p,p′)

  → Neutral current (N.C.)

  Charge-exchange reactions; (p,n), (^{3}He,t), etc.

  → Charged current (C.C.)

Summary of direct measurements

Reaction	Method	Accuracy
$d(\nu_e,e^-)$, $d(\nu,\nu')$	Solar ν, reactor, ^{3}H-β	~2%
$^{12}C(\nu_e,e^-)$	Real-time meas.	~15%
$^{12}C(\nu_e,\nu_e)$	Real-time meas.	~30%
$^{13}C(\nu_e,e^-)$	Real-time meas.	76%
$^{56}Fe(\nu_e,e^-)$	Real-time meas.	37%
$^{71}Ga(\nu_e,e^-)$	Radiochemical	11%
$^{127}I(\nu_e,e^-)$	Radiochemical	33%

^{12}C+ν ; Experiment vs. Theory

	$(\nu_e,e^-)^{12}N_{g.s.}$	$(\nu_e,e^-)^{12}N^*$	β^- $[^{12}B(1^+)]$	$[(\bar{\nu}_e,\bar{\nu}_e')+(\nu_\mu,\nu_\mu')]^{12}N_{g.s.}$	$(\nu_\mu,\nu_\mu')^{12}C^*$	β^+(EC) $[^{12}N(1^+)]$
KARMEN[1]	9.1 ±0.5±0.8	5.1 ±0.6±0.5	23.6 ms	10.4 ±1.0±0.9	3.2 ±0.5±0.4	11.0 ms
LSND [2]	8.9 ±0.3±0.9	4.3 ±0.4±0.6				
QRPA [3]	11.53	6.1	21.33 ms	9.92	3.60	10.34 ms
SM [4]	9.06~8.48	5.22~4.87		9.76~8.27	2.68~2.26	
CRPA [5]	8.9	5.4		10.5		

*Cross sections are given in unit of 10^{-42} cm^2.

Overall accuracy ~20%

[1] B.E. Bodmann et al., Phys. Lett. B332, 251 (1994)
R. Maschuw, Prog. Part. Nucl. Phys. 40, 183 (1998)
[2] L.B. Auerbach et al., Phys. Rev. C64, 065501 (2001)
[3] M.-K. Cheoun et al., Phys. Rev. C81, 028501 (2010)
[4] T. Suzuki et al., Phys. Rev. C74, 034307 (2006)
[5] E. Kolbe et al., J. Phys, G29, 2569 (2003)

Heavy element; $^{127}\mathrm{I}(\nu_e,e^-)^{127}\mathrm{Xe}$

- Close to the second peak in r-process nucleosynthesis
- Data by neutrino-activation method available;

$\langle\sigma\rangle = (2.84 \pm 0.91(\mathrm{stat}) \pm 0.25(\mathrm{syst})) \times 10^{-40}\ \mathrm{cm}^2$

(J.R. Distel et al., PRC68, 054613 (2003))

- Calculations;

$\langle\sigma\rangle = (2.1\text{-}3.1) \times 10^{-40}\ \mathrm{cm}^2$ (Engel et al., PRC50, 1702 (1994))

$4.2 \times 10^{-40}\ \mathrm{cm}^2$ (Kosmas & Oset, PRC53, 1409 (1996))

- Contained in inorganic scintillator materials; NaI, CsI, LiI
- Proposed as solar-ν detector (W.C. Haxton 1988)

^{127}I(ν_e,e$^-$)^{127}Xe cross section measurement at LAMPF (ν-activation method)

J.R. Distel et al., Phys. Rev. C68, 054613 (2003)

Target; 1540kg ^{127}I (NaI solution)

ν-flux; $(3.4\sim4.6)\times10^{7}$ /cm^2/s

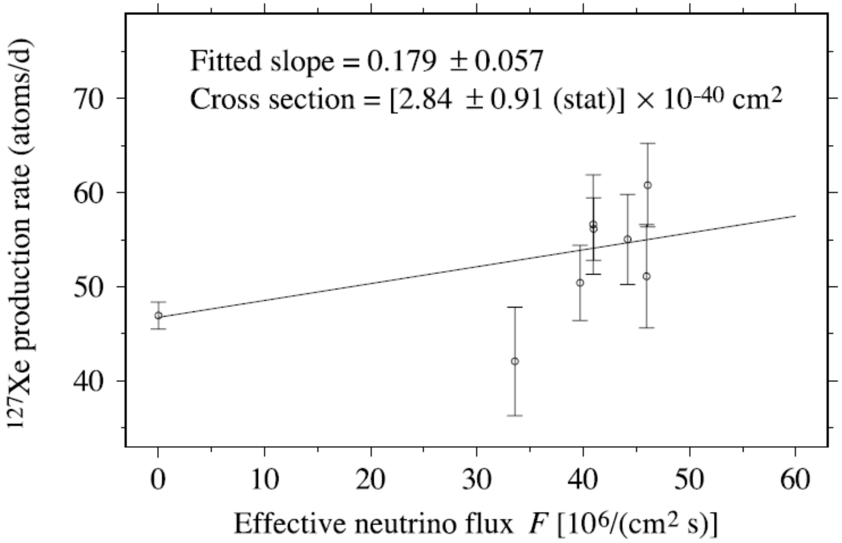
Total exposure; 4.41×10^{14} νs

^{127}Xe(EC)$\rightarrow^{127}$I ($T_{1/2}$=36.4d)

Signal; Auger e$^-$ (4.7keV)

& γ (203keV, 375keV)

Φ_ν vs ^{127}Xe rate



$<\sigma>=(2.84\pm0.91(\text{stat})\pm0.25(\text{syst}))\times10^{-40}$ cm^2 (33%)

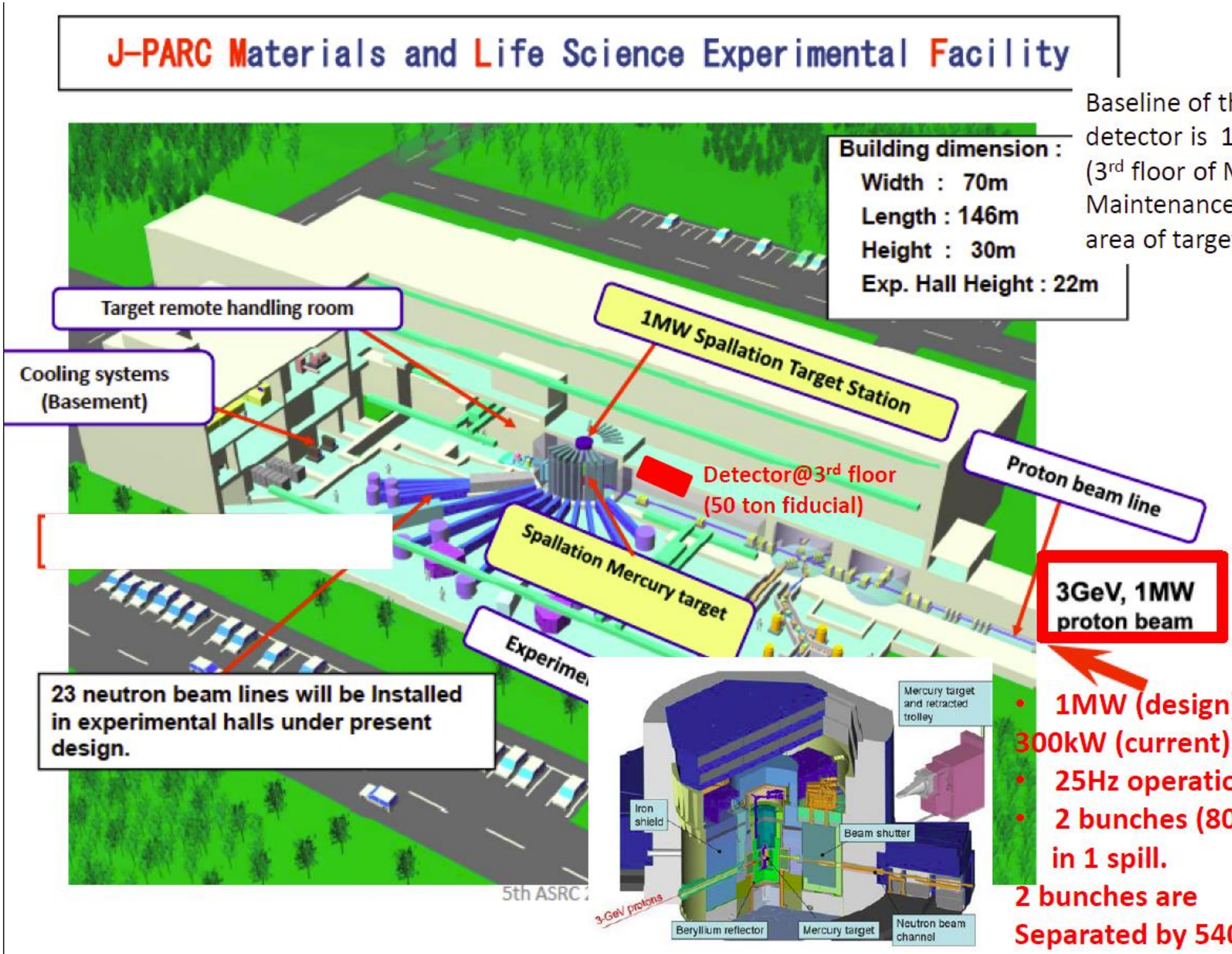
J-PARC


Linac
3 GeV
Neutrino
Materials and Life Science Facility
50 GeV
Hadron Exp. Facility

M. Harada *et al*, arXiv:1310.1437 [physics.ins-det]

JSNS^2

J-PARC Sterile Neutrino Search using νs
from J-PARC Spallation Neutron Source (E56, stage-1 approved)



Building dimension :
Width : 70m
Length : 146m
Height : 30m
Exp. Hall Height : 22m

23 neutron beam lines will be Installed in experimental halls under present design.

Baseline of the detector is 17m (3rd floor of MLF ; Maintenance area of target)

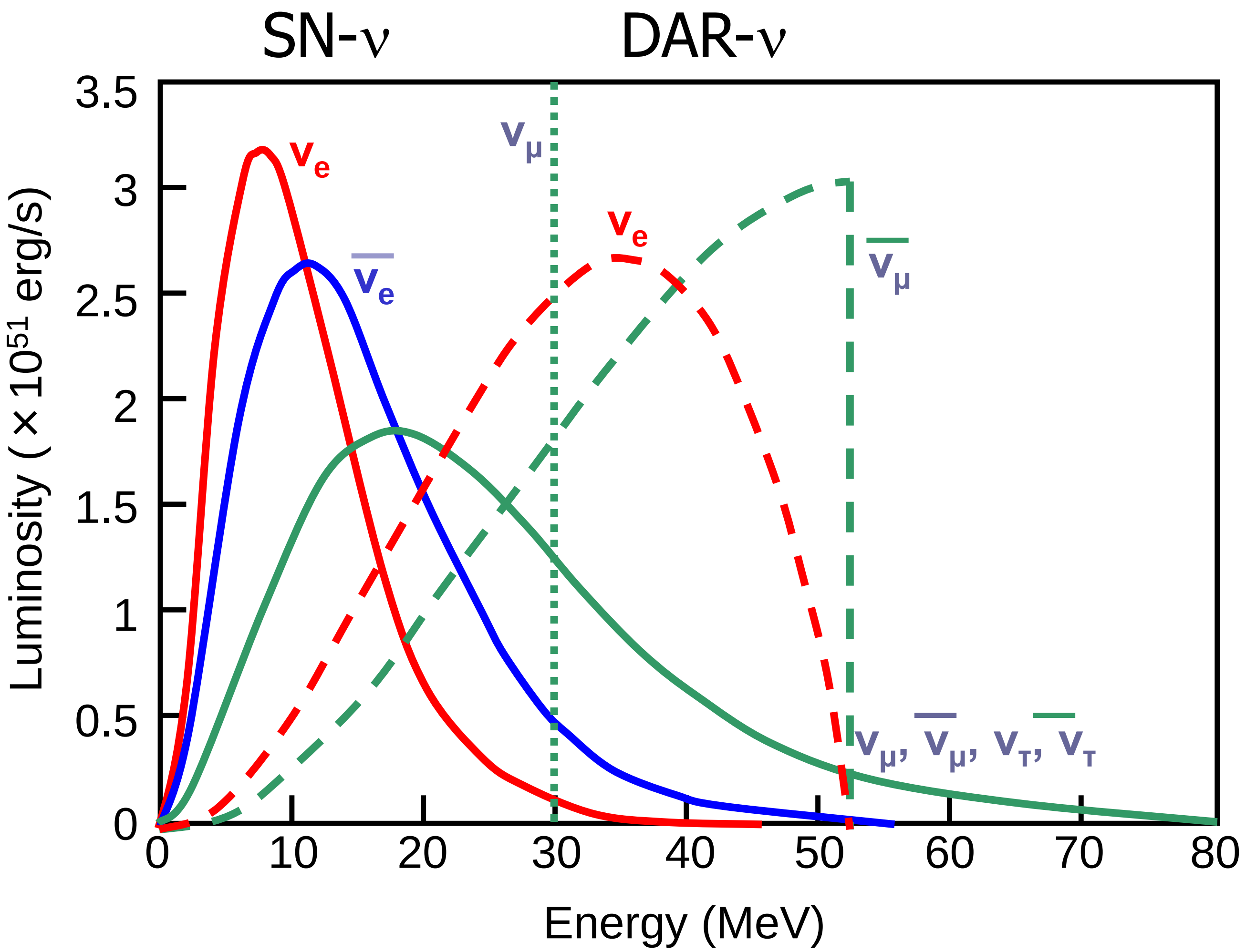
- **1MW (design)**

300kW (current)

- **25Hz operation**
- **2 bunches (80ns) in 1 spill.**

2 bunches are Separated by 540ns

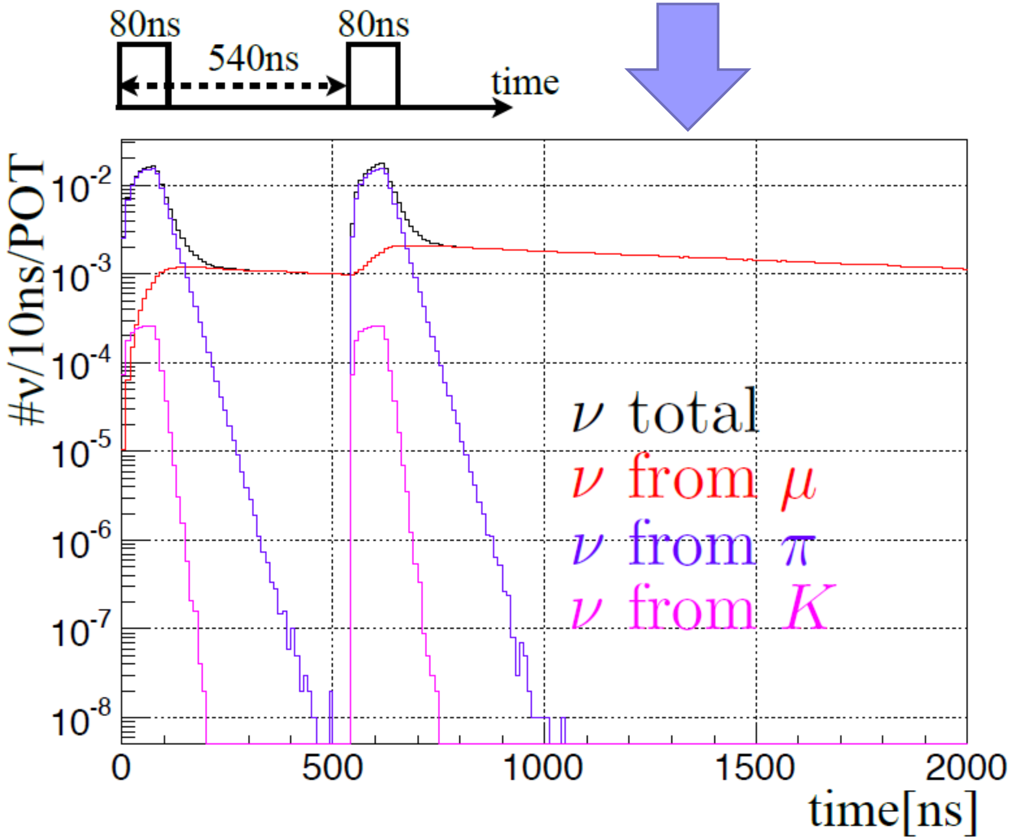
Energy spectra of decay at rest ν



Neutrino beam profile

- Pulse width; 80ns ×2
  (double pulses,
  540ns interval)
- Repetition rate; 25Hz
- ν from decay-at-rest μ ;
  well separated from
  beam pulse
  → low background

Pure $\nu_e + \overline{\nu}_\mu$!



Yield estimation; $^{127}\mathrm{I}(\nu_e, e^-)^{127}\mathrm{Xe}$

$\Phi_\nu \sim 0.95\times10^{7}$ /cm²/s @L=20m, 1MW

$^{127}\mathrm{I} \sim 4.0\times10^{27}$ atoms (**segmented NaI(Tl)**, 1ton)

$\varepsilon = \varepsilon_{det} \times$ (Live Time) ~ 0.7

$\sigma \sim 3\times10^{-40}\ \mathrm{cm}^2$

$\Rightarrow$ Signal rate $\sim 8.0 \times 10^{-6}$ /s = 115 /y (4000h)

Major background ;

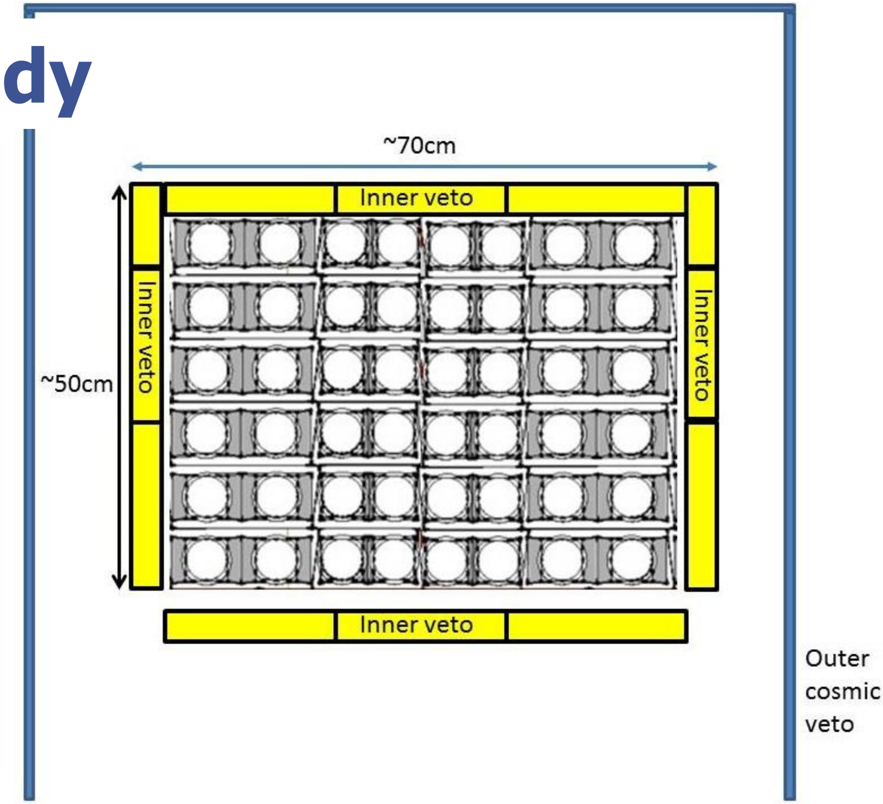
high-E neutrons making electrons inside NaI via

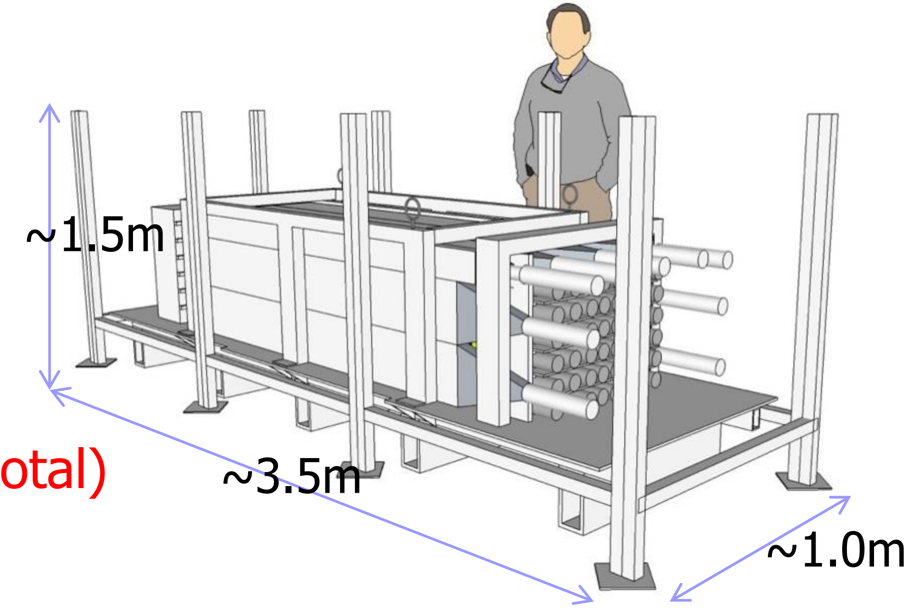
$n+A \rightarrow \pi^- + X,\ \pi^- \rightarrow \mu^- \rightarrow e^-$

500kg detector for BG study

- Main scintillators; (provided by RCNP/LEPS2)
  - 24 scintillators in total. **(~500kg)**
  - 4 scintillators / layer and 6 layers
  - 2 Narrower (central part)
  - 2 Wider (in edge sides)
  - Each scintillator has 4 PMTs, and 2 PMTs / one side
- Inner cosmic veto (yellow)
  - 4.3cm thick PL scintillators
  - One side readout.
  - Rejection Efficiency >~99.5%
- Outer cosmic veto (blue)
  - PLs are used to surround main part.
  - Size; 1m x 1m or 1m x 2.3m, 1cm (t)

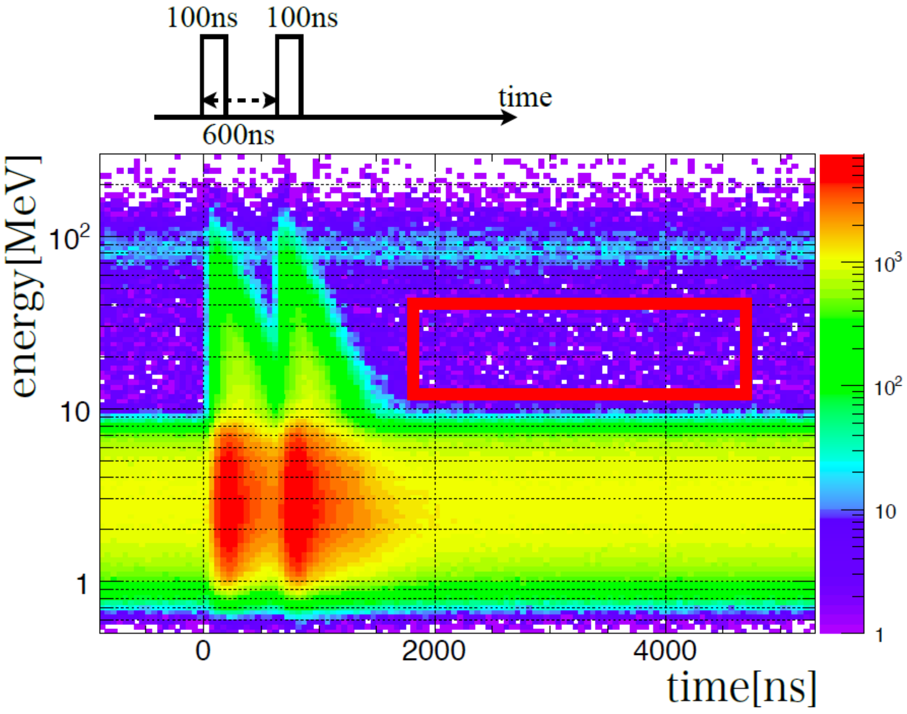
>99.8% (total)

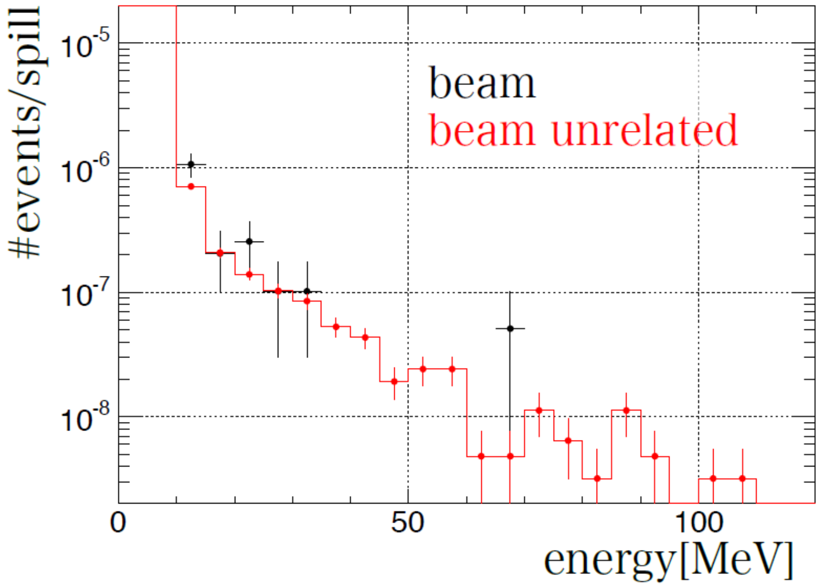




Beam-related background

S. Ajimura et al., to be appeared in PTEP, doi; 10.1093/ptep/ptv078





*Proton pulse arrives every 40ms.

Prompt; t_p=1.75~4.65μs

Delayed; t_d =t_p +20ms

→ Michel e- < 1.3×10^{-5} /s/MW

S/N ratio & Statistics

$\Phi_\nu \sim 0.95\times10^7$ /cm^2/s @L=20m, 1MW

^{127}I $\sim4.0\times10^{27}$ atoms (segmented NaI(Tl), 1ton)

$\varepsilon = \varepsilon_{det} \times$ (Live Time) $\sim$ 0.7

$\sigma \sim 3\times10^{-40}$ cm^2

⇒ Signal rate ~ 8.0×10^{-6} /s = 115 /y (4000h)

⇔ BG rate = 262 /y

Stat. error ~22% with 1yr measurement

JSNS^2 collaboration

S. Ajimura[1], T.J.C. Bezerra[2], E. Chauveau[2], T. Enomoto[2], H. Furuta[2], M. Harada[3], S. Hasegawa[3], T. Hiraiwa[1], Y. Igarashi[4], E. Iwai[4], T. Maruyama[4], S. Meigo[3], T. Nakano[1], M. Niiyama[5], K. Nishikawa[4], M. Nomachi[1], R. Ohta[4], H. Sakai[2], K. Sakai[3], S. Sakamoto[3], T. Shima[1], F. Suekane[2], S.Y. Suzuki[4], K. Suzuya[3], and K. Tauchi[4]

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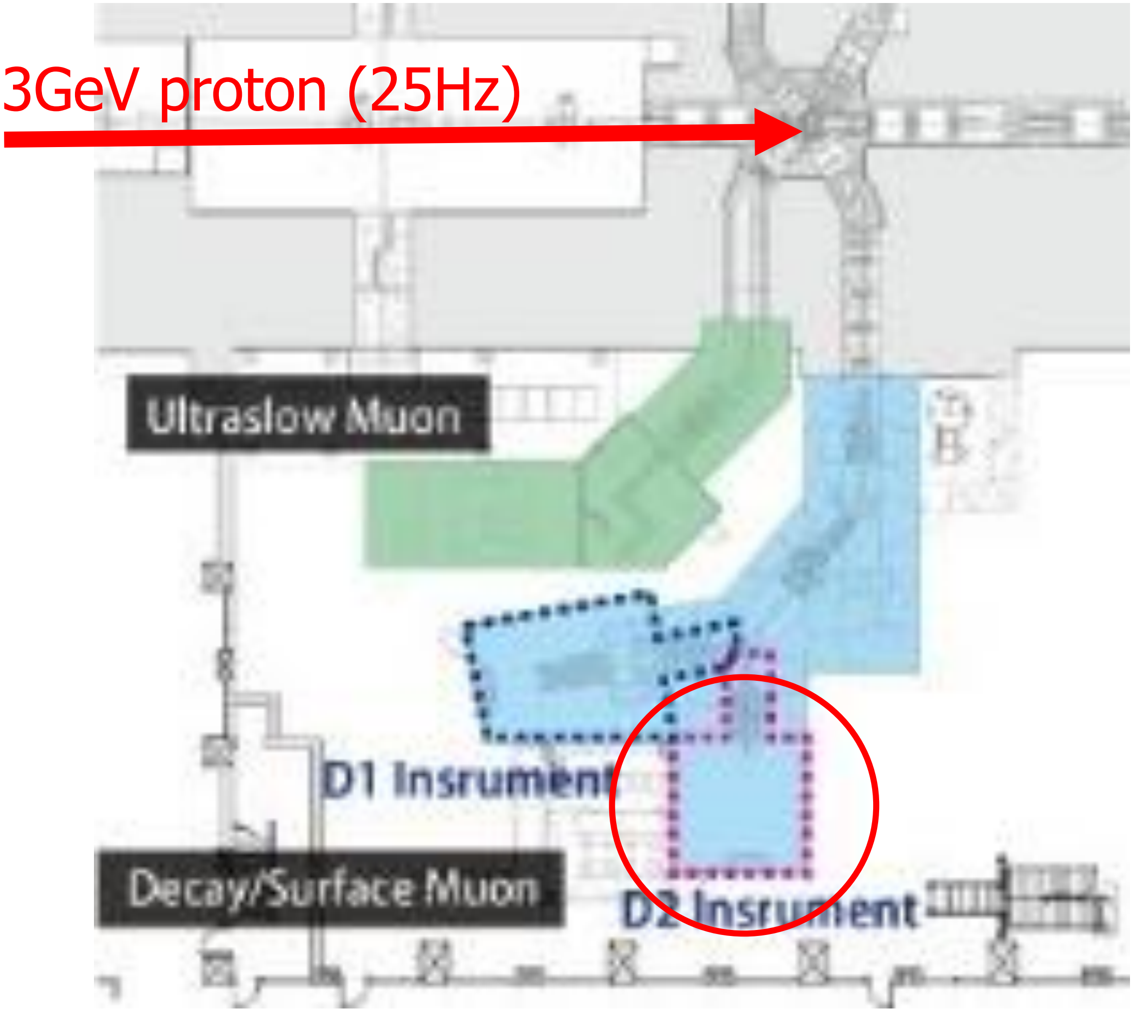
[2]Research Center for Neutrino Science, Tohoku University, Sendai, Miyagi, JAPAN
[3]J-PARC Center, JAEA, Tokai, Ibaraki JAPAN
[4]High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki, JAPAN
[5]Department of Physics, Kyoto University, Kyoto, JAPAN

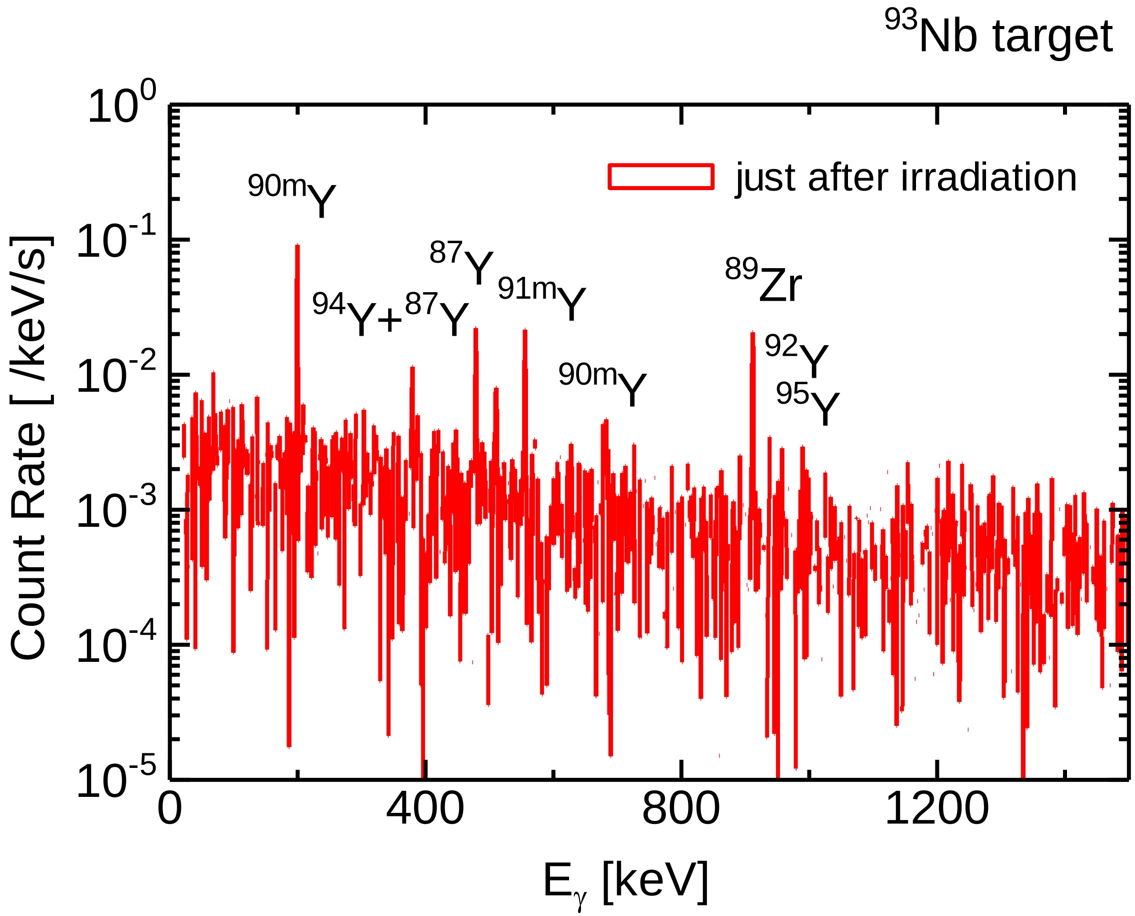
2. μ-capture experiment @J-PARC/MUSE


Muon-target station

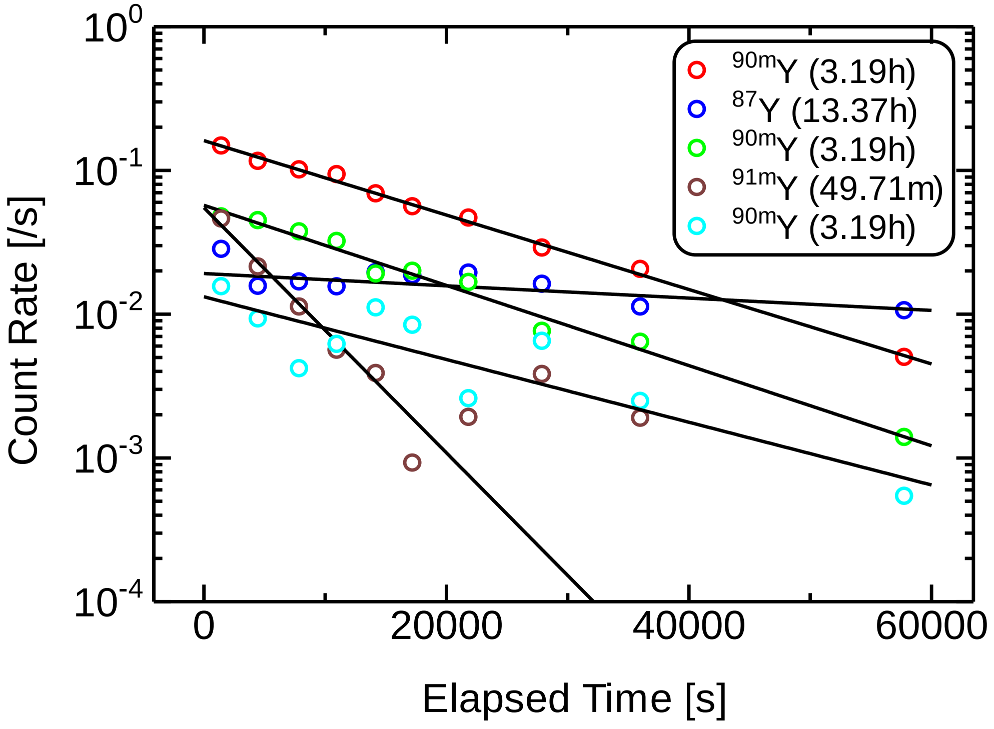
3GeV proton (25Hz)

Off-line γ-ray spectrum (^{nat}Nb target, 20mg/cm^2)

$\Phi_{\mu-}$ ~10^6 /s, exposure time = 50 min.



Decay curves of yttrium from Zr(μ^-,ν_e+xn)

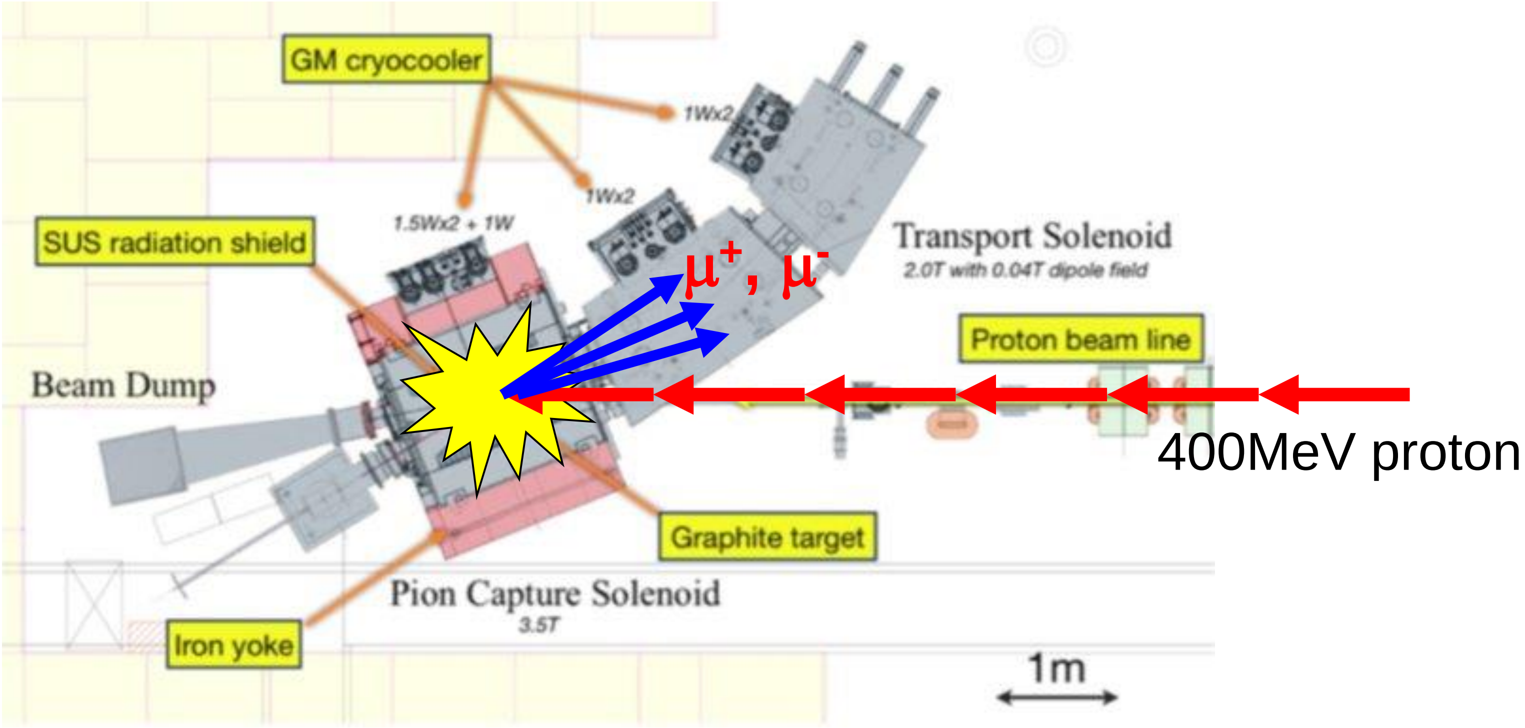


Zr impurity in Nb metal;
1~10ppm (typical)

⇔ 10^{16} zirconium atoms

Target with much smaller quantity can be measured with more intense μ^- beam and ultra low-BG detector.

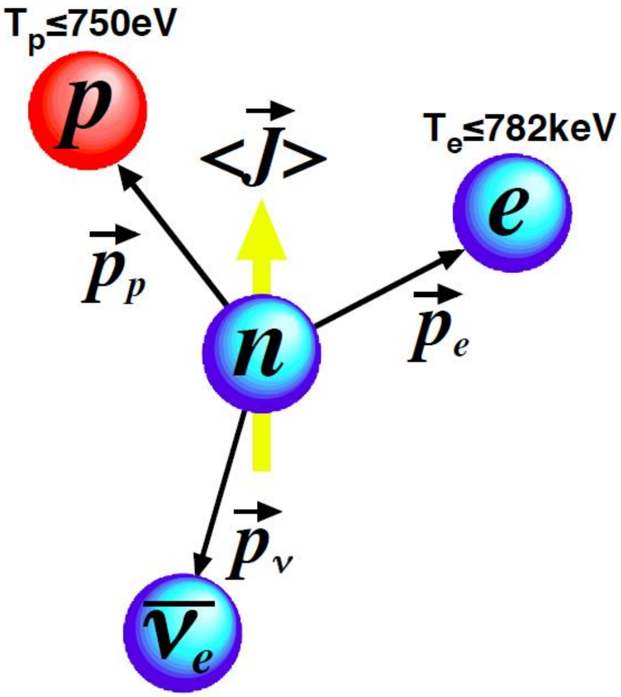
RCNP/MuSIC High-intensity **DC** muon source



Stopped μ^- rate ~10^8 /s@400W

--- comparable to J-PARC/MUSE@1MW

3. Neutron β-decay



(lowest order)

$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} = \frac{\left(G_F V_{ud}\right)^2}{\left(2\pi\right)^5}\left(1+3\lambda^2\right) p_e E_e E_\nu^2$$

$$\times\left[1 + a\frac{\overrightarrow{p_e}\cdot\overrightarrow{p_\nu}}{E_e E_\nu} + b\frac{m_e}{E_e} + \frac{\langle\vec{J}\rangle}{J}\cdot\left\{A\frac{\overrightarrow{p_e}}{E_e} + B\frac{\overrightarrow{p_\nu}}{E_\nu} + D\frac{\overrightarrow{p_e}\times\overrightarrow{p_\nu}}{E_e E_\nu}\right\}\right]$$

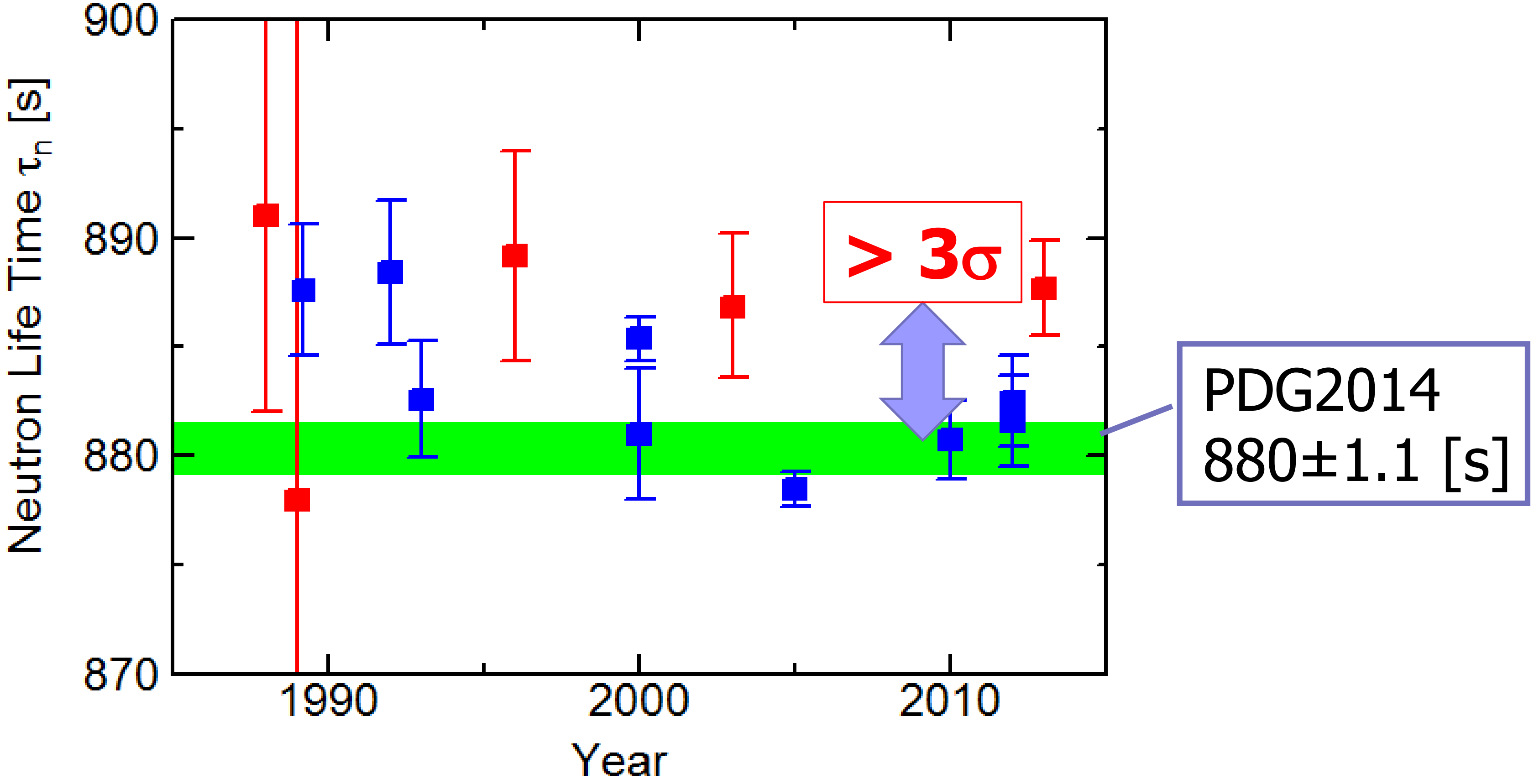
$$\lambda = |\lambda| e^{-i\phi}\ , \quad a = \frac{1-|\lambda|^2}{1+3|\lambda|^2}\ , \quad A = -2\frac{|\lambda|\cos\phi + |\lambda|^2}{1+3|\lambda|^2}\ ,$$

$$B = -2\frac{|\lambda|\cos\phi - |\lambda|^2}{1+3|\lambda|^2}\ , \quad D = 2\frac{|\lambda|\sin\phi}{1+3|\lambda|^2}$$

- Life time τ_n ; key parameter to BBN, especially for ^{4}He
- Asymmetry λ ; bare g_V , g_A

Life time τ_n

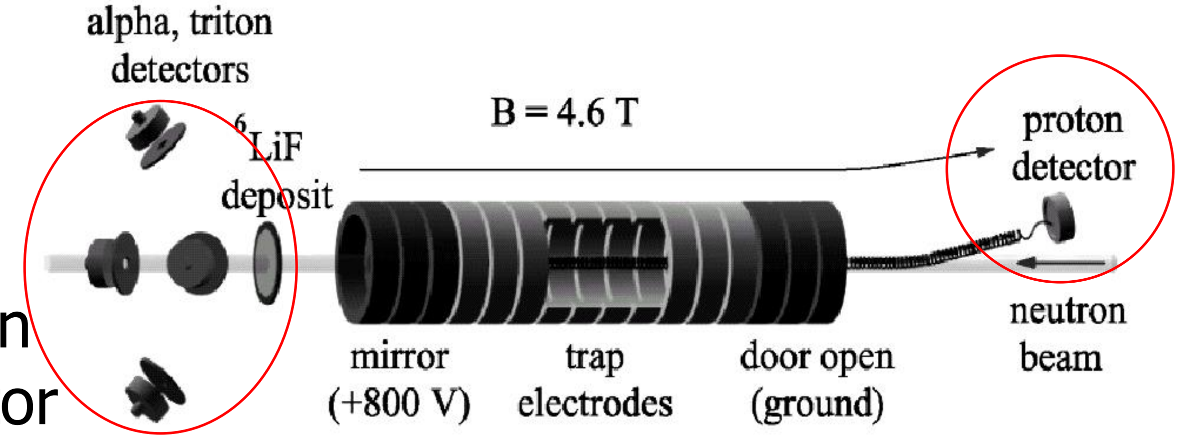
🟥 In-flight decay method
🟦 UCN storage method



PDG2014
880±1.1 [s]

NIST experiment

J.S.Nico et al., PRC71, 055502 (2005)



Proton detector

Neutron detector (^{6}Li(n,α)^{3}H)

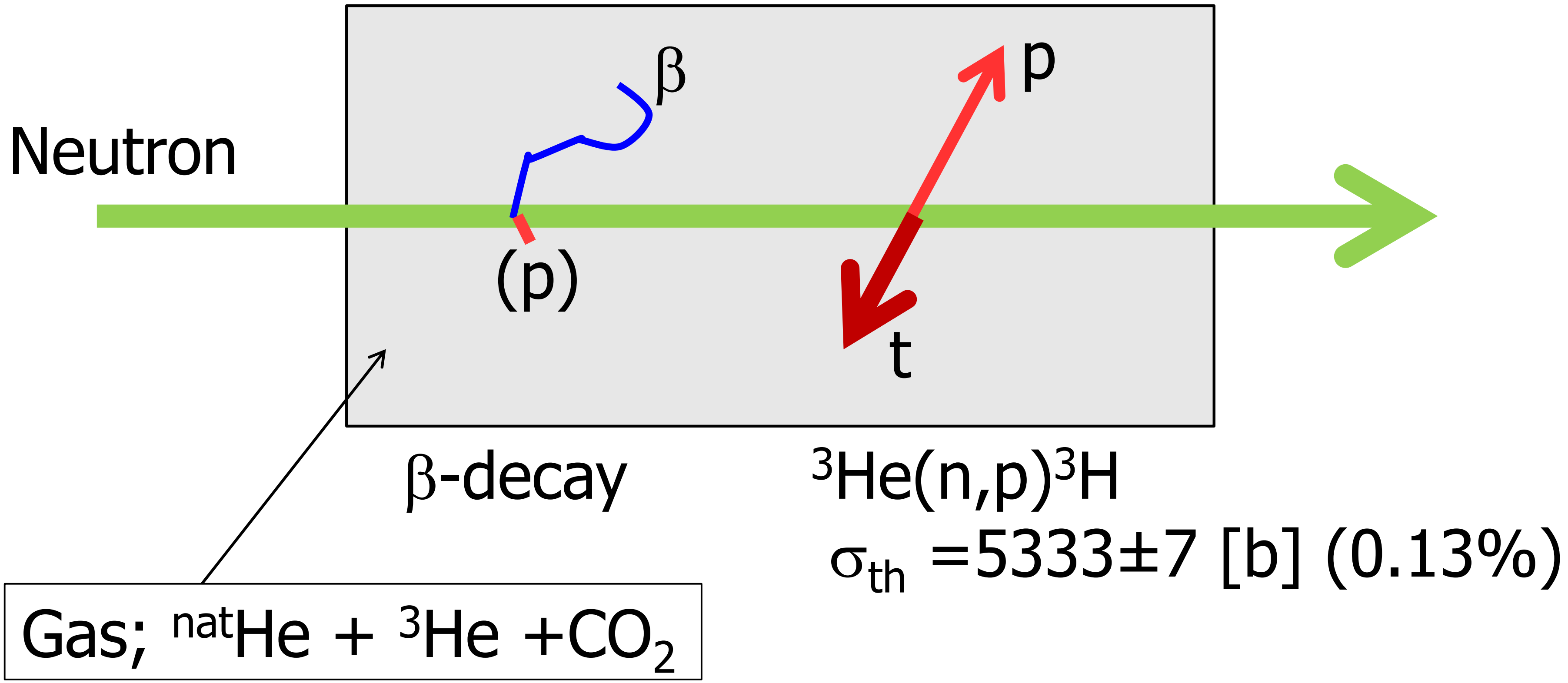
$$N_n = L\int_A \frac{\Phi_n(v)}{v}\,da$$

$$R_p = \dot{N}_p = \frac{\varepsilon_p L}{\tau_n}\int_A \frac{\Phi_n(v)}{v}\,da$$

$$R_\alpha = \dot{N}_\alpha = \varepsilon_{th} v_{th}\int_A \frac{\Phi_n(v)}{v}\,da \qquad \Rightarrow \frac{R_p}{R_\alpha} = \tau_n^{-1}\left(\frac{\varepsilon_p}{\varepsilon_{th} v_{th}}\right)L$$

Present method

--- simultaneous measurement of
neutron beta-decay and ^{3}He(n,p)^{3}H with
the same detector (**T**ime-**P**rojection **C**hamber)



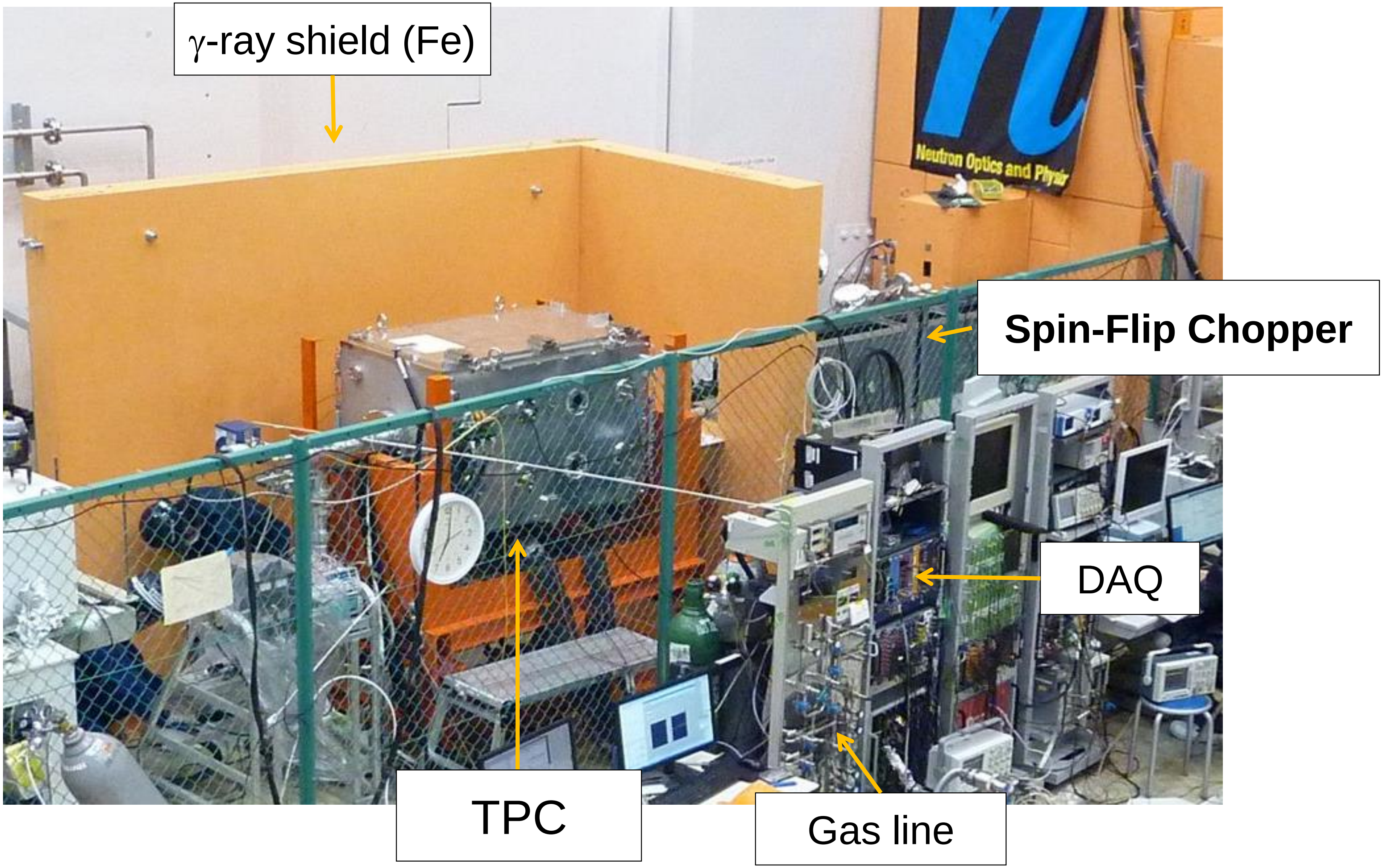
β-decay

^{3}He(n,p)^{3}H
σ_{th} =5333±7 [b] (0.13%)

Gas; ^{nat}He + ^{3}He +CO_2

J-PARC/MLF/BL05

Y. Arimoto et al.,
Prog. Theor. Exp. Phys. 02B007 (2012)


γ-ray shield (Fe)

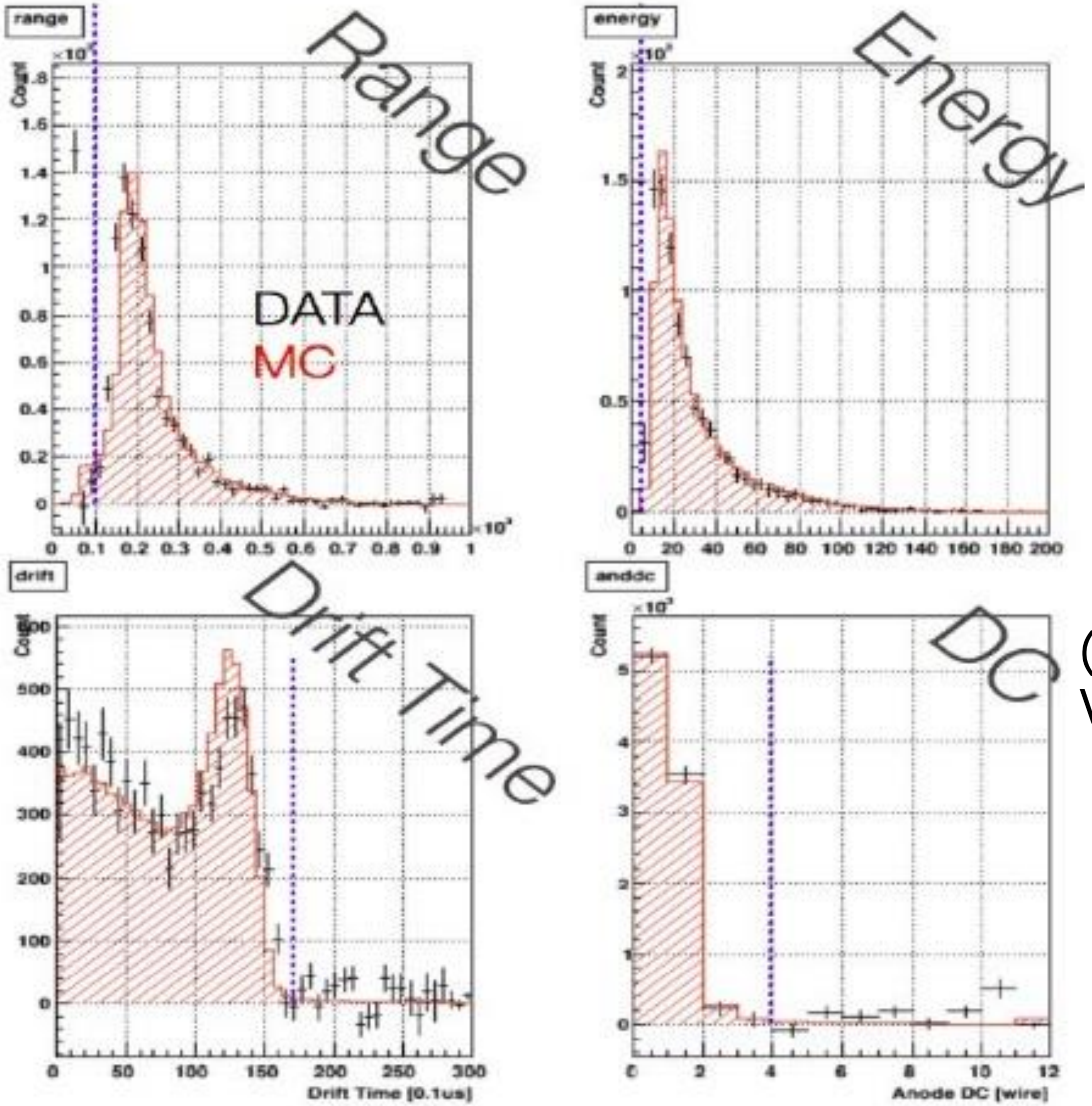
Spin-Flip Chopper

DAQ

TPC

Gas line

TPC data; comparison with MC simulation



(Distance from Vtx to Beam axis)

Error budget (preliminary)

(* under consideration.)

Error source	Correction	Uncertainty
Statistics	---	20 sec
^{3}He density	---	4 sec
Temperature distribution	O(1) sec	O(1) sec
^{3}He(n,p)^{3}H cross section	---	1.1 sec
β-^{3}He(n,p)^{3}H pile up	-3 sec	*
Analysis efficiency	-39 sec	*
Contam. of ^{3}He(n,p)^{3}H	~0.3 sec	*
Contam. of ^{14}N(n,p)^{14}C	-8.6 sec	0.6 sec
Contam. of ^{17}O(n,α)^{14}C	-4.3 sec	0.2 sec
BG from scattering in TPC	*	*
BG from Spin Flip Chopper	< 4 sec (*)	< 4 sec (*)

NOP collaboration

(**N**eutron **O**ptics and **P**hysics)

R. Katayama[1], N. Higashi[1], K. Hirota[2], T. Ino[3], Y. Iwashita[4], M. Kitaguchi[2],
R. Kitahara[6], K. Mishima[3], N. Nagakura[1], H. Oide[7], H. Otono[8], R. Sakakibara[2],
Y. Seki[9], T. Shima[10], H.M. Shimizu[2], T. Sugino[2], N. Sumi[11], H. Sumino[5],
K. Taketani[3], G. Tanaka[11], T. Tomita[11], T. Yamada[2], S. Yamashita[12], M. Yokohashi[2],
H. Yokoyama[2] and T. Yoshioka[7]

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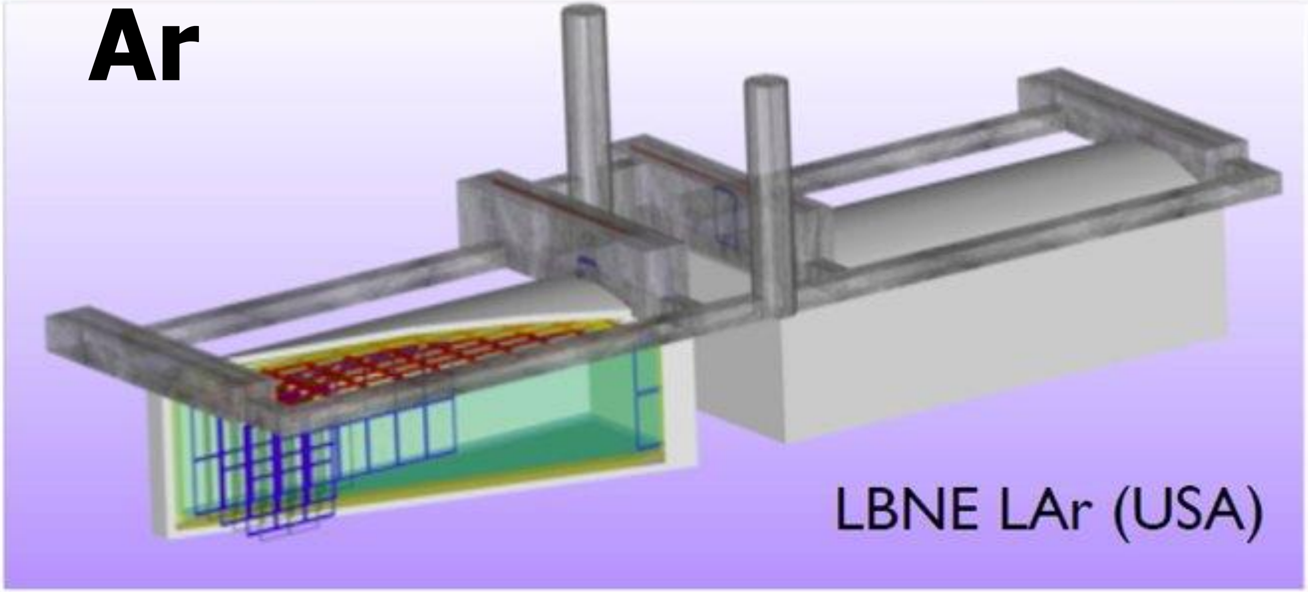
[12] *International Center for Elementary Particle Physics, University of Tokyo*

Summary

Experimental studies of nuclear weak responses with high-intensity secondary particle beams are in progress;

- Direct measurement of ν-A reaction rates with DAR ν;
  JSNS^2 (sterile) has been approved as E56 exp.(stage-1).
  We will include $\nu+{}^{12}C$ and $\nu+{}^{127}I$ in future.
- High-intensity μ sources; J-PARC/MUSE (pulse) and RCNP/MuSIC (DC) provide new opportunity to study μ-capture by rare stable isotopes and RI (,hopefully).
- J-PARC/MLF will start 1MW operation in next April to deliver world brightest slow neutrons. It will improve statistical and systematic accuracies in neutron lifetime measurement.

Ar



LBNE LAr (USA)

The LArTPC Detectors

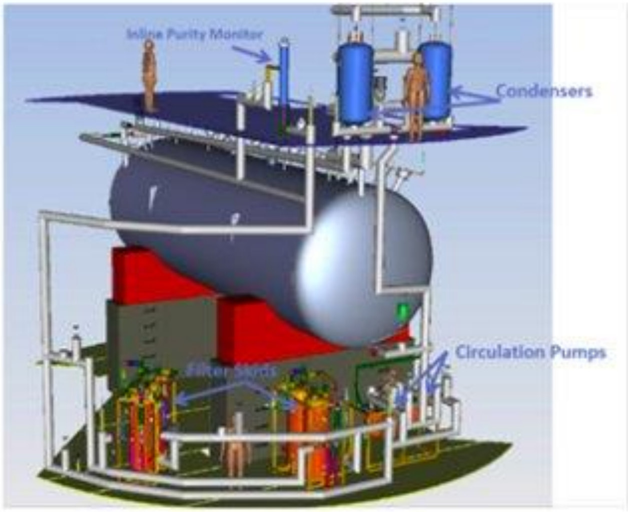
(0.1-10 kT)

in the

$\mathcal{O}$(10-100 MeV)

LAr has a unique sensitivity to the electron neutrino component of the SN flux

MicroBooNE (FNAL-US)



Neutrino flux

	RAL/ISIS	LAMPF	SNS	J-PARC/MLF
I_p [mA]	0.2	1	1~1.4	0.333
E_p [GeV]	0.8	0.8	1	3
π^+/proton	0.065	0.065	0.11	0.455
Φ_ν@20m [10^6/cm^2/s]	1.1	5.5	9.4~13	**12.8**

Yield estimation; $^{23}\mathrm{Na}(\nu_e,e^-)^{23}\mathrm{Mg}$

$\sigma \sim 2\times10^{-41}\ \mathrm{cm}^2$ W.E. Ormand et al., Phys. Lett. B308, 207 (1993)

$\Rightarrow$ Signal rate $\sim 0.53 \times 10^{-6}$ /s = 7.7 /y (4000h)

$\Leftrightarrow$ $^{127}\mathrm{I}(\nu_e,e^-)^{127}\mathrm{Xe}$ signal rate = 115 /y

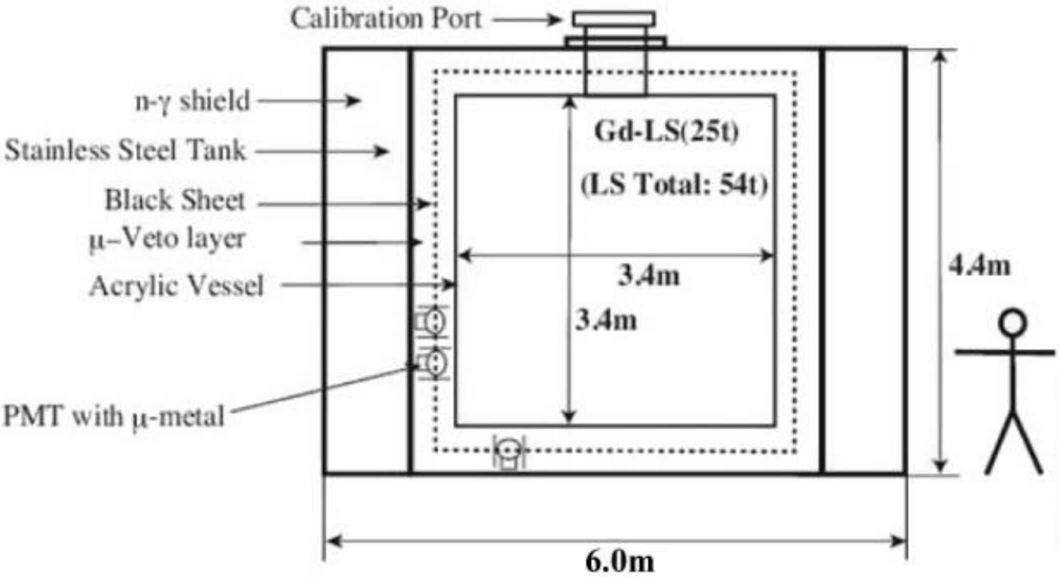
Detector

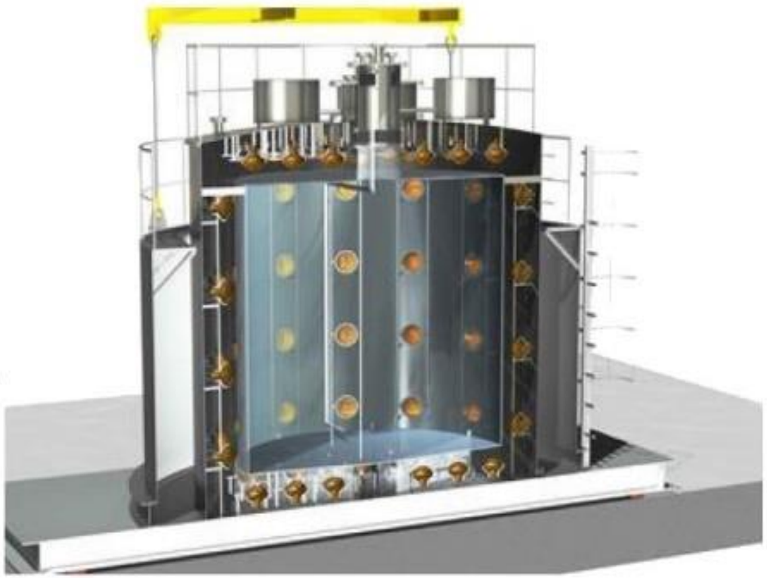
Gd-loaded Liq. Scintillator or water Cherenkov, 25ton × 2, detecting

$$\overline{\nu}_e + p \rightarrow n + e^+$$ $t_e = 1 \sim 10\mu\mathrm{s}$, $E_e = 20 \sim 60\mathrm{MeV}$

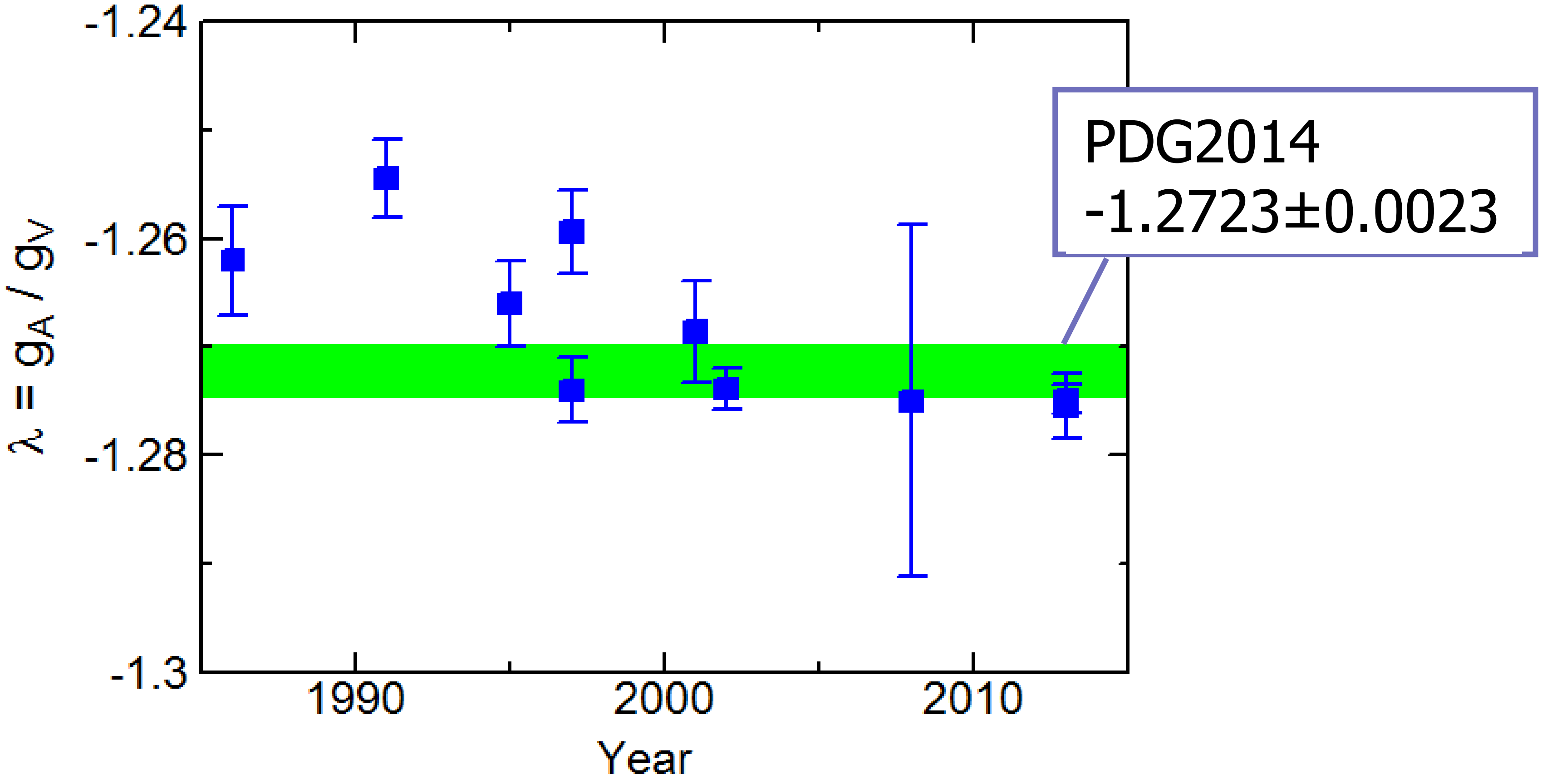
$$n + {}^{157}Gd \rightarrow {}^{158}Gd + \gamma$$ $t_\gamma = 1 \sim 100\mu\mathrm{s}$, $E_\gamma = 6 \sim 12\mathrm{MeV}$

(253000b@thermal) → Delayed coincidence





Asymmetry λ



PDG2014
-1.2723±0.0023

Simultaneous measurement

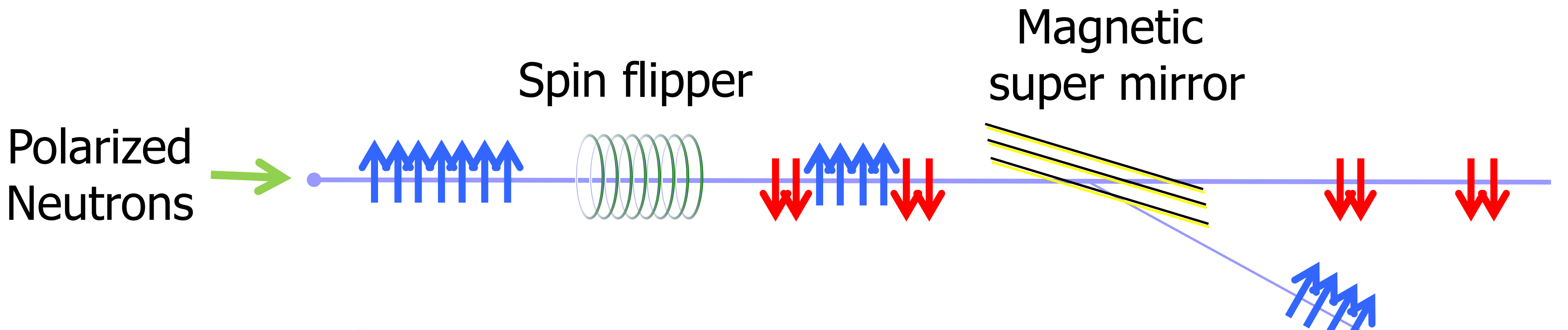
of neutron β-decay and ^{3}He(n,p)^{3}H with
the same detector (**T**ime-**P**rojection **C**hamber)

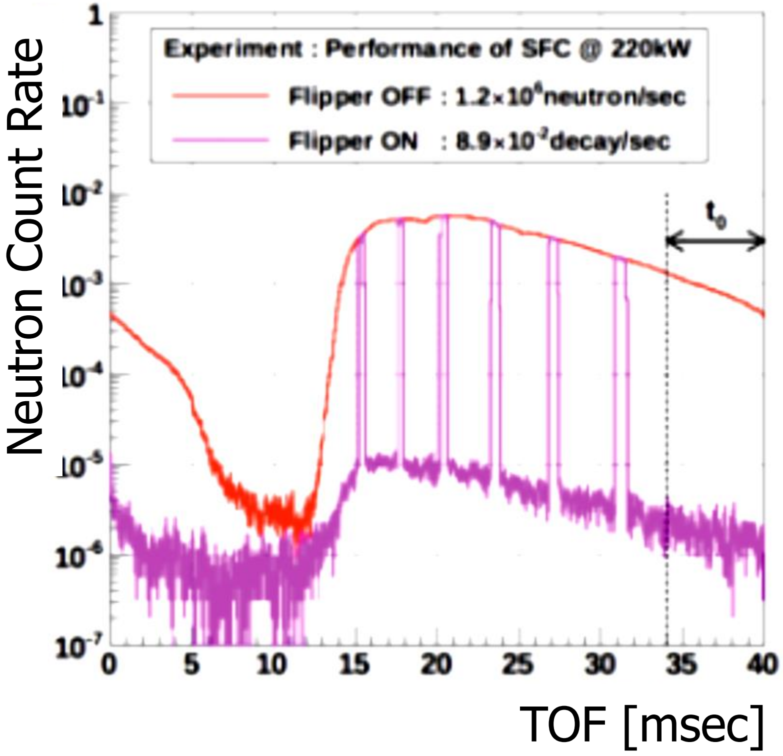
$$\tau_n^{-1} = \frac{N_e/\varepsilon_e}{N_p/\varepsilon_p}\,\rho_{^3He}\,\sigma_{^3He}(v_0)\,v_0$$

N_e , N_p : Count rate of β and proton
ε_e , ε_p : Detection efficiencies
ρ_{3He} : Atom density of ^{3}He
v_0 : Velocity of thermal neutron =2200 m/s
$\sigma_{3He}(v_0)$: Cross section of ^{3}He(n,p)^{3}H at 2200m/s,
5333 ± 7 barn (0.13%)

Spin-Flip Chopper

K. Taketani et al.,
NIM A634, S134-S137

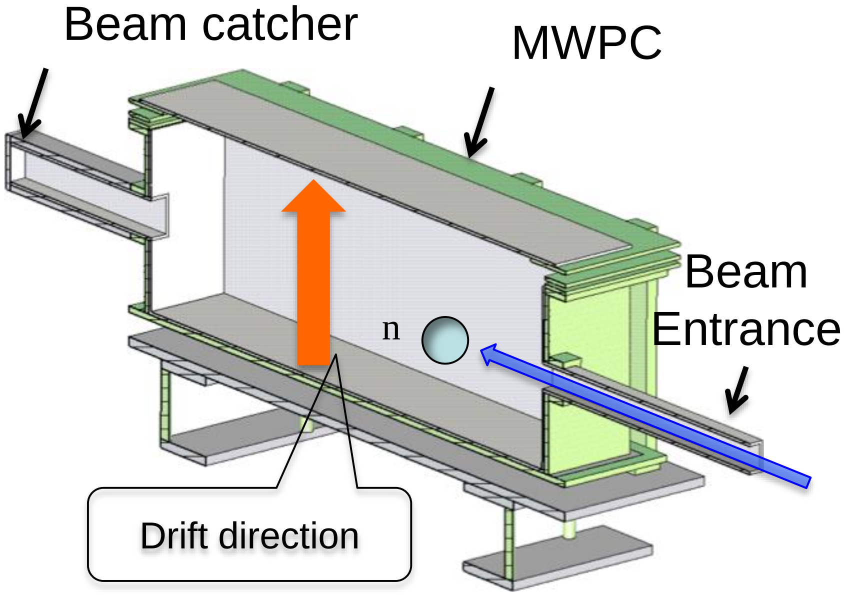


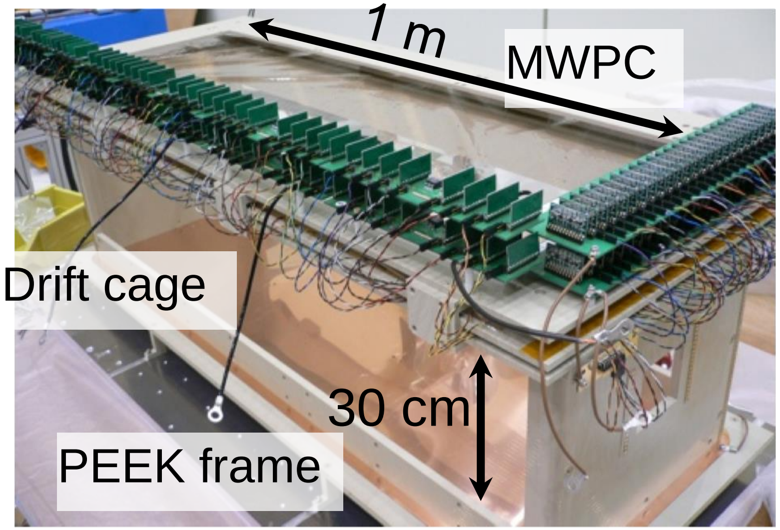


Beam ON : Beam OFF
~400 : 1

Details of setup (Time Projection Chamber)

We developed the TPC which has a low background count rate and a high efficiency for β-rays.





Anode wire	29 of W-Au wires(+1750V)
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

High efficiency detection for **both of β-decay and ^{3}He reaction**

PEEK frame & inner ^{6}Li wall suppress BG.

S/N ~ 1:1