X-ray spectroscopy of Xi$^-$ atoms at J-PARC: E03 and future

2021/5/13

T. O. Yamamoto

JAEA (Japan)

for the E03 collaboration

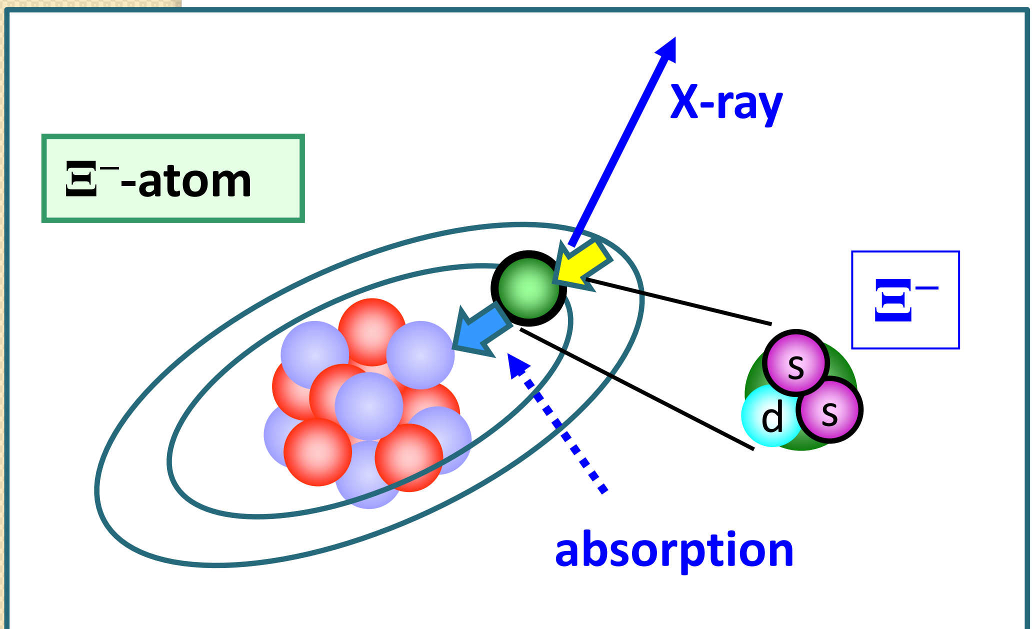
Contents

- X-ray spectroscopy of Ξ^- atom
- First try [J-PARC E07]
- Fe Ξ^- atom measurement [J-PARC E03]
  - Pilot run for detector optimization
  - 1st-phase data taking
- Future measurement [J-PARC E70]
- Summary

X-ray spectroscopy of Ξ⁻-atom

We are aiming for
world first measurement of X ray from Ξ⁻-atom

→ Information on the ΞA optical potential

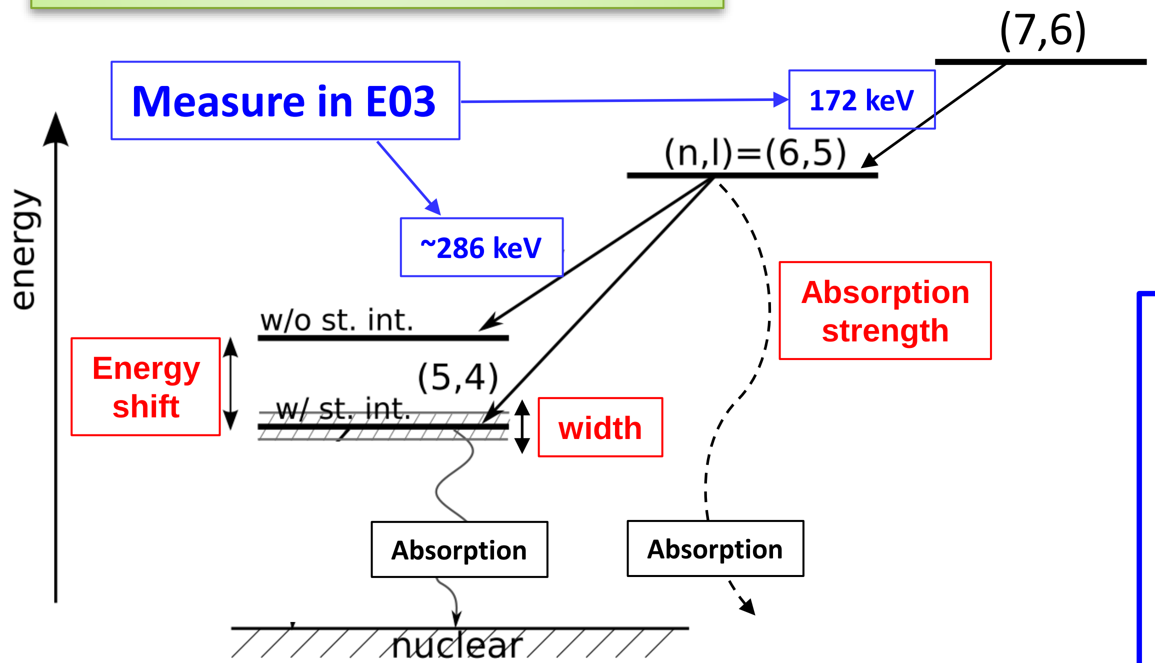


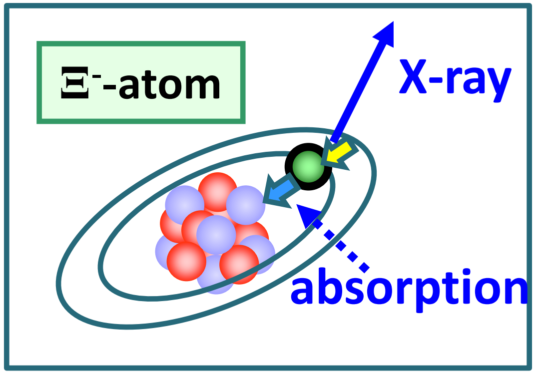
- **Information on (effective) ΞN interaction**
  large baryon mixing?
  (small ΔM(ΞN-ΛΛ)=28 MeV)
- **ΞA interaction and it's A dependence**
  Role of Ξ⁻ in neutron star?

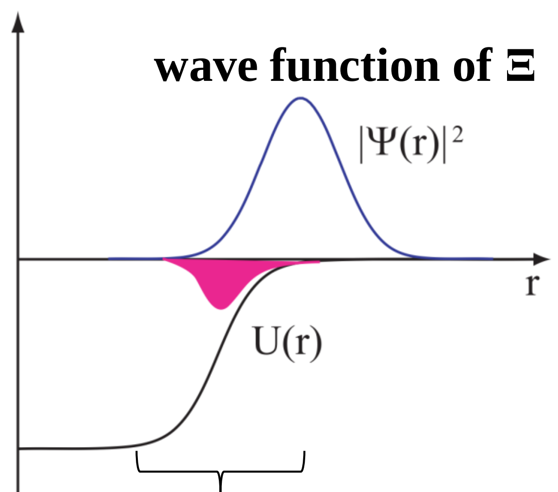
Establishment of experimental method in the J-PARC E03 (Fe-Ξ⁻ atom)
→ Systematic measurement (over wide mass range) in future

X-ray spectroscopy of Ξ⁻-atom

Level scheme of Fe-Ξ⁻ atom







Sensitive to near surface potential shape

Measurement of energy shift and width
→ Ξ⁻A real and imaginary term (near surface)

This method has been successfully applied for negative charged particles (π^-, K^-, $\bar{p}$, Σ^-)

Physics motivation

- Valuable information on ΞN (effective) interaction

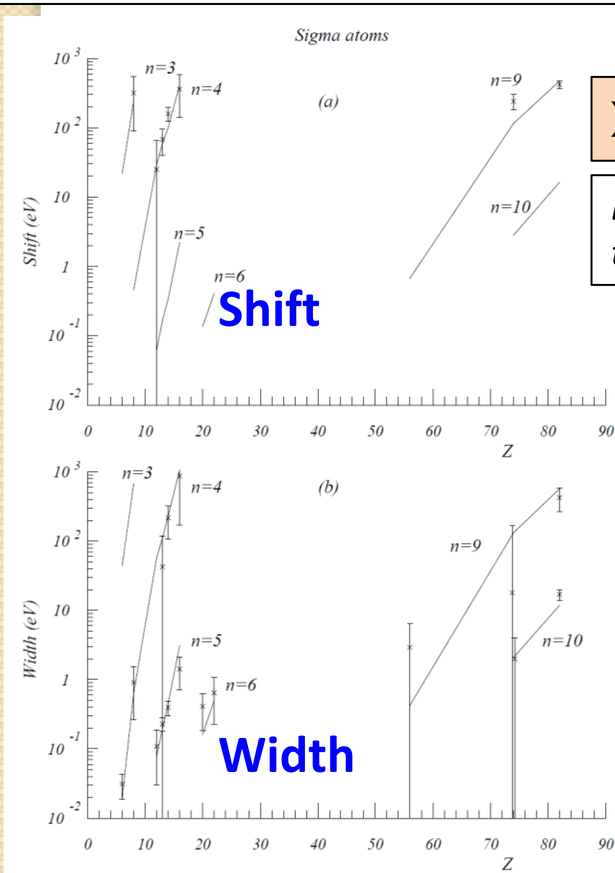
Need systematic X-ray measurement over wide mass range

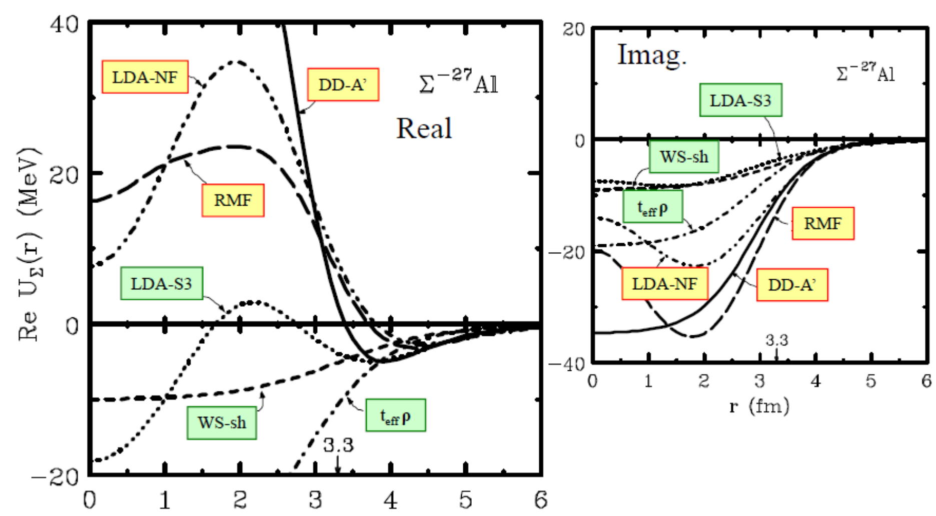
→ **Potential shape, mass dependence**

as in the case of Σ^- atom data

Σ^- atom data

E. Friedman, A. Gal
the International School of Physics Enrico Fermi (2007)



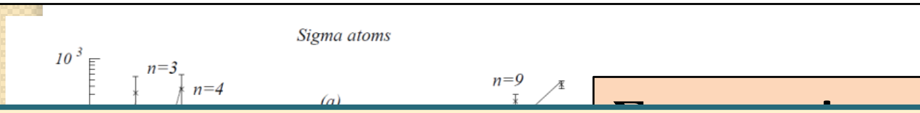


Physics motivation

- Valuable information on ΞN (effective) interaction

Need systematic X-ray measurement over wide mass range
→ Potential shape, mass dependence

as in the case of Σ^- atom data



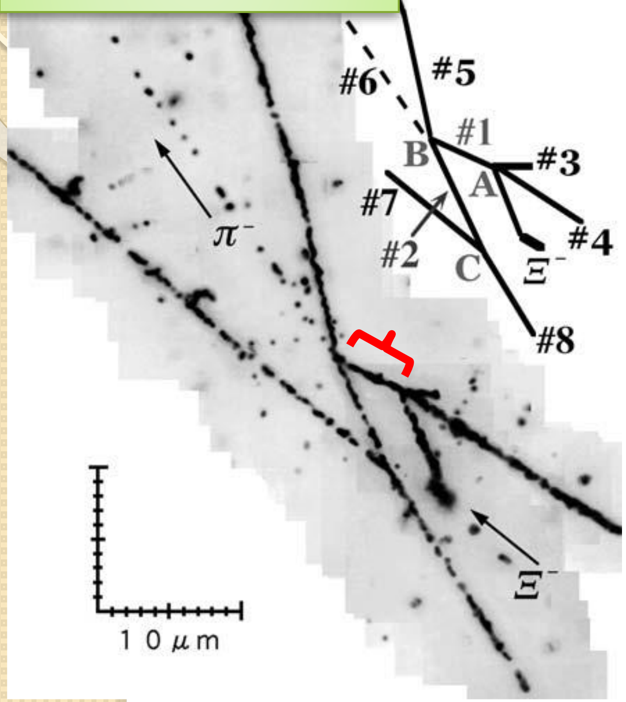
Our strategy for Ξ⁻-atom — *No Ξ⁻-atom data so far*

A ↓

- C (Z=6)-atom : J-PARC E07(-2017) & future measurement
  (also N-atom, O-atom…)
- Fe (Z=26)-atom : J-PARC E03 (-2021)
- Br (Z=35)-atom : } Our first try in J-PARC E07(-2017)
- Ag (Z=47)-atom : }
- Pb (Z=82)-atom : PANDA

Impact on emulsion data

NAGARA event



Stopped Ξ⁻s form Ξ-atoms before reaction

$$^{12}\mathrm{C} + \Xi^- \rightarrow {}^{\;6}_{\Lambda\Lambda}\mathrm{He} + {}^{4}\mathrm{He} + t$$

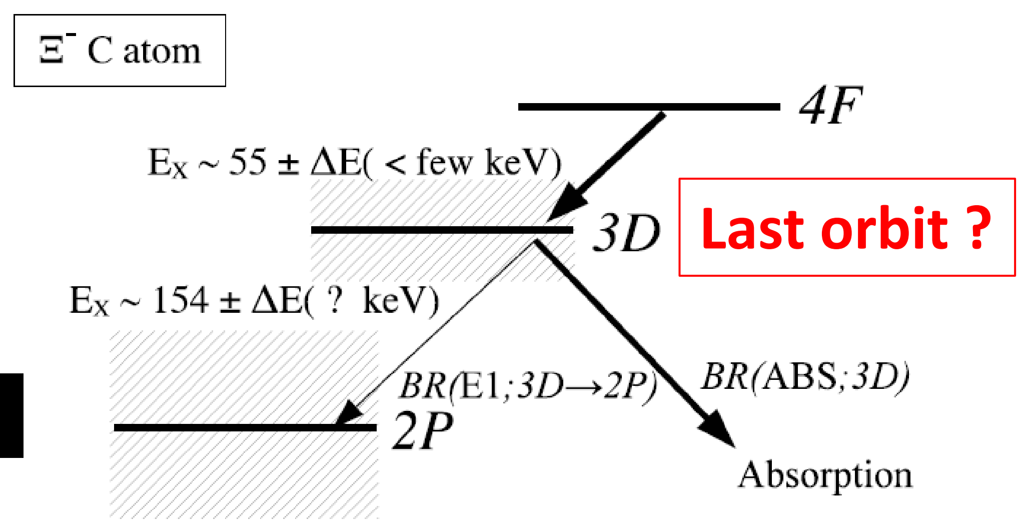
$${}^{\;6}_{\Lambda\Lambda}\mathrm{He} \rightarrow {}^{5}_{\Lambda}\mathrm{He} + p + \pi^- .$$

$B_{\Lambda\Lambda}$ = 6.91 ± 0.16 MeV

H. Takahashi et al, Phys. Rev. Lett. 87 (2001) 212502.

obtained from analysis of both production and decay point

Depends on B_Ξ of C Ξ⁻-atom [B_Ξ = 0.13 MeV] (energy center and error)



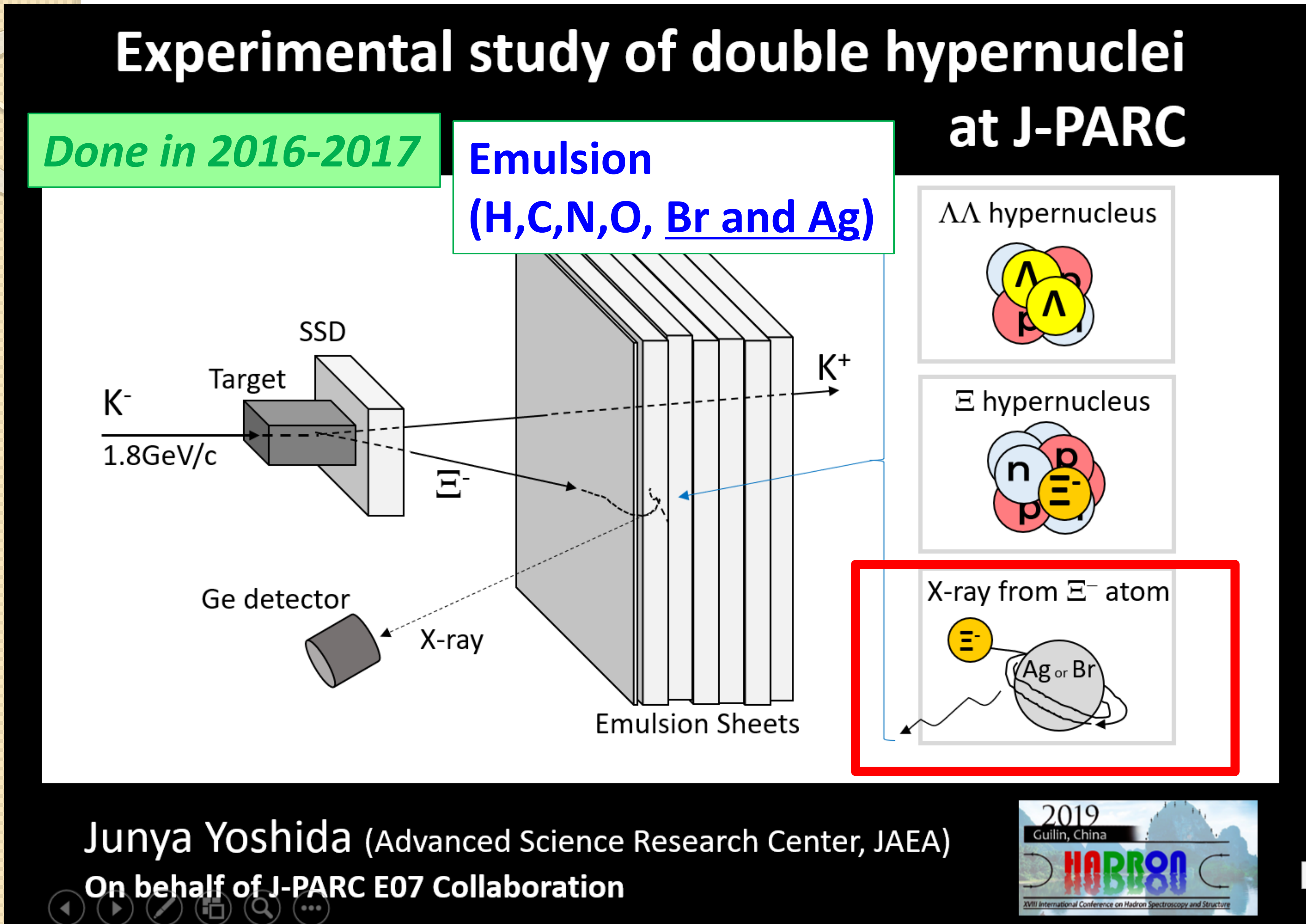
Theoretical prediction:

3D absorption is dominant

C. J. Batty, E. Friedman, and A. Gal
Phys. Rev. C59, 295 (2001)

X-ray data will support $B_{\Lambda\Lambda}$ analysis

Our first try in J-PARC E07



Our first try in J-PARC E07

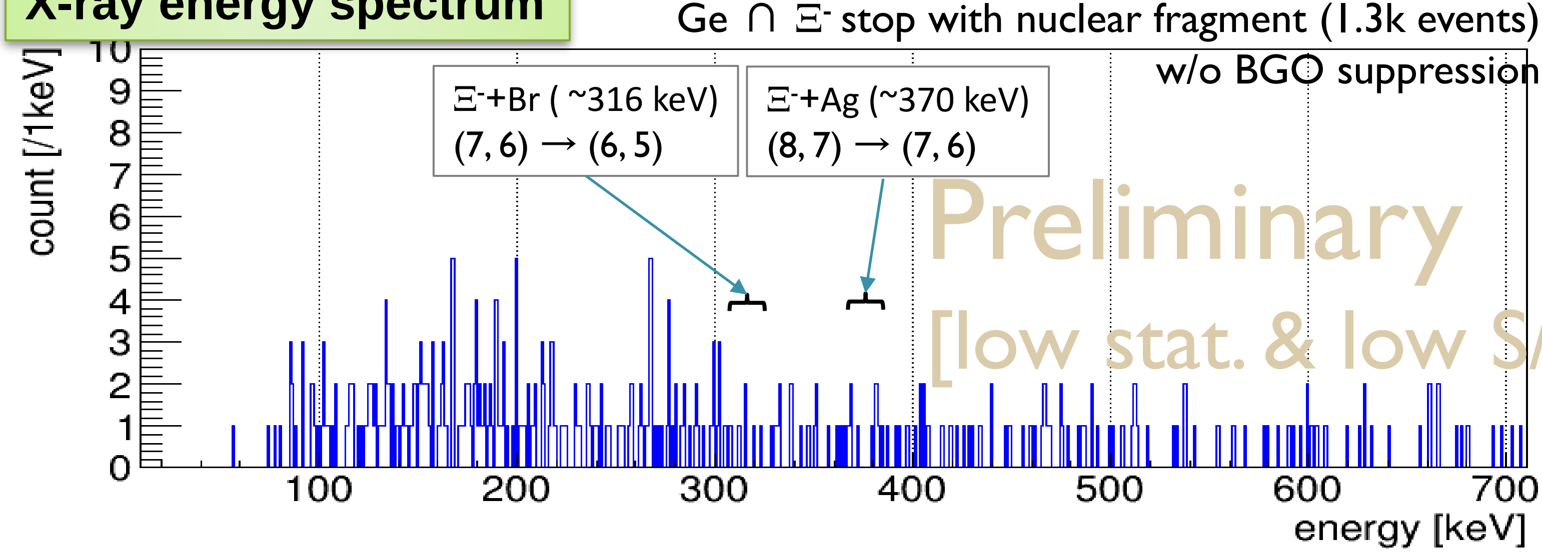
For Ag- and Br-atom

Measurement (1) : Emulsion combined analysis

- **S/N ratio ○** [we can tag Ξ⁻ stop in emulsion]
- **Yield rate ×**
  - Low stop prob. (long flight, low density)
  - Mixture target (H, C, N, O, Br and Ag)
  - Not optimum setup for X-ray detector

J. Yoshida and M. Fujita HADRON 2019

X-ray energy spectrum

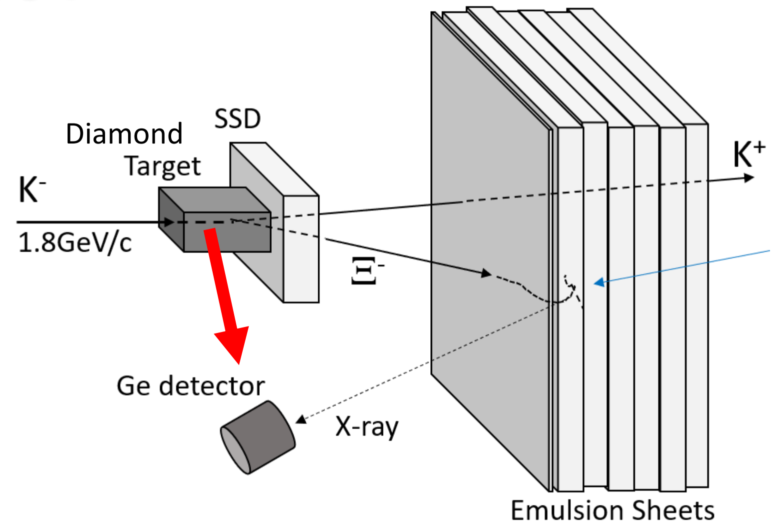


Expected # of event = 10-20 (for Ag) w/ full stat.

Emulsion analysis is on going to search "special" event (not for just Ξ⁻ stopped event)
→Not enough analyzed Ξ stop event (20-30%) so far

Our first try in J-PARC E07

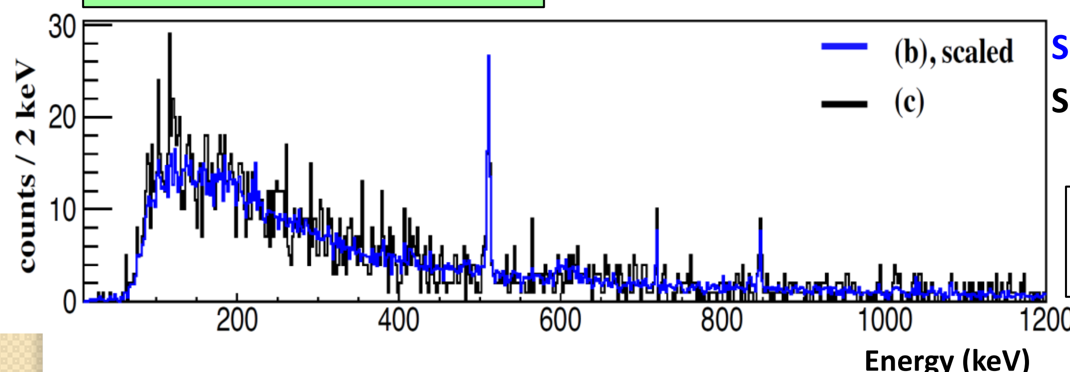
For C-atom



Measurement (2) : **w/o emulsion info.**

- **S/N ratio △** **[we can reject only SSD hit event]**
- **Yield rate △**
  - **Low stop probability (low density)**
  - **Not optimum setup for X-ray detector**

Result (Full statistics)



Select Ξ stop like

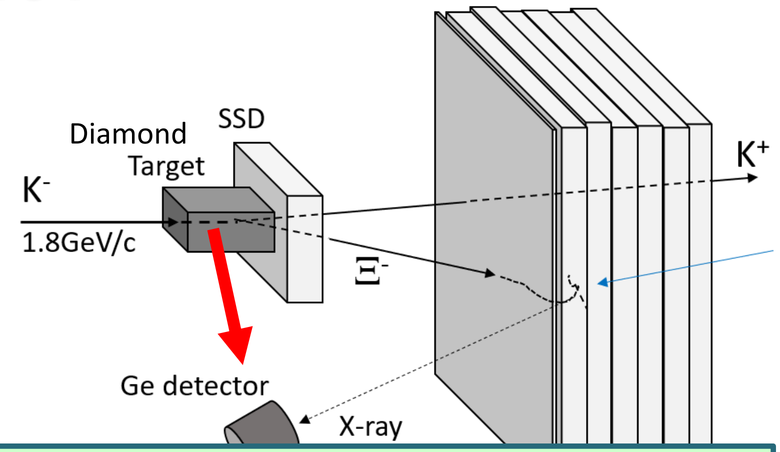
Select low momentum Ξ stop like

M. Fujita
Doctoral Thetis, Tohoku Univ. (2019)

Unfortunately, no significant peak was observed…

Our first try in J-PARC E07

For C-atom

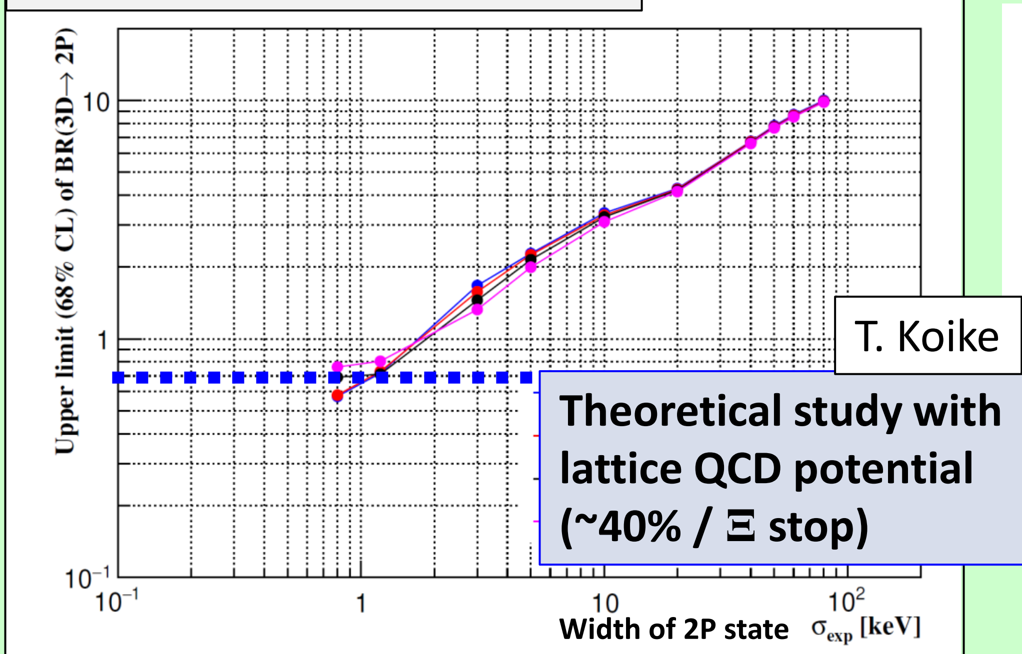


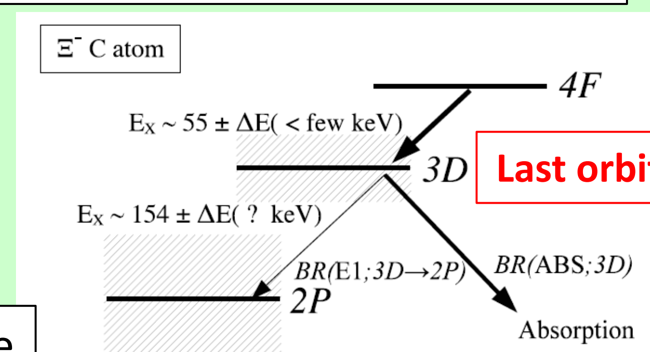
Measurement (2) : w/o emulsion info.

- **S/N ratio** △ [we can reject only SSD hit event]
- **Yield rate** △
  - Low stop probability (low density)
  - Not optimum setup for X-ray detector

Upper limit for BR(3D->2P)

M. Fujita, Doctoral Thetis, Tohoku Univ. (2019)





We achieved upper limit close to theoretical prediction

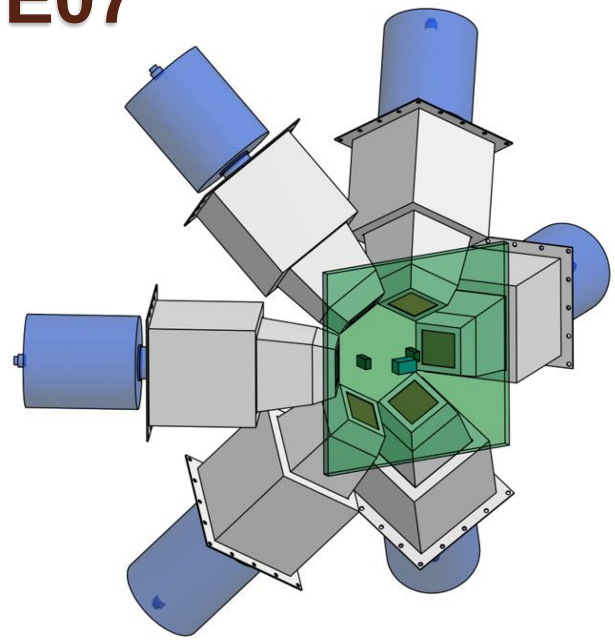
We will retry the measurement for C-atom

Performance of Ge detector in E07

We checked performance of
X-ray spectrometer (Hyperball-X Ge array)

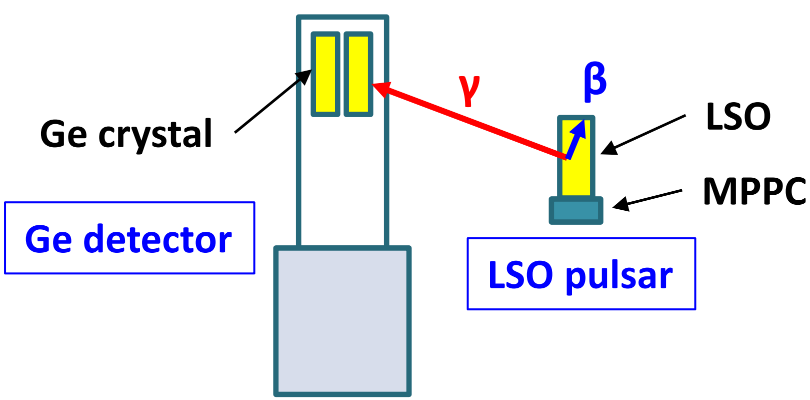
Almost same system as
our coming measurement

- Energy resolution: 2.0~2.5 keV [FWHM]
- Calibration accuracy: < 0.05 keV

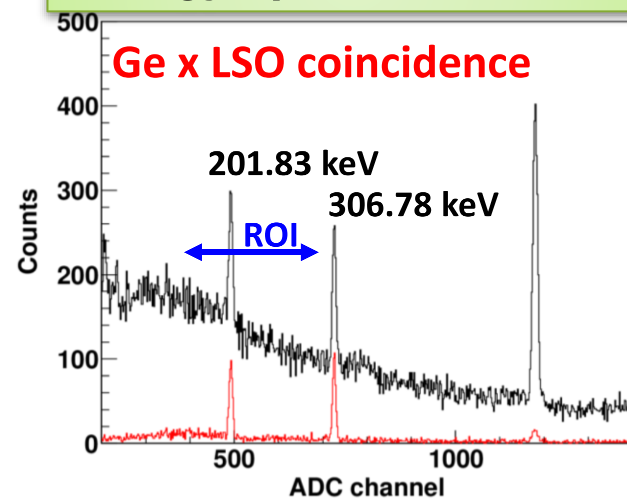


LSO triggerable source
[β-γ coincidence]

In beam calibration
[every one hour]

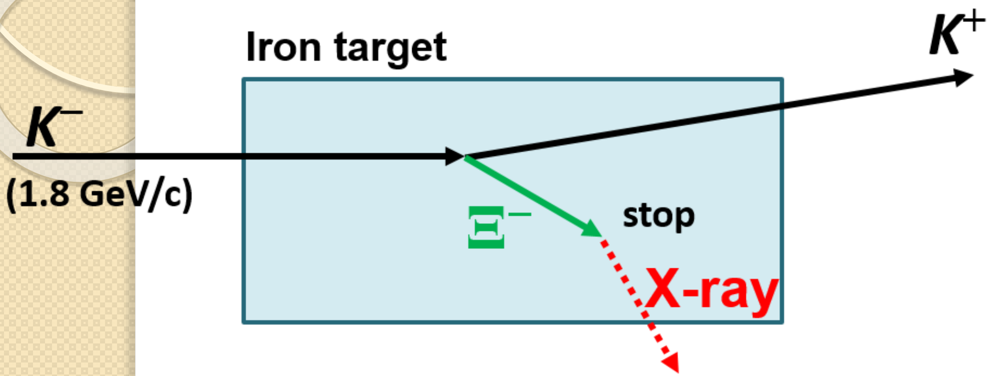


Energy spectrum w/ LSO



Fe Ξ^- atom measurement [J-PARC E03]

We are aiming for world first measurement of X ray from Ξ^--atom



Feature of the measurement:

- S/N ratio △
  [we can not tag Ξ^- stop, but high stopping prob.]
- Yield rate ○
  - High stop probability
  - Optimum detector setup

Advantage of Fe target

[Technical reason]

Enough dense (~7.9 g/cm^3) for higher stopping probability of Ξ^-

[Physics reason]

Absorption strength (and width) reported in theoretical case study is suitable for our measurement

Calculated by T. Koike

(5,4) state : $\Delta E \sim \Gamma \sim$ 4keV [W.S. shape potential of -24-3i MeV]

Recent Lattice & ChiralEFT calc.
Shows <1/10 smaller imaginary strength

Experimental setup (E03)

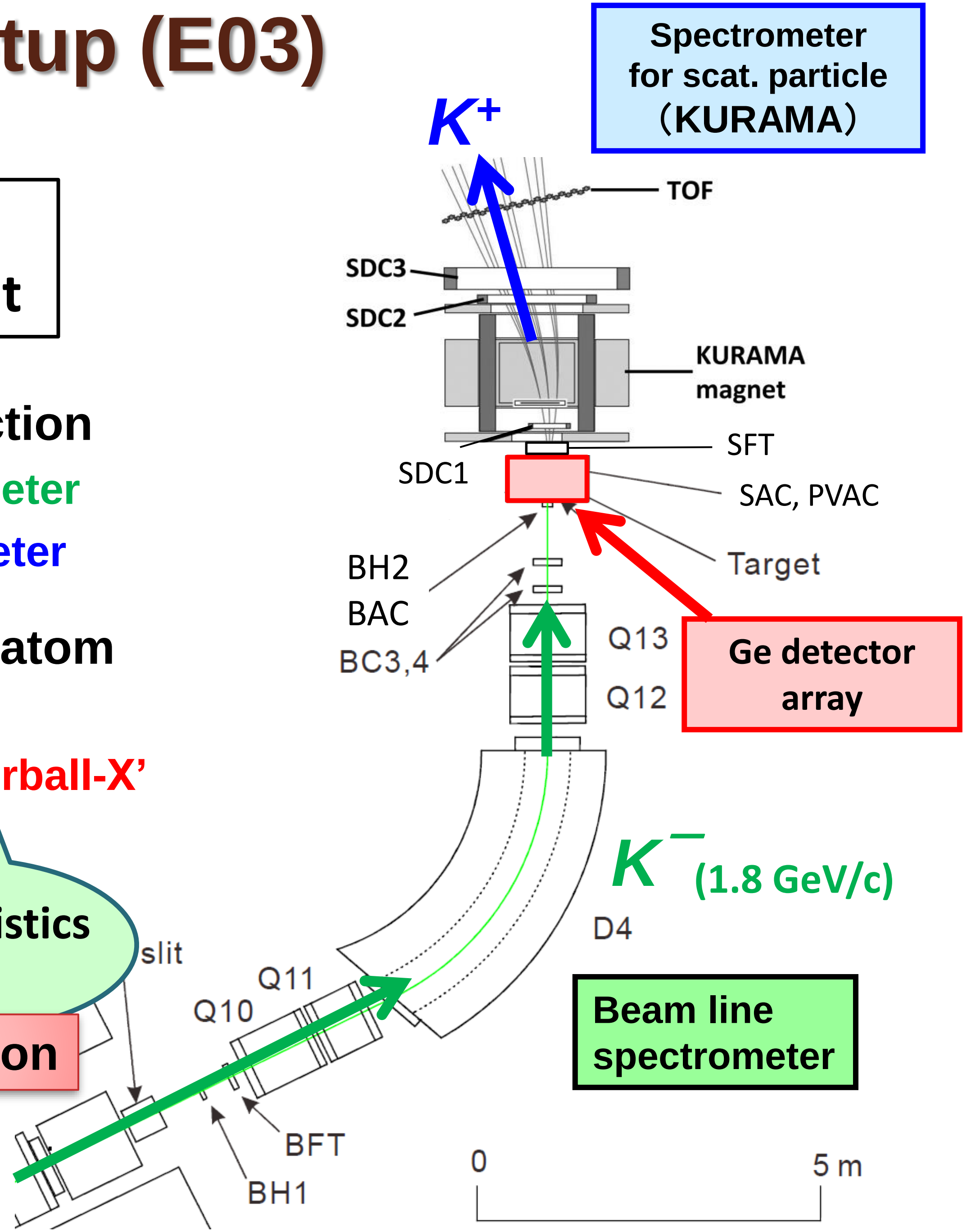
reaction-X ray coincidence experiment

- **Tag $(K^-,K^+)\Xi^-$ production**
  - **Beam line spectrometer**
  - **KURAMA spectrometer**
- **Detect X ray from Ξ^- atom**
  - **Ge detector array**
    Hyperball-J or **Hyperball-X'**

Full statistics run

10% statistics run

Focus on



Strategy of E03

We decided to run with 10% statistics (1st-phase) for not full accelerator intensity

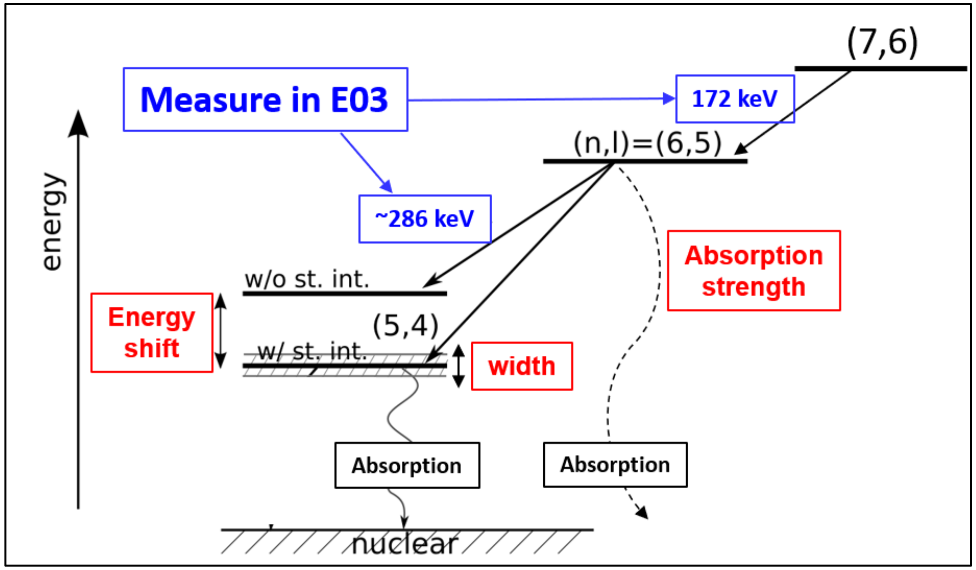
< 1st phase > 10% statistics (~20 days with present beam power)

- (7→6) transition will be seen
  → "World first measurement of X ray from Ξ atom"
- (6→5) finite shift & width (if Γ<1 keV)
- information of absorption strength from (6→5)/(7→6)

< 2nd phase > 100% statistics

- (6→5) shift & width
  (if Γ~4 keV)

Reported from theoretical case study (no strong experimental constrain)



Hyperball-J Ge detector array

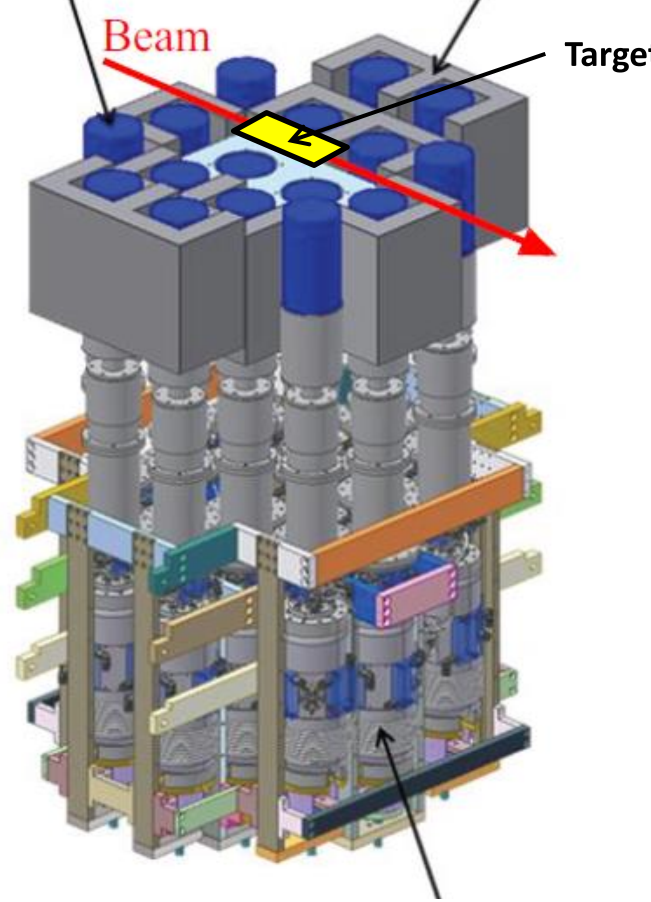
will be used in full statics E03 run

Features

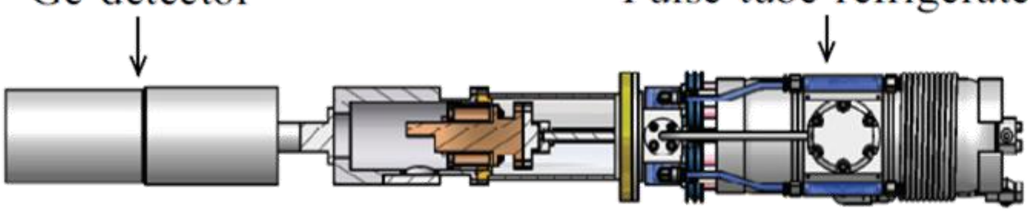
- **Large photo-peak efficiency**
  → ε ~6 % @1 MeV with 32 Ge detectors
- **Fast readout system**
- **Low temp. Ge detector for radiation hardness**
  → Mechanical cooling
- **Fast background suppressor**
  → PWO counter

for high intensity hadron beam

Lower half of Hyperball-J

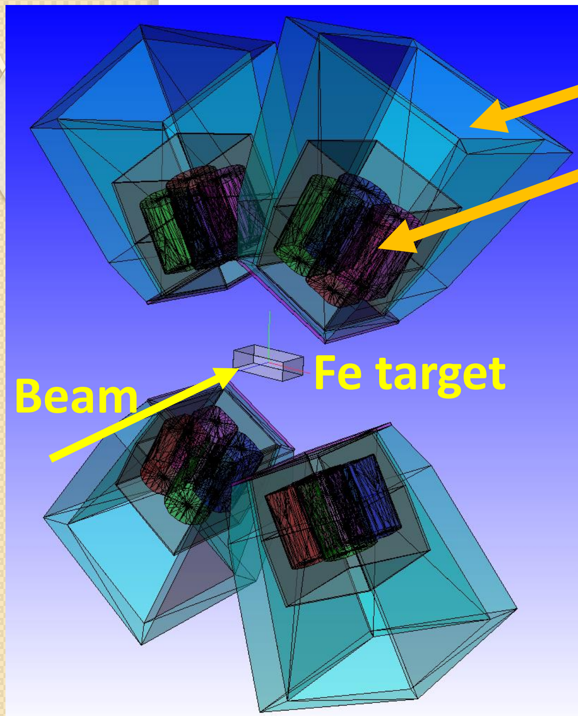


Developed Ge detector



Hyperball-X' for 1st phase

Optimum for low beam intensity



BGO suppressor

"clover-type" Ge detector (4 segmented crystals)

4 detector units with vertically covered configuration

- Horizontally wide beam profile and target
- Self-absorption of X ray is serious for horizontal direction

	HBX'	HBJ
High rate capability	△ * slow amp. * segmented crystal	○ * fast amp. * large crystal * radiation hardness
Energy resolution	2.5 keV (FWHM)	4 keV (FWHM)

Γ~1keV case,
Higher energy resolution has great merit
- better peak significance
- small error on shift & width

Pilot run for realistic estimation

First time to use our Ge detector array with "heavy" target

We have experience for A $\leq$ 19 target,
but A=56 target will be used in J-PARC E03

<Unknown factor>

- Live time of Ge detector
- B.G. level in final X-ray spectrum

Need data with actual beam and target

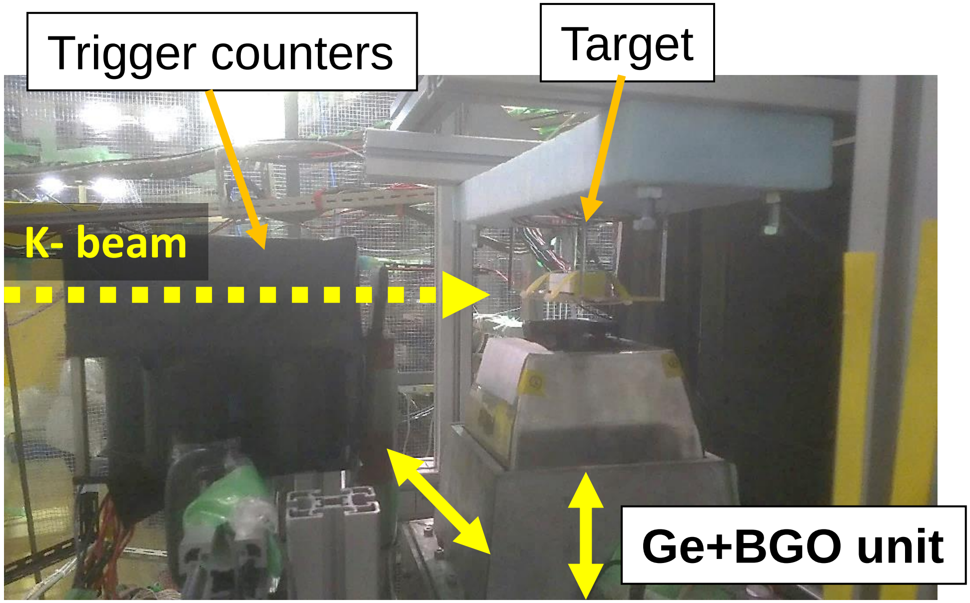
Pilot run for E03-1st June 2017 (2.5h) + Feb. 2018 (19h)

Setup: KURAMA + clover-type Ge + Iron target

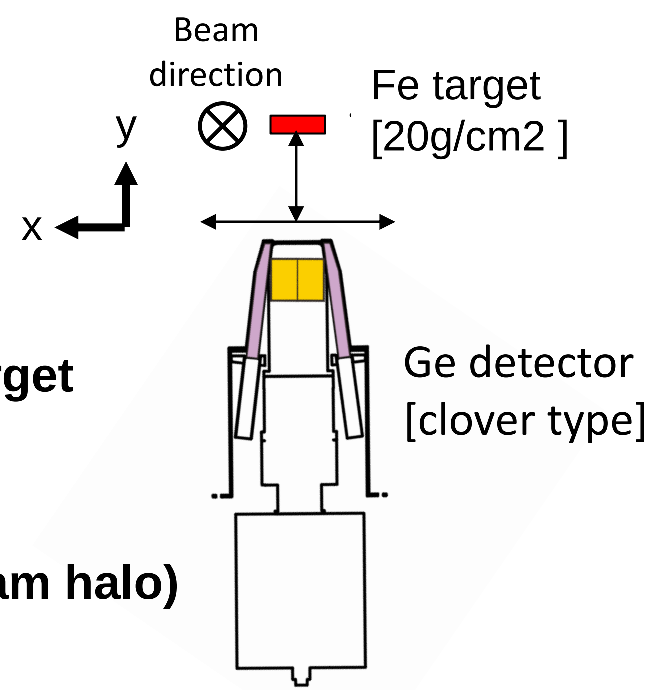
- optimization of Ge detector position and beam intensity (Live time vs coverage)
- data for realistic B.G. estimation

Pilot run

- study ①
  Position and beam intensity dependence of “Ge live time”
  Direct measurement using dummy signal
- study ②
  B.G. level in energy spectrum
  Ξ^- production x Ge coincidence
  (very low statistics physics run)

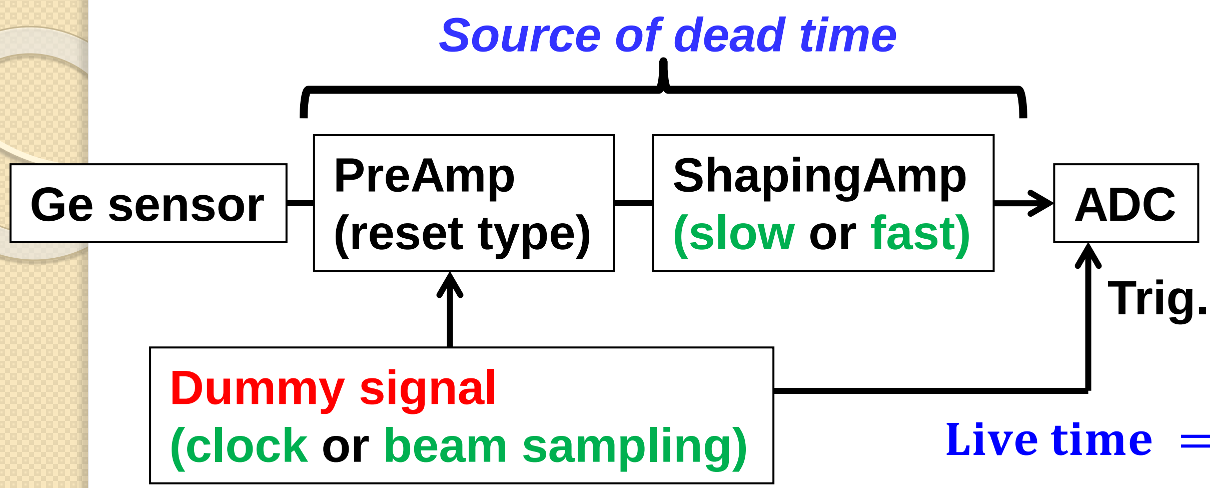


<Scan parameters>
- **Ge detector position**
  X, Y(2D) scan
- **Beam intensity**
  π+K = 200 - 800 k/spill
- **Slow amp. or fast amp.**



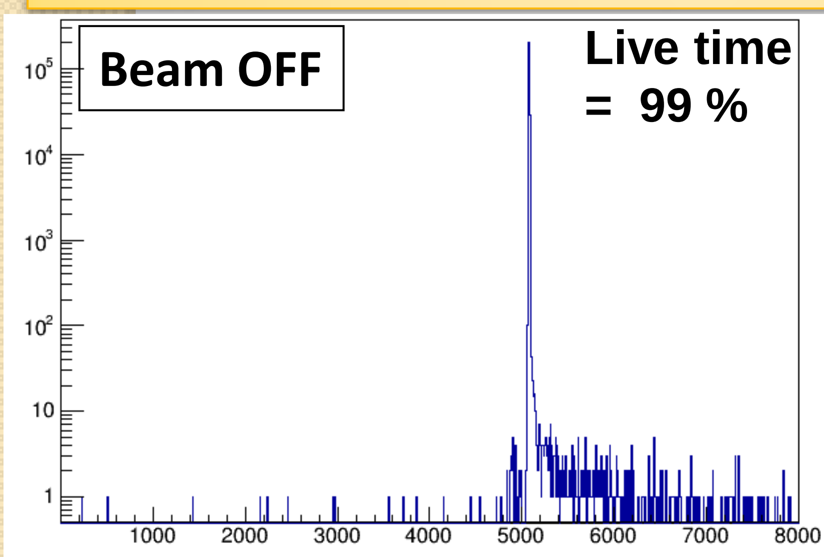
Y : distance Ge↔Target
X : horizontal
(effect of not symmetrical beam halo)

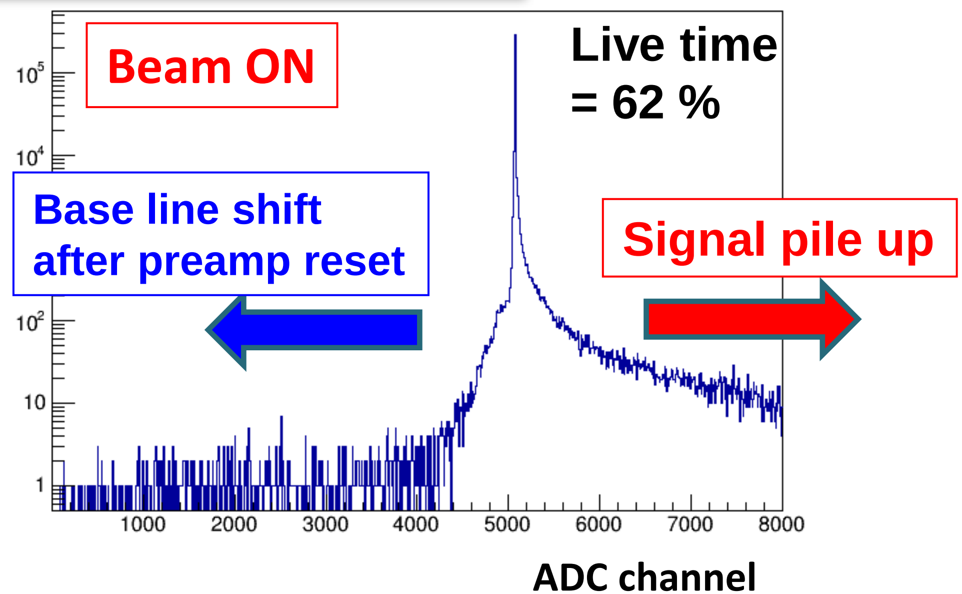
Direct measurement of live time



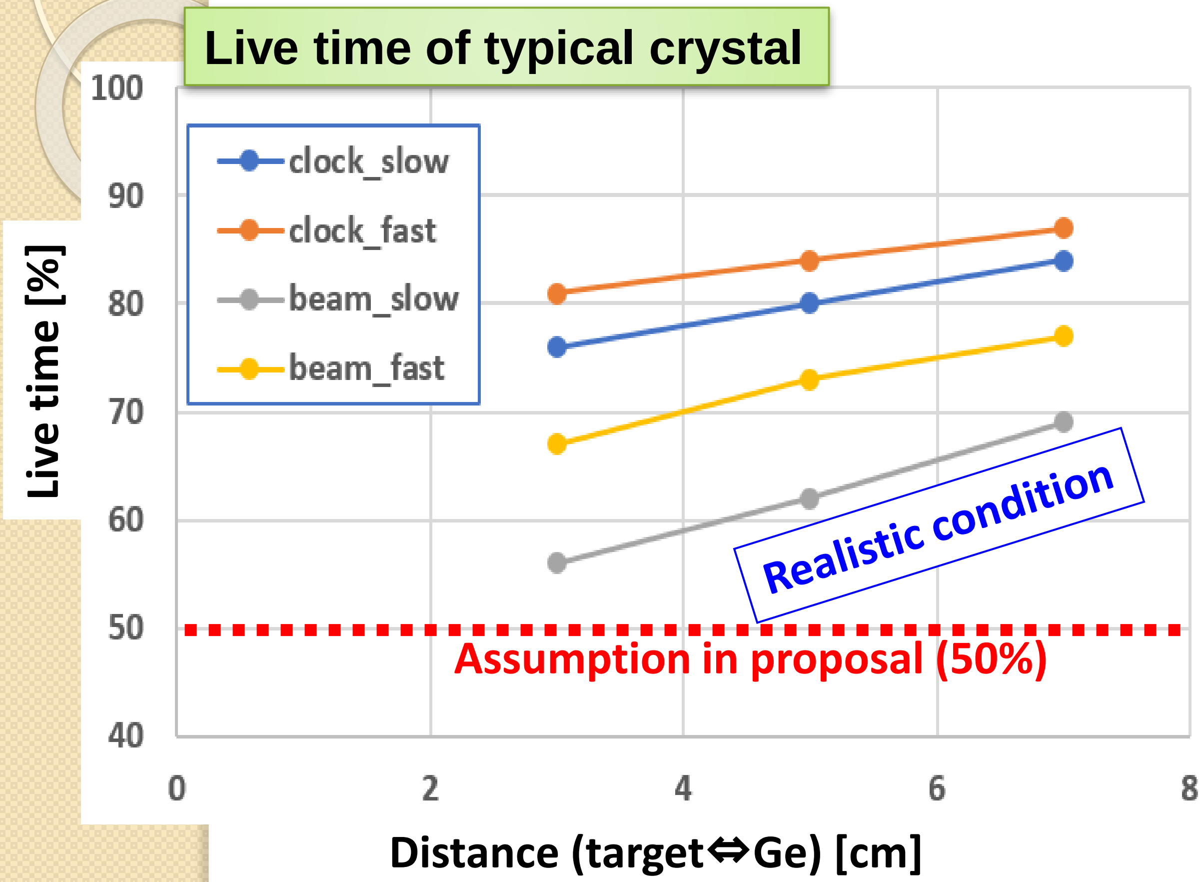
$$\text{Live time} = \frac{\text{\# of peak counts in ADC}}{\text{\# of trig.}}$$

Energy spectrum w/ dummy input trig. (typical condition)

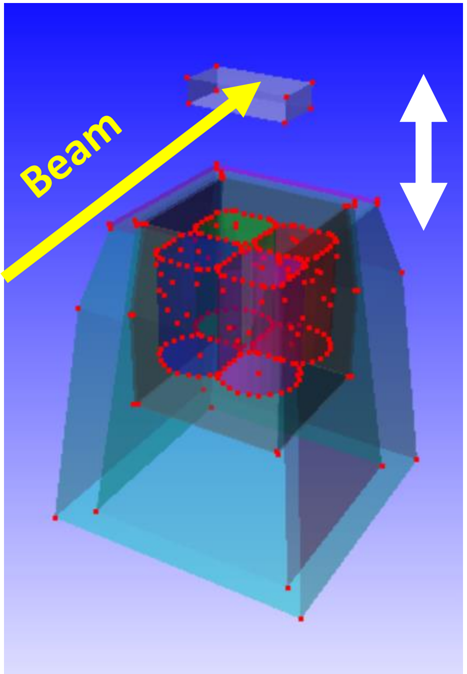




Measured live time



Beam condition :
K$^-$ beam [1.8GeV/c]
π+K= ~500k/spill

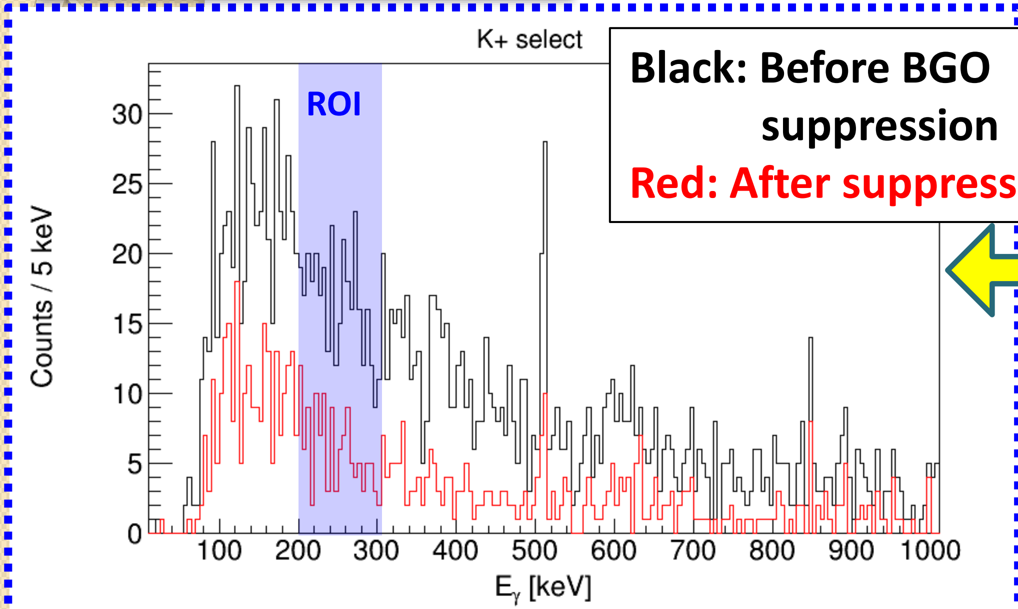


Yield ∝ Photo-peak eff * Live time * analysis eff

Optimum condition:
~6cm distance + 500k/spill(2s) beam intensity

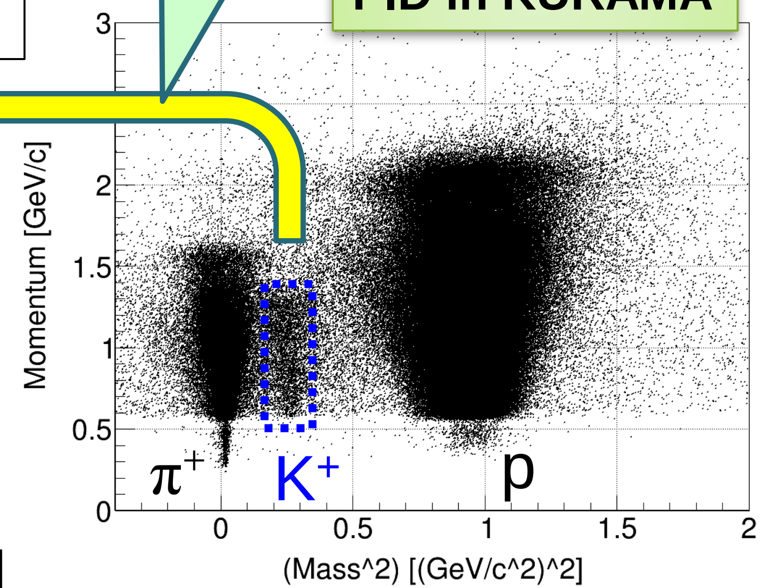
B.G. level measurement

Ge energy spectrum



Select Ξ^- production events

PID in KURAMA



Integrated event# (200-300 keV)

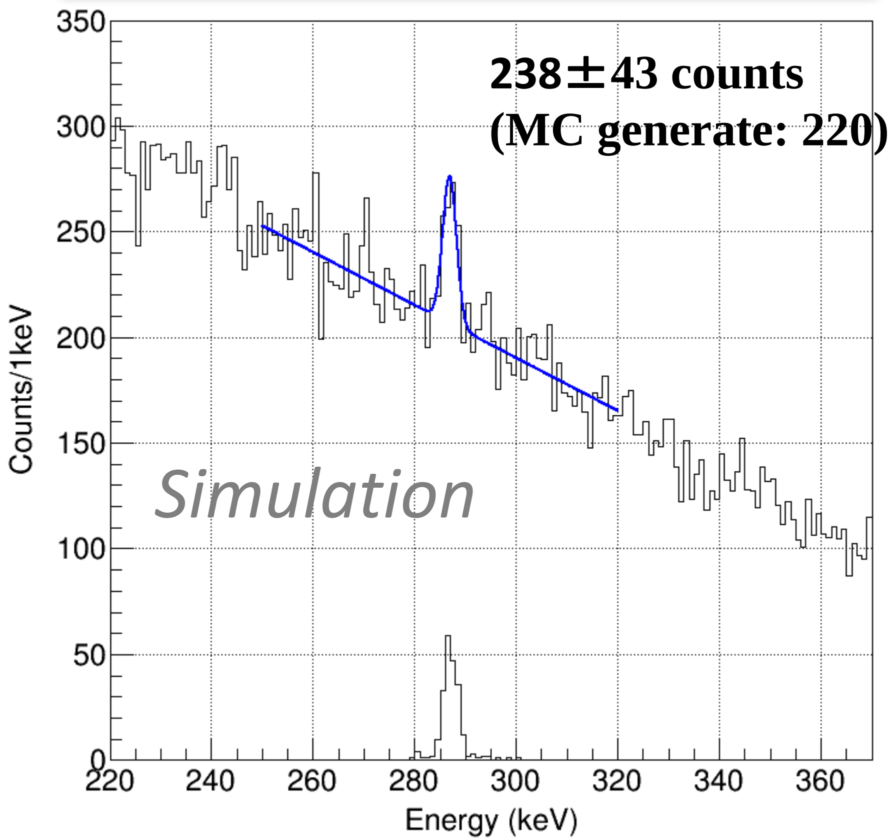
PID	nEvent Ξ^- production	nEvent in Ge spectrum	
		Before	After
K^+	4744	335 (7.1%)	123 (2.6%)

B.G. level [/ Ξ^- production]: 90% of our assumption

Not serious

Expected spectrum for E03-1st phase

Expected X-ray energy spectrum for (6→5) transition [width=1 keV]



We estimated yield & B.G. level using result of the pilot run

(7→6) transition will be seen

- * Weak absorption [width~=0]
- * Higher X-ray yield
  [×3 yield of (6→5) transition]

No physics output, but first measurement of Xi-atom X-ray

(6→5) transition will be seen

if width ~= 1 keV

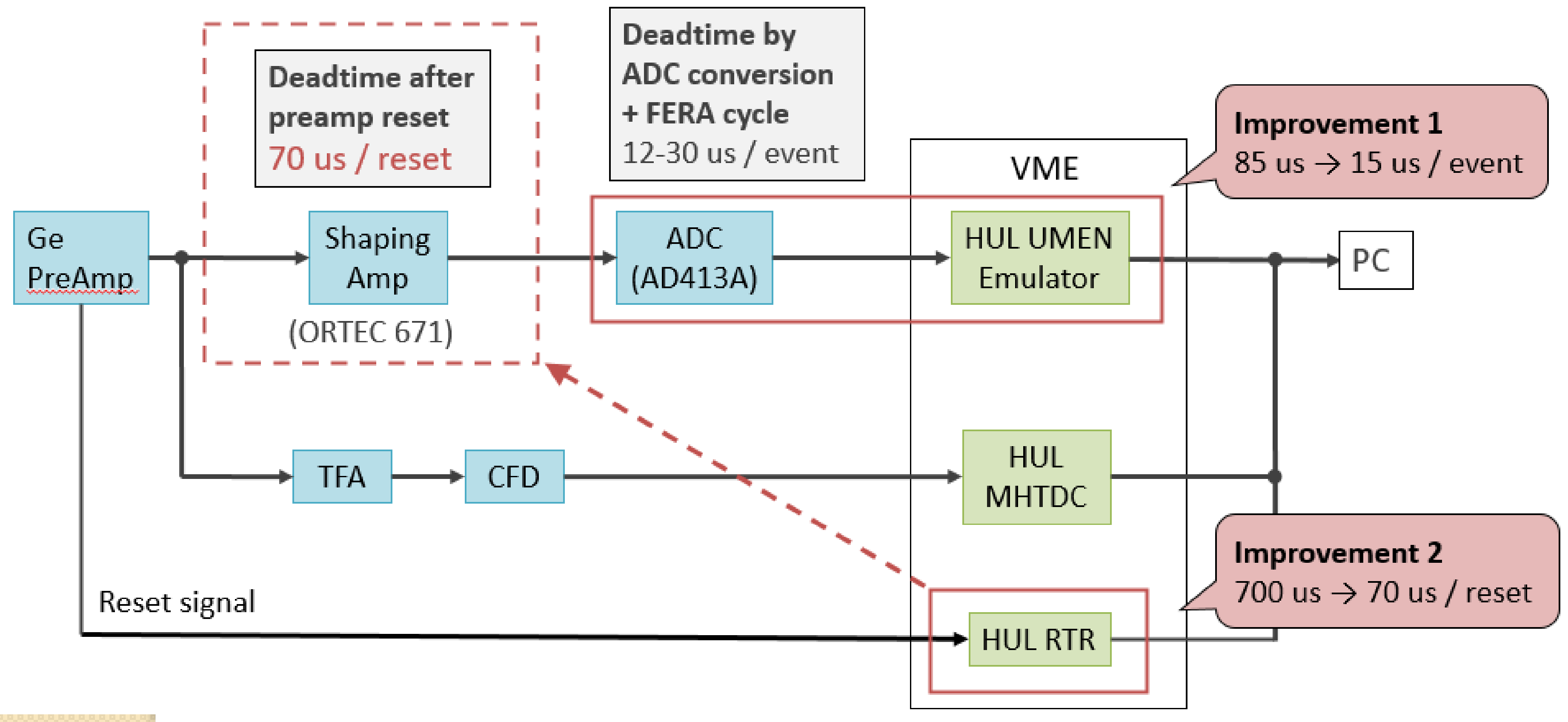
Physics outputs

- Chance for finite shift & width
  error in shift : 0.3 keV
- Yield for absorption strength

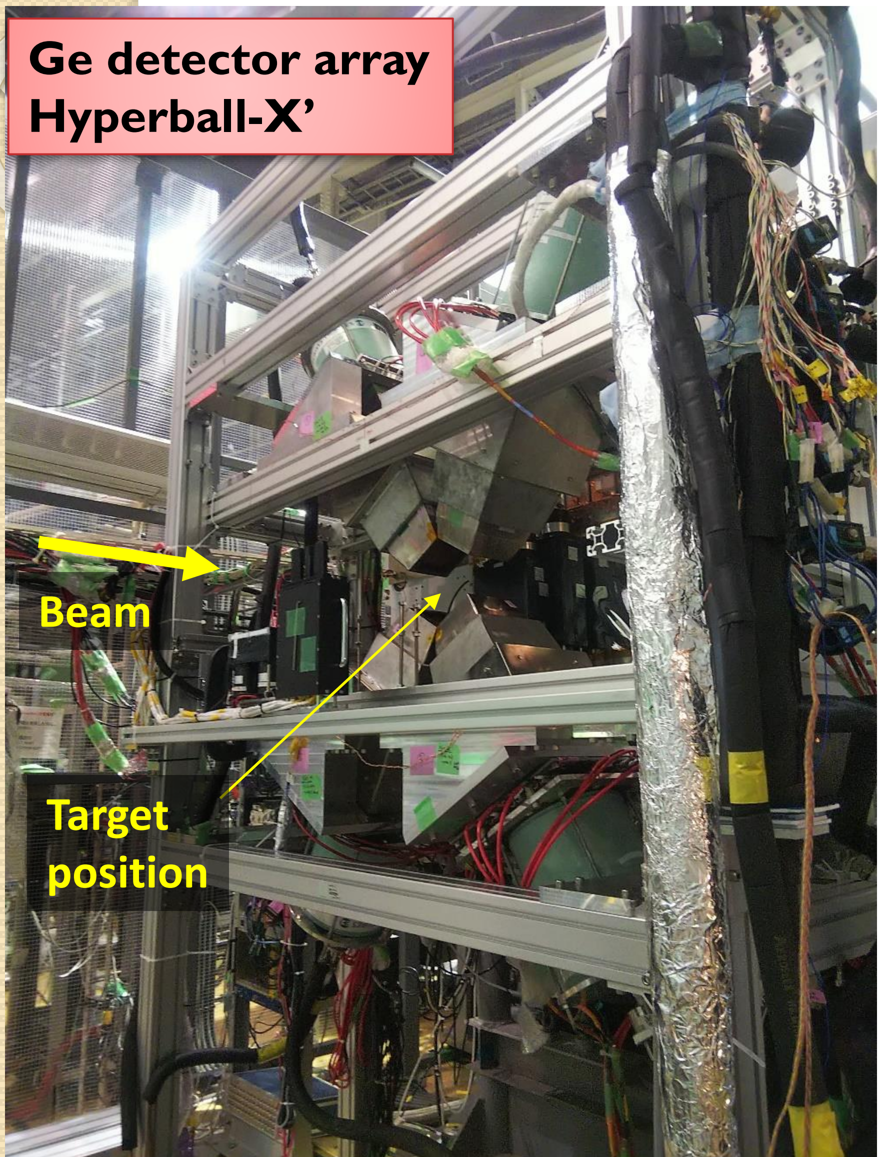
Update of Ge detector readout

Readout system was updated by introducing universal logic module using FPGA

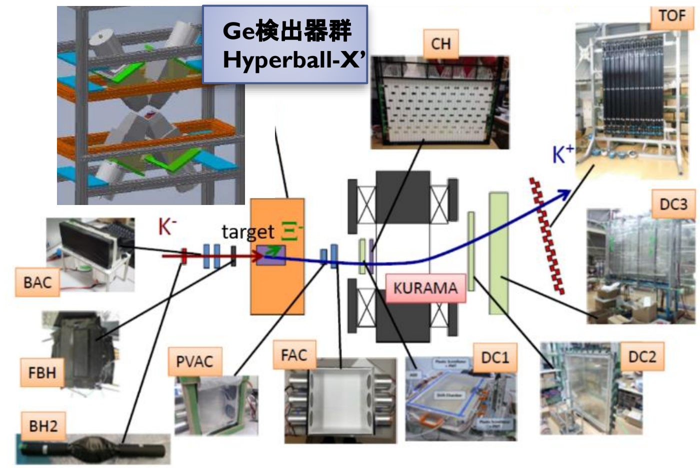
- **Memory module for CAMAC FERA system**
  - **-> DAQ eff ~= 90% with 5kHz trig. rate**
- **Module to record "preamp. reset time interval"**
  - **-> Shorter deadtime [700us -> 70us] by correcting baseline shift after reset**



Detector preparation



E03 setup @ K1.8



Magnetic spectrometer (for tagging Ξ⁻ production)

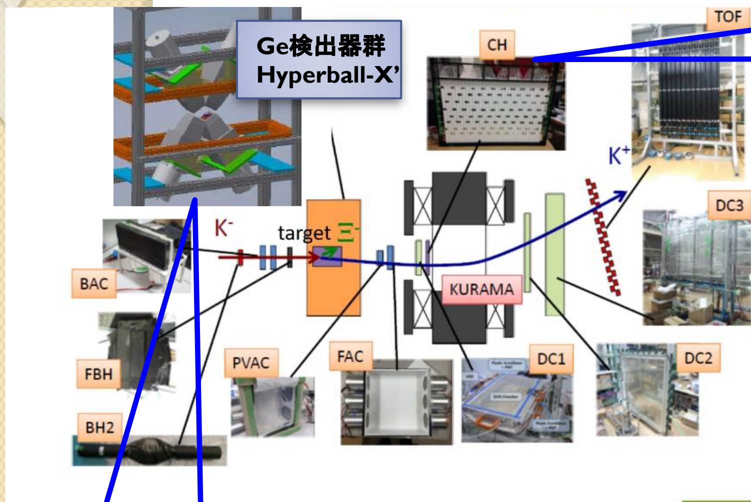
KURAMA spectrometer
- modified from previous E40
- common with next E42

Ge detector array (for detecting X rays)

Hyperball-X' **(modified from E07)**
- Clover-type Ge detector x4
- BGO Compton suppressor x4

Detector performance in E03

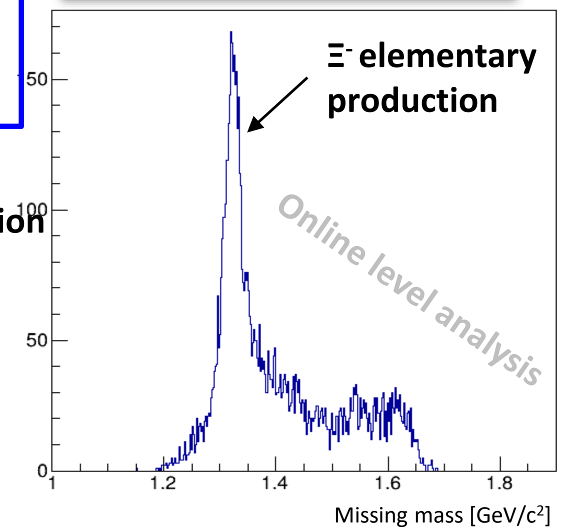
E03 setup @ K1.8



KURAMA spectrometer
(tag Ξ⁻ production)

- K-,K+ PID
- Momentum reconstruction
- Reaction vertex
- Production yield

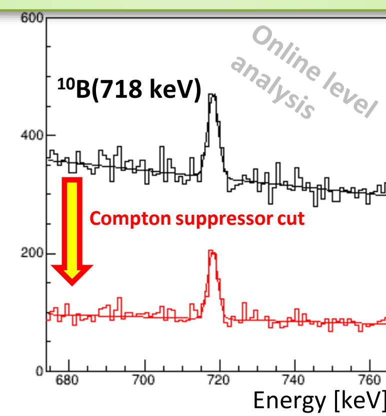
Missing mass spectrum (CH$_2$ target)



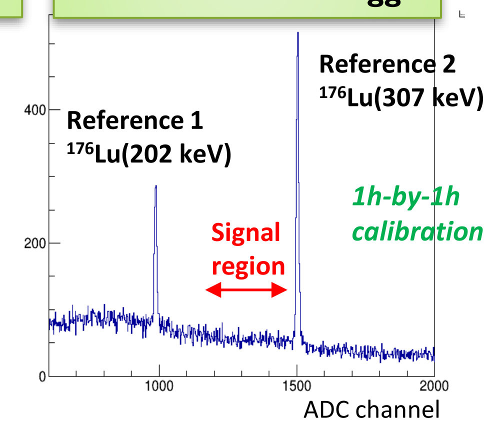
Ge array Hyperball-X'
(detect X rays)

- In-beam energy resolution
  ~2.3 keV [FWHM] for 307 keV
- Efficiency[geometrical, throughput]
- CH$_2$ target（^{10}B） gamma-ray
  Reaction-Ge coincidence measurement
  also, Iron target gamma ray (847 keV) was detected
- Compton suppressor performance
- Enough statistics for In-beam calibration

Reaction-γ coincidence spectrum (CH$_2$ target)



Calibration spectrum w/ in-beam calib. trigge



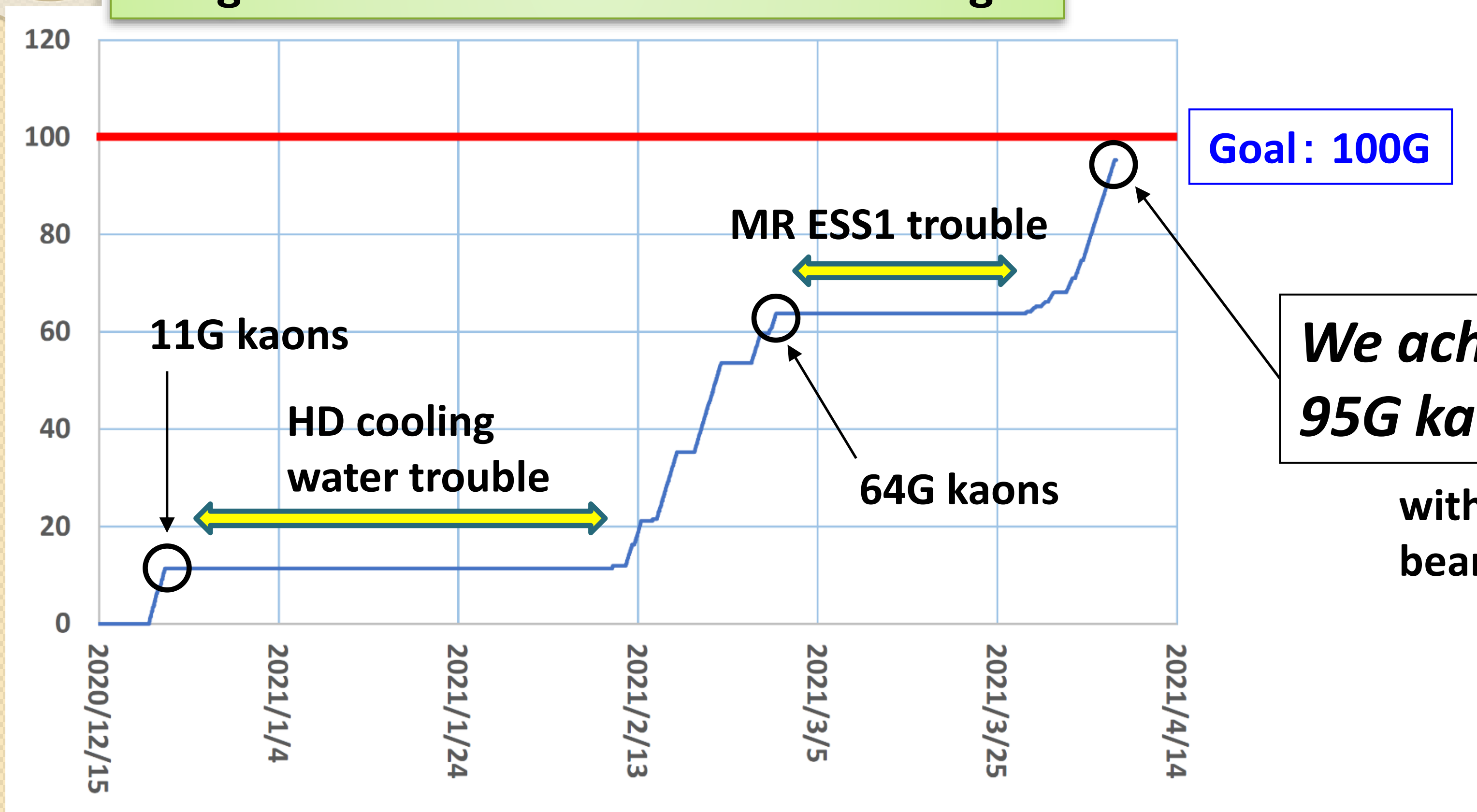
Our detector system worked well

E03 data taking summary

Beam intensity
K-: 410k/spill
π-: 90k/spill
* spill cycle = 5.2s,
spill length = 2.0s

We just finished 1st phase data taking in 2021/4

Integrated # of Kaon beams at Iron target



We achieved 95G kaons!

with ~20 days beamtime

We got almost full statistics for 1st phase data taking

Data taking of E03-1st (2020/12-2021/4) was just finished

We just started data analysis.

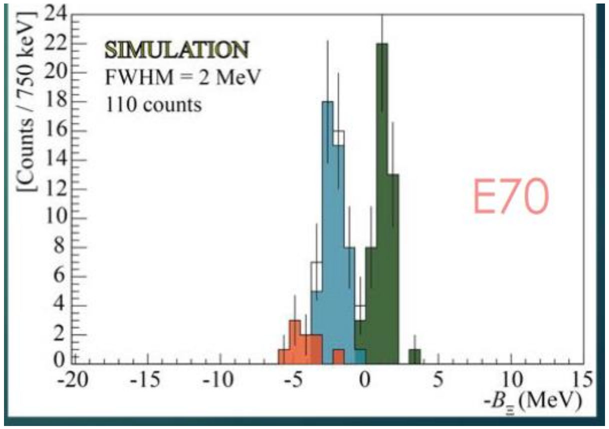
- **Event selection**
- **Calibration**
- **B.G. suppression**

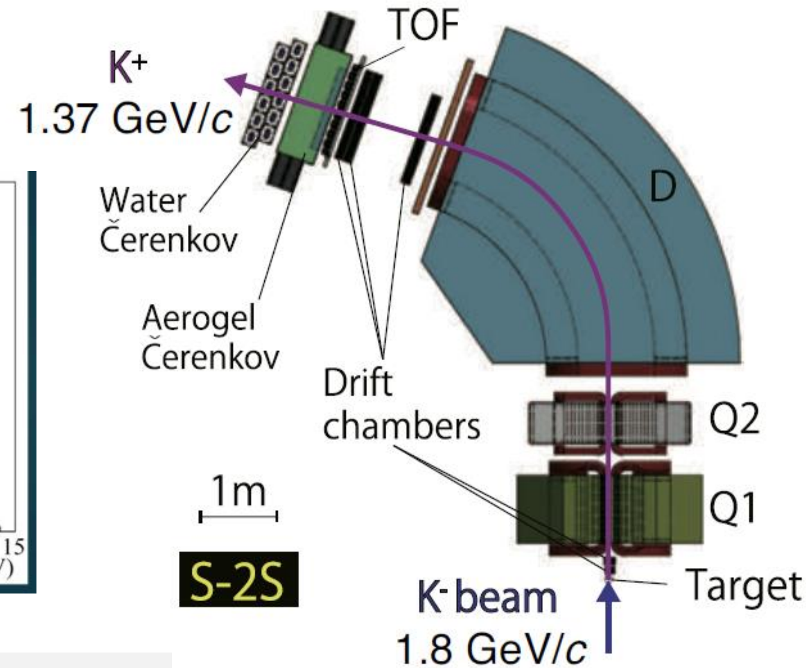
We will report result in near future

Future measurement with S-2S

High resolution Ξ⁻ hypernuclear spectroscopy with the same reaction.

T. Nagae, J-PARC PAC (2019)





Systematic measurement will be performed:

Target = ^{12}C (E70), ^{7}Li (E75), etc. in future?

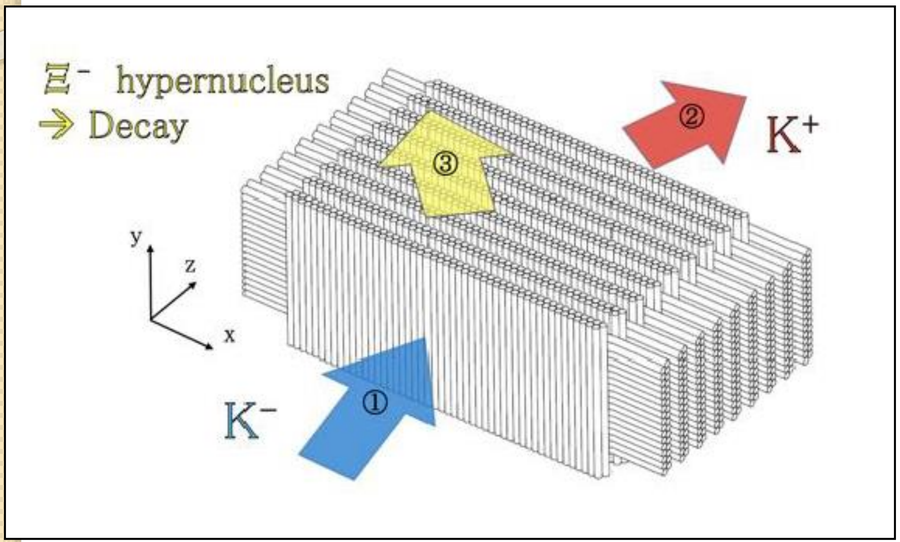
Byproduct

Chance for X-ray measurement in parallel

	S-2S
Magnet Configuration	QQD
Acceptance [msr]	55
Magnetic field [T]	1.5
Resolution [FWHM]	5.5×10^{-4}
Bending angle [deg]	70

Active fiber target [E70]

First target for S-2S experiment: ^{12}C
(E70 physics run in 2022-2023)

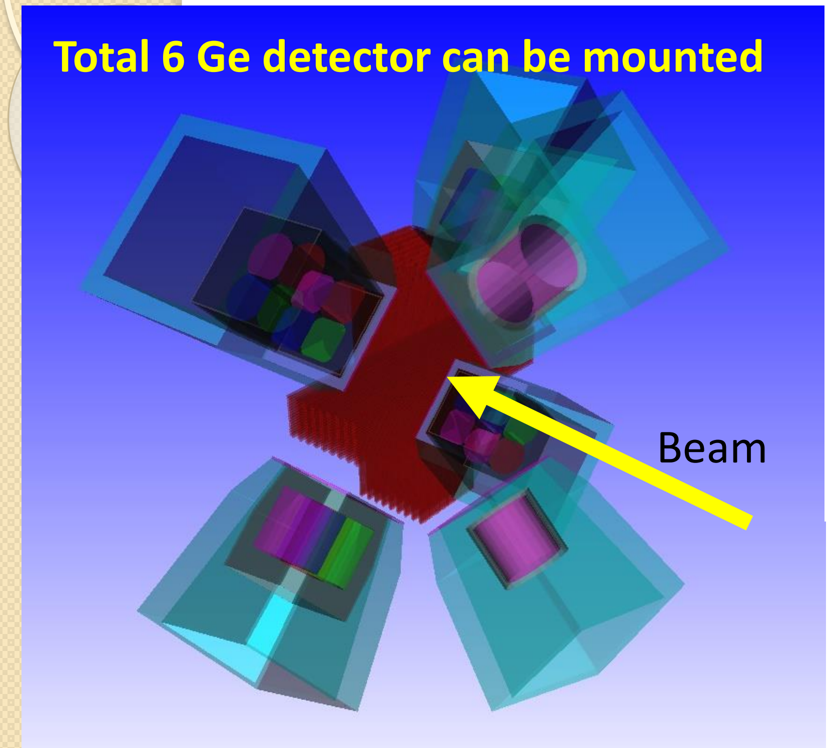


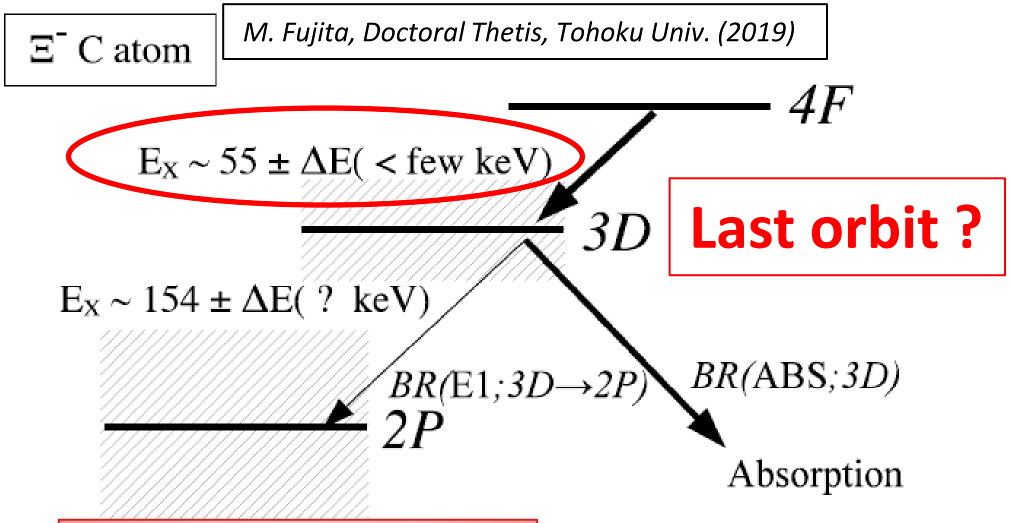
Active fiber target for energy loss correction

Merit for X-ray measurement

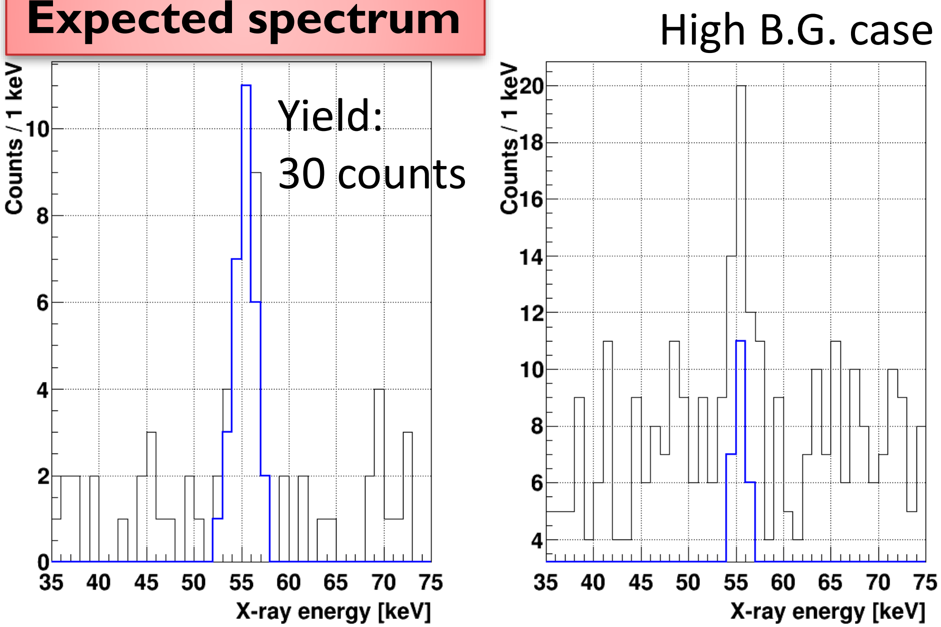
Feature of the X-ray measurement:
- S/N ratio ○ [we can tag Ξ^- stop]
- Yield rate ×
  - Very low stop probability (low density)
  - Smaller acceptance of S-2S

Second try for C-atom measurement





Expected spectrum

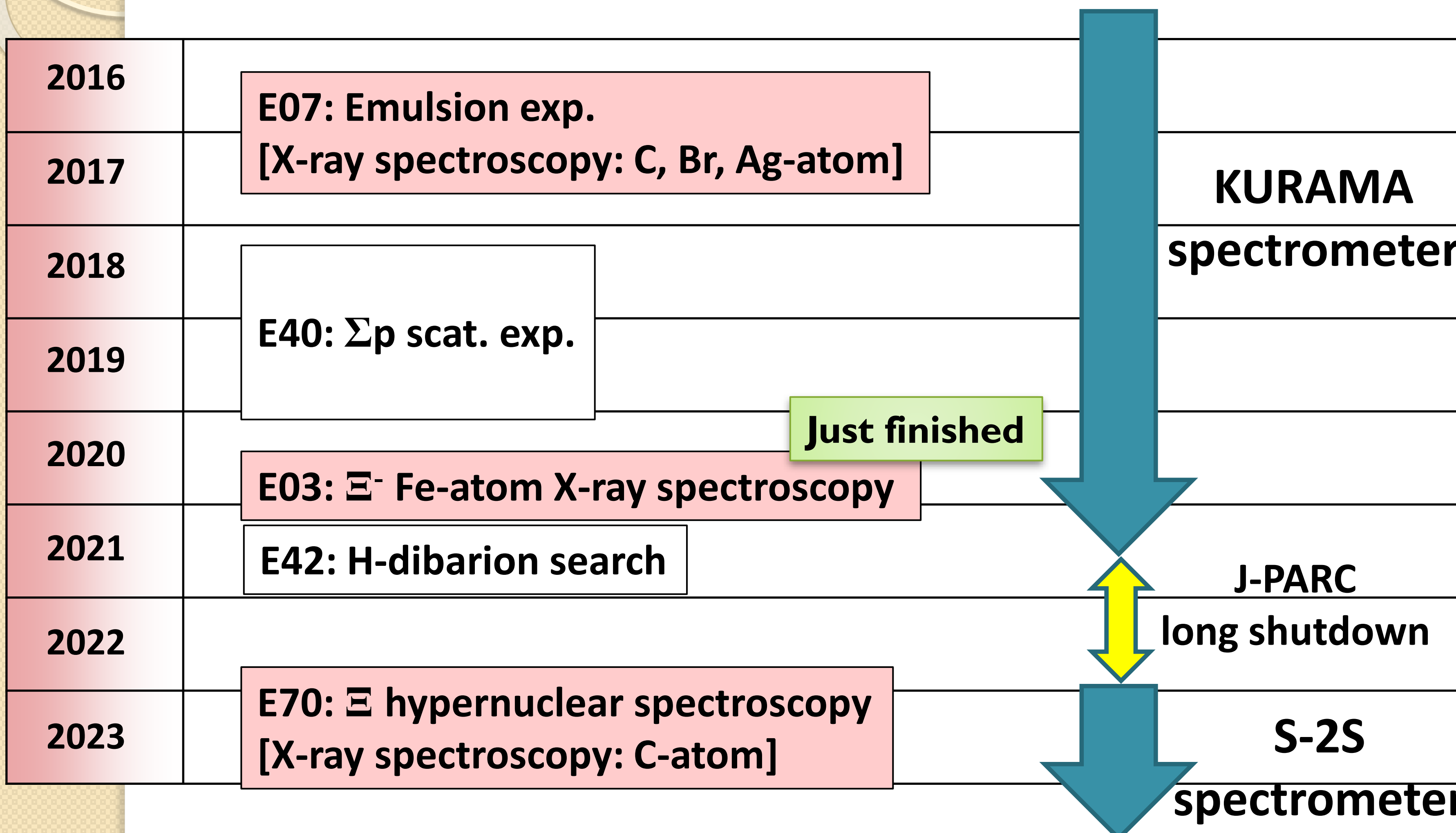


Assumption for yield estimation:

- 30% X-ray yield / Ξstop
  [lower than QCD based calc. (~40%)]
- ~1 month beamtime for E70

We have chance to observe X ray

X-ray spectroscopy of Xi-atom at J-PARC K1.8 beam line



Summary

We are aiming for
world first measurement of X ray from Ξ^--atom

→ Information on the ΞA optical potential

- Test of Experimental technique in J-PARC E07
  [X-ray spectroscopy: C, Br, Ag-atom]
- E03 (Ξ^- Fe-atom measurement)
  2 phase strategy for current ACC condition
  - Pilot run for E03 1st-phase [2017-2018]
  - 1st-phase data taking [2020-2021] Just finished
- Future measurement in S-2S exp. (J-PARC E70)
  [X-ray spectroscopy: C-atom]