Muon Science
from fundamental to application

Koichiro Shimomura KEK-IMSS,J-PARC/MLF

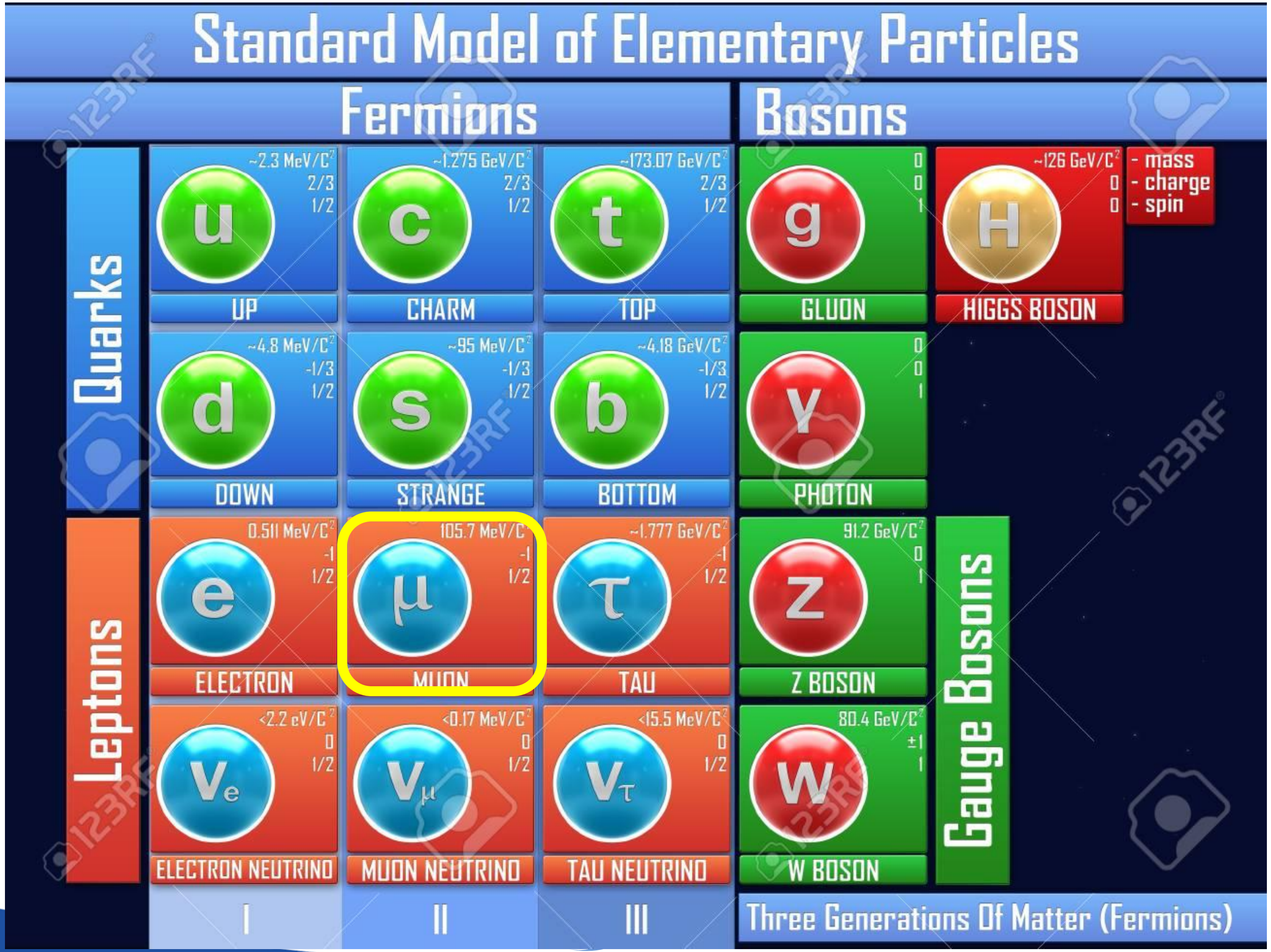
Insight through Accelerators.

KEK

Contents

- What is muon ?
- Muon spin spectroscopy (μSR)
- Non-destructive element analysis by negative muonic X ray
- Transmission muon microscope

What is muon ?　Today's understanding



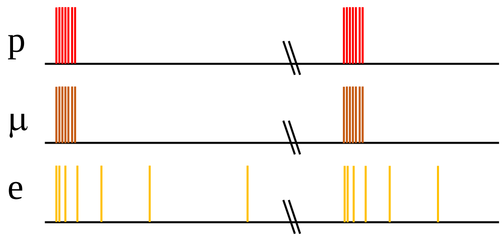
What is muon ?　Today's understanding

- Mass　1/9 of proton　200 of electron
- Positive muon ~ light proton
- Negative muon ~ heavy electron
- Spin 1/2
- 2nd generation of charged lepton
- Electro-Weak Interaction　○
- Strong Interaction　×
- Spin polarized in birth
- Relatively long life time (2.2μs) parity non conserving decay
- High transmission capability (useful for imaging)

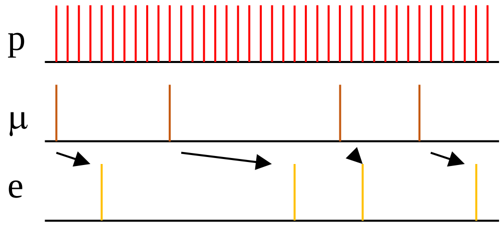
⇒These unique feature enable us to produce various applications

Meson factory

- Meson Factory
  - **Pulse beam facility (J-PARC, RAL)**
    - Accelerator: **Synchrotron**
    - Merit: High power beam
      - Pulse synchronized exp.
      - Long time measurement

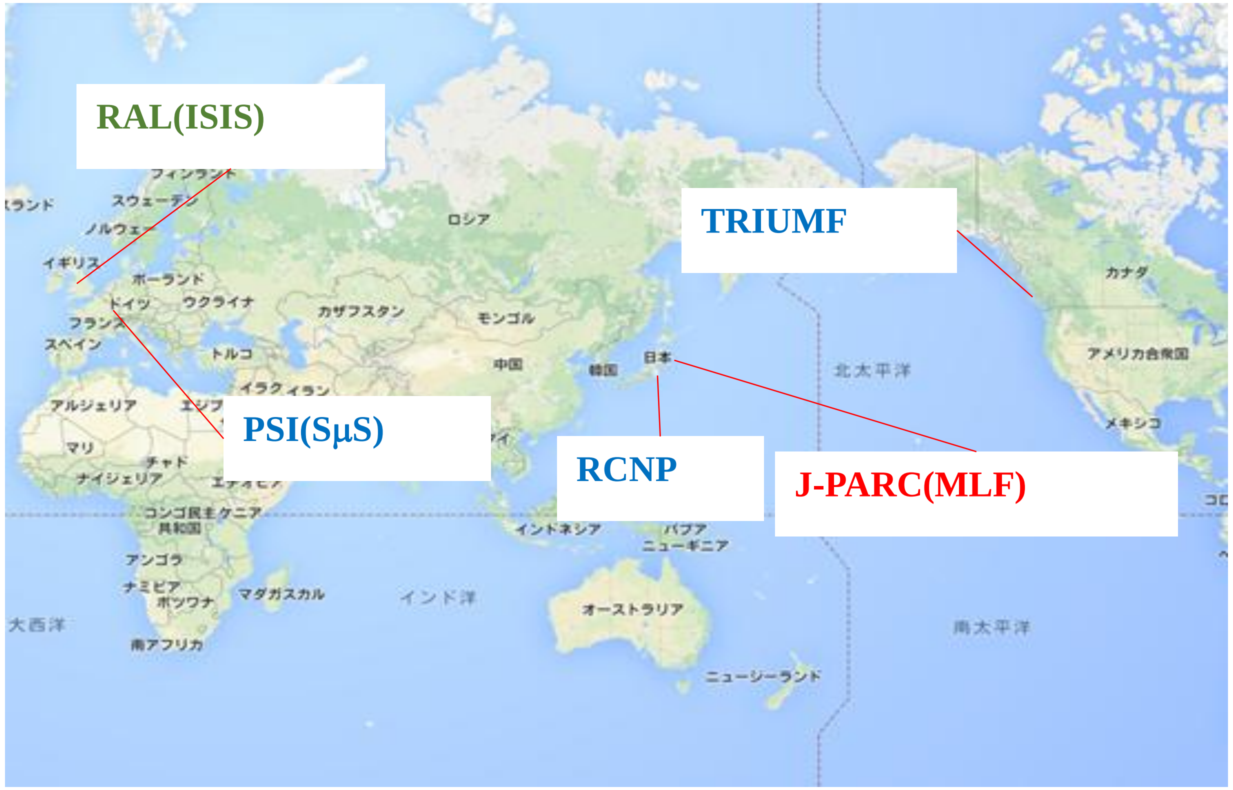


  - **DC beam facility (TRIUMF, PSI)**
    - Accelerator: **Cyclotron**
    - Merit: High time resolution
      - Event by event data taking
      - Low background

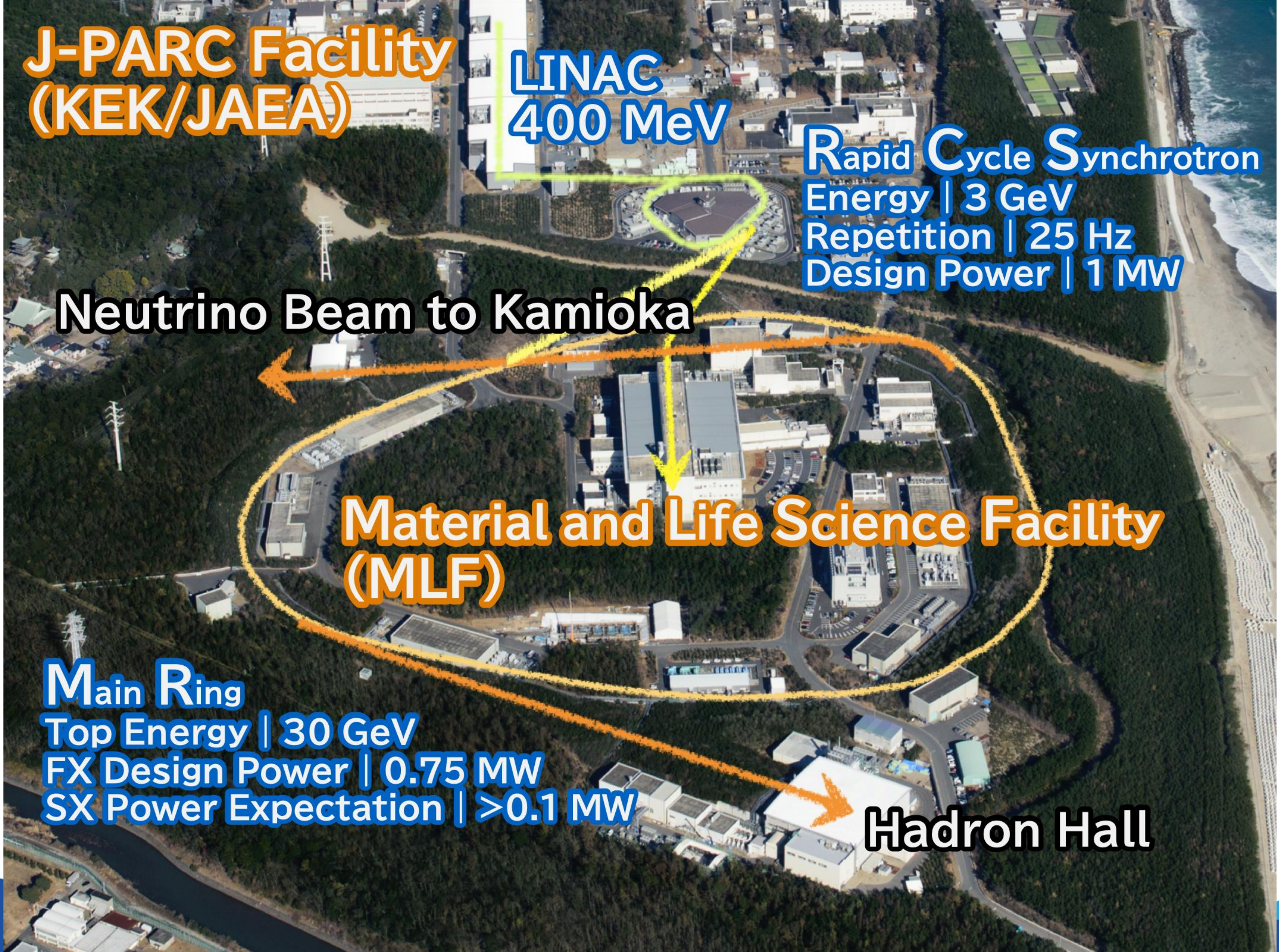


Meson factory

- Meson Factory
  - Pulse
    - **J-PARC(MLF)：Japan**
    - RAL(ISIS)：United Kingdom
  - DC
    - PSI(SμS)：Switzerland
    - TRIUMF：Canada
    - RCNP：Japan



Facility	Type	Power	Proton beam energy	Proton beam current	Frequency	Pulse width
J-PARC	**Pulse**	**1.0 MW**	**3 GeV**	**333 μA**	**25 Hz**	**100 ns**
RAL	Pulse	160 kW	800 MeV	200 μA	50 Hz	100 ns
PSI	DC	1.3 MW	590 MeV	2.2 mA	50 MHz	-
TRIUMF	DC	75 kW	500 MeV	150 μA	23 MHz	-
RCNP	DC	0.4 kW	400 MeV	1 μA	18 MHz	-


J-PARC Facility
(KEK/JAEA)
LINAC
400 MeV
Rapid Cycle Synchrotron
Energy | 3 GeV
Repetition | 25 Hz
Design Power | 1 MW
Neutrino Beam to Kamioka
Material and Life Science Facility
(MLF)
Main Ring
Top Energy | 30 GeV
FX Design Power | 0.75 MW
SX Power Expectation | >0.1 MW
Hadron Hall

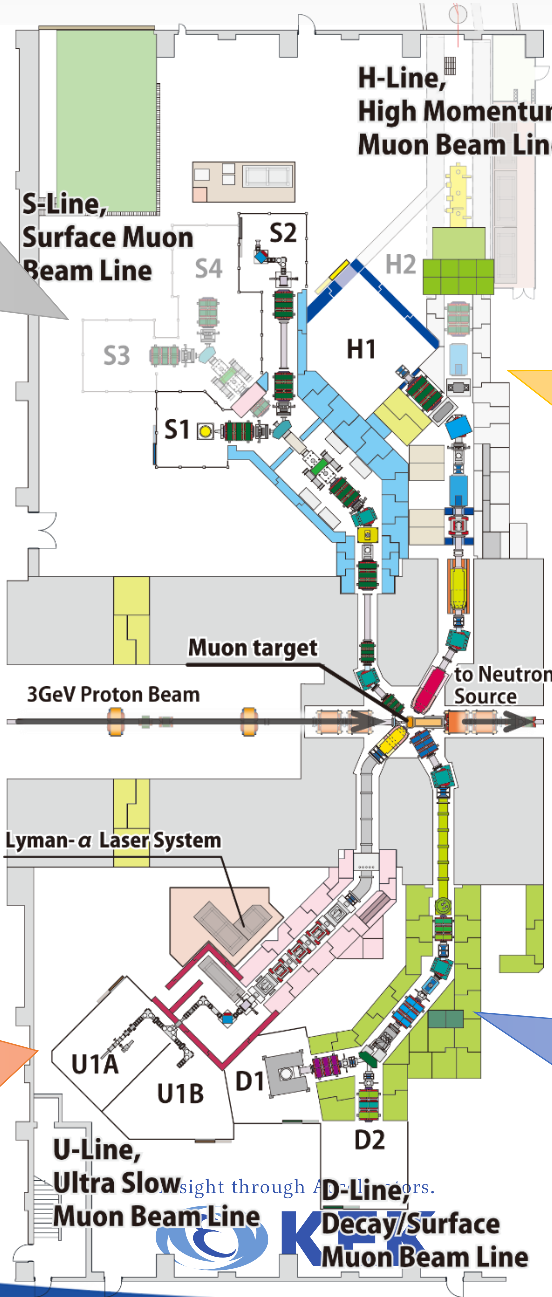
MUSE

S-line μ+

Slow beam（4 MeV), dedicated to bulk μSR ultralow temperature/high magnetic field/ pulsed excitations.

U-line μ+

Ultra slow beam（0.1 ～ 30 keV), near-surface, sub-micron scale condensed matter physics, chemistry, etc.



H-line μ±

Slow（4 MeV）～fast（50 MeV）beam, for particle physics, atomic physics (“precision frontier”)

D-line μ±

Slow（4 MeV）～ fast（50 MeV）, general-purpose beamline with 2 exp. areas.

Muon spin spectroscopy (μSR)

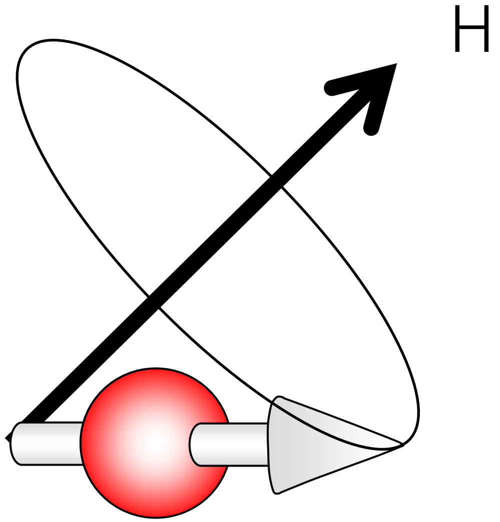
μSR

Parity Violation of muon decay

Muon Spin is easily observed by detecting decay positron.

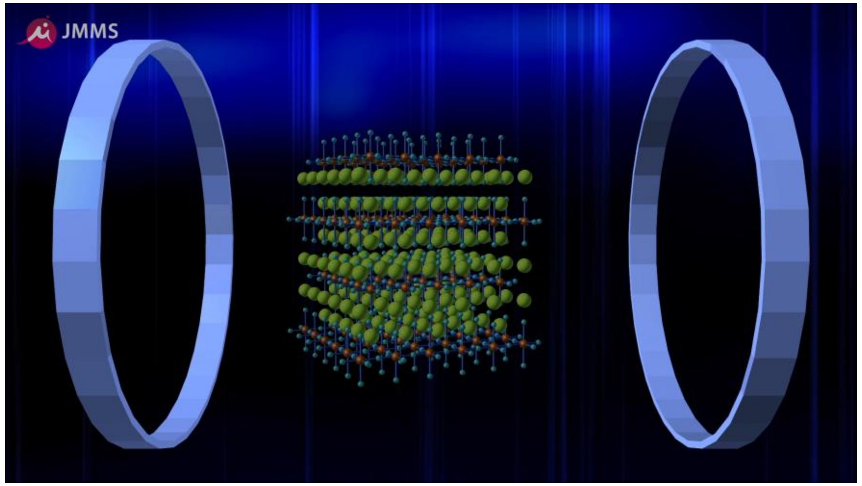
Gyromagnetic ratio

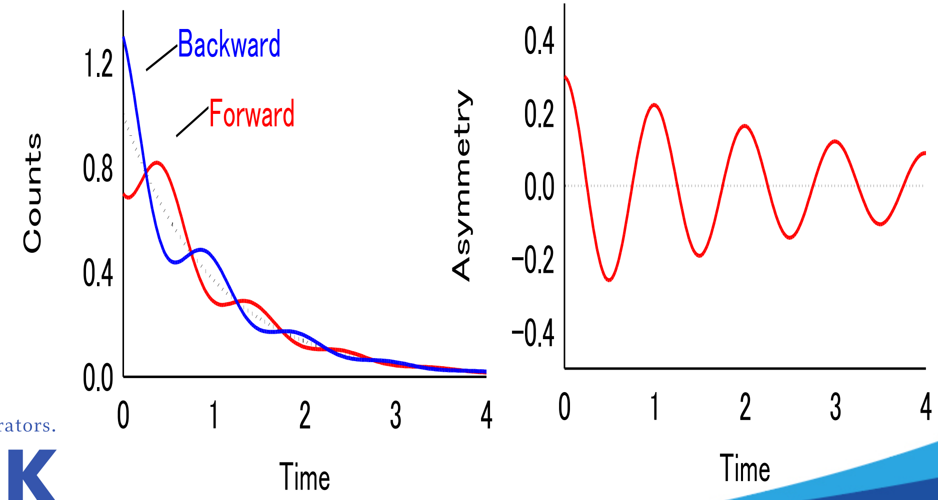
$\gamma_{\mu} = 2\pi \times 13.55$ kHz/G



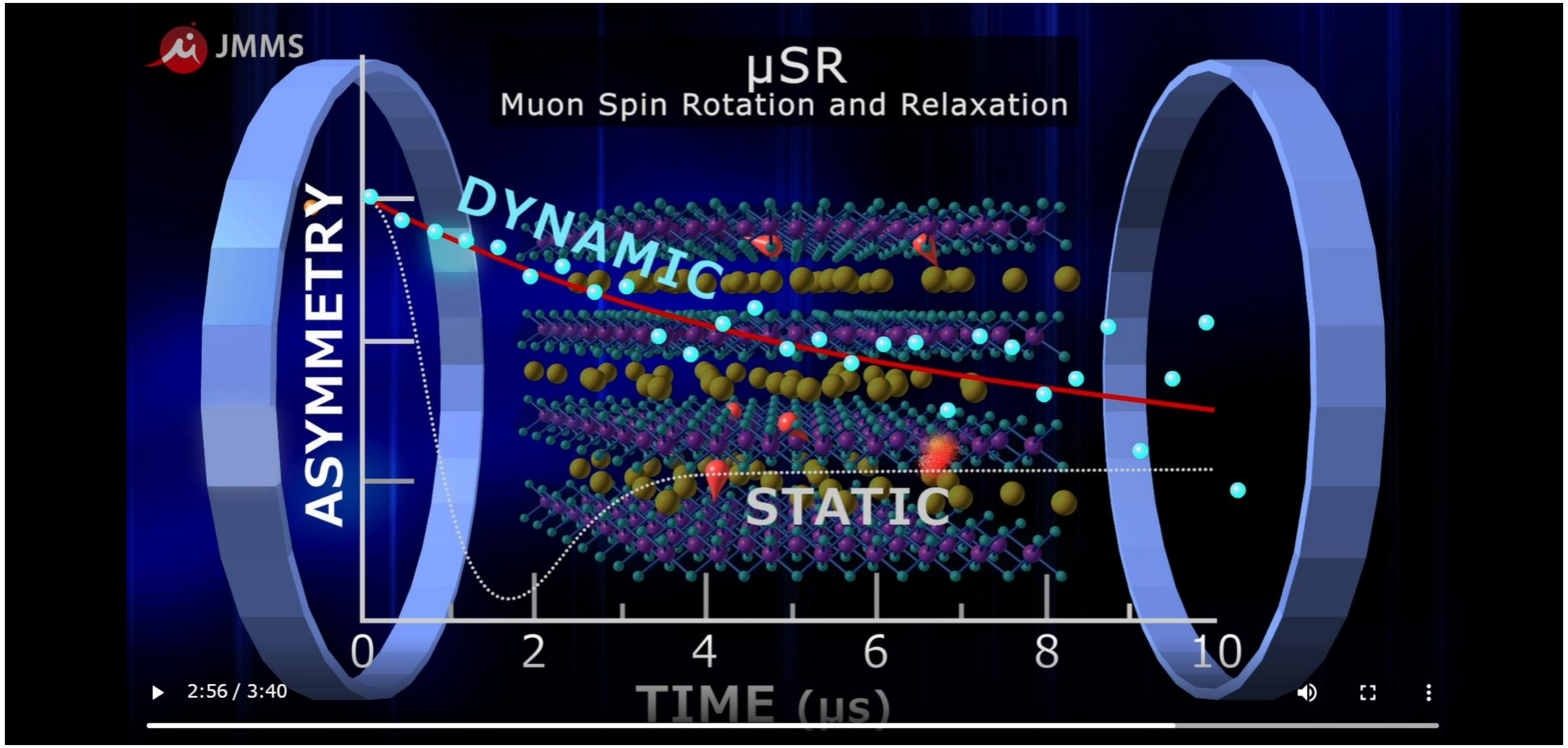
Lamor precession

$(\omega = \gamma_{\mu} H)$





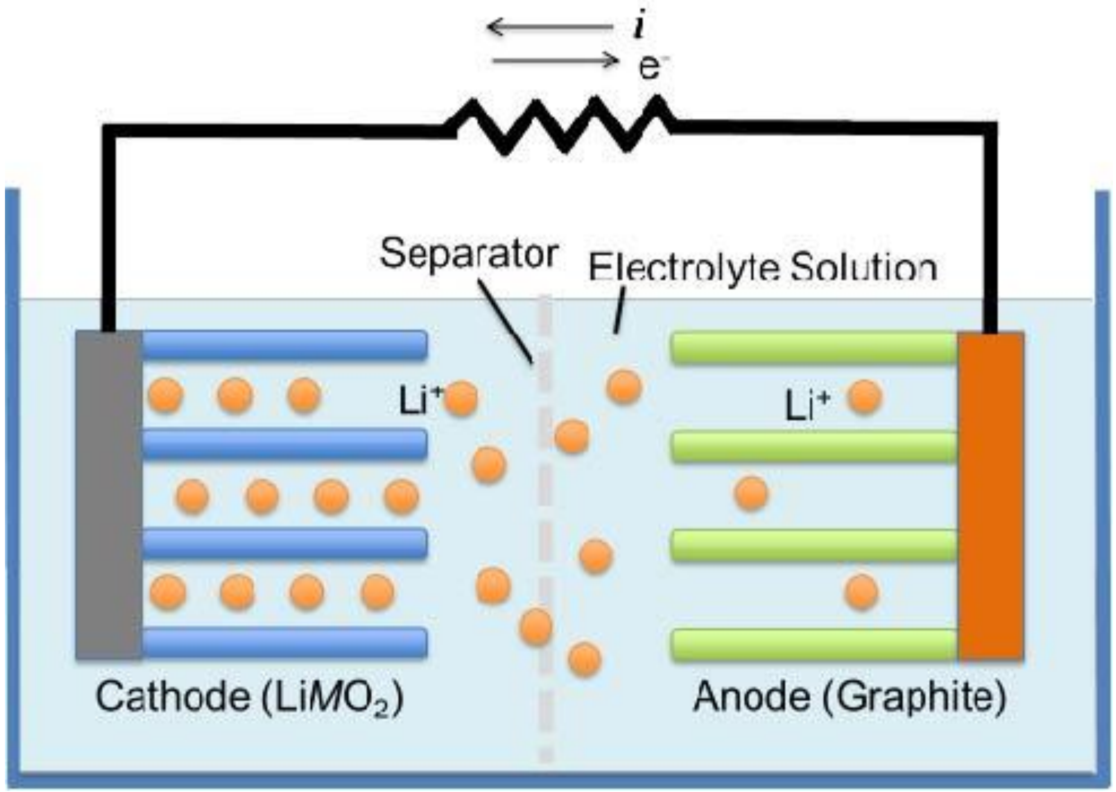
Using Muons, diffusion of Li-ion can be probed



http://jmeson.org/image/musr-video
Japanese Meson and Muon Society HP(JMMS)

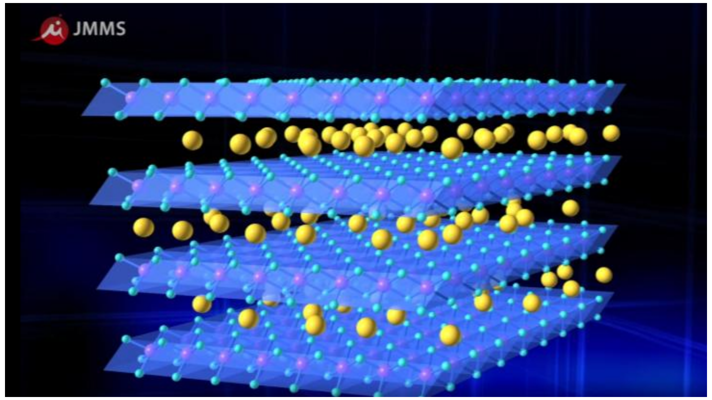
I.Umegaki

Li-ion battery



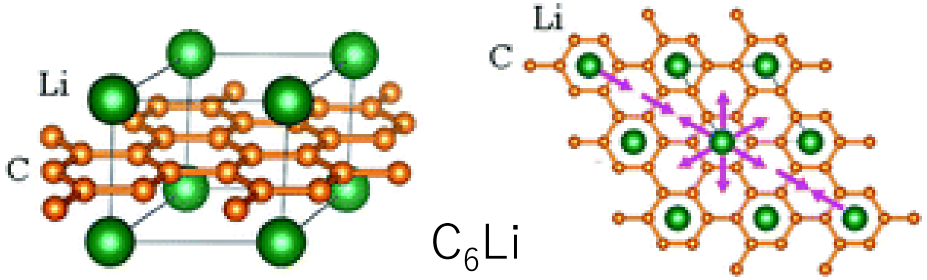
Schematic drawing of a Li-ion battery

Cathode $LiCoO_2 \Leftrightarrow Li^+ + CoO_2 + e^-$



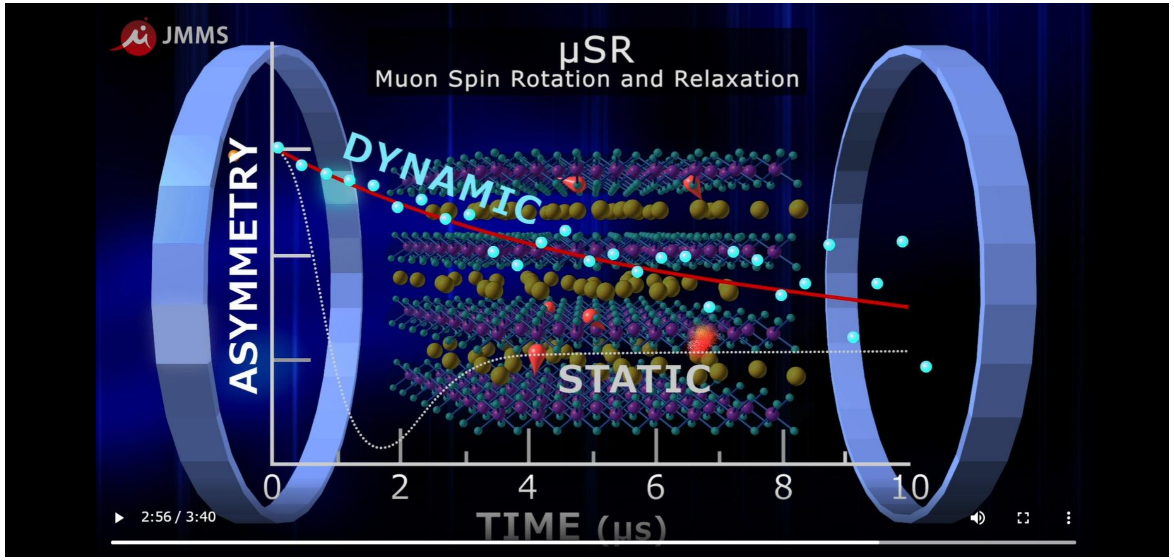
$LiCoO_2$

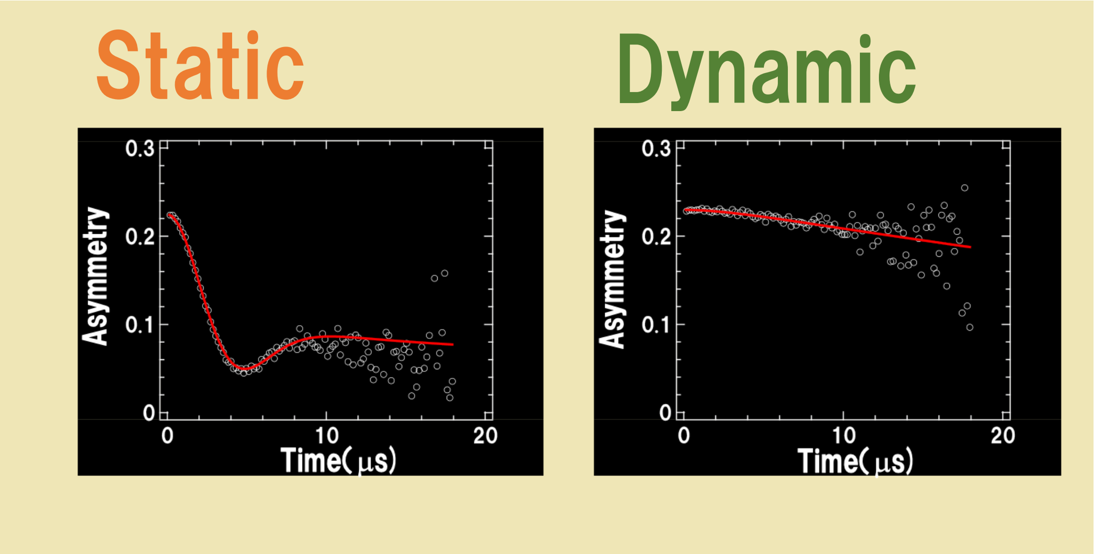
Anode $6C + Li^+ + e^- \Leftrightarrow C_6Li$



C_6Li

Application of muon spin relaxation (μSR)





By μSR method, Li ion diffusion in a Li-ion battery active material can be detected.

JMMS http://jmeson.org/muon-video/

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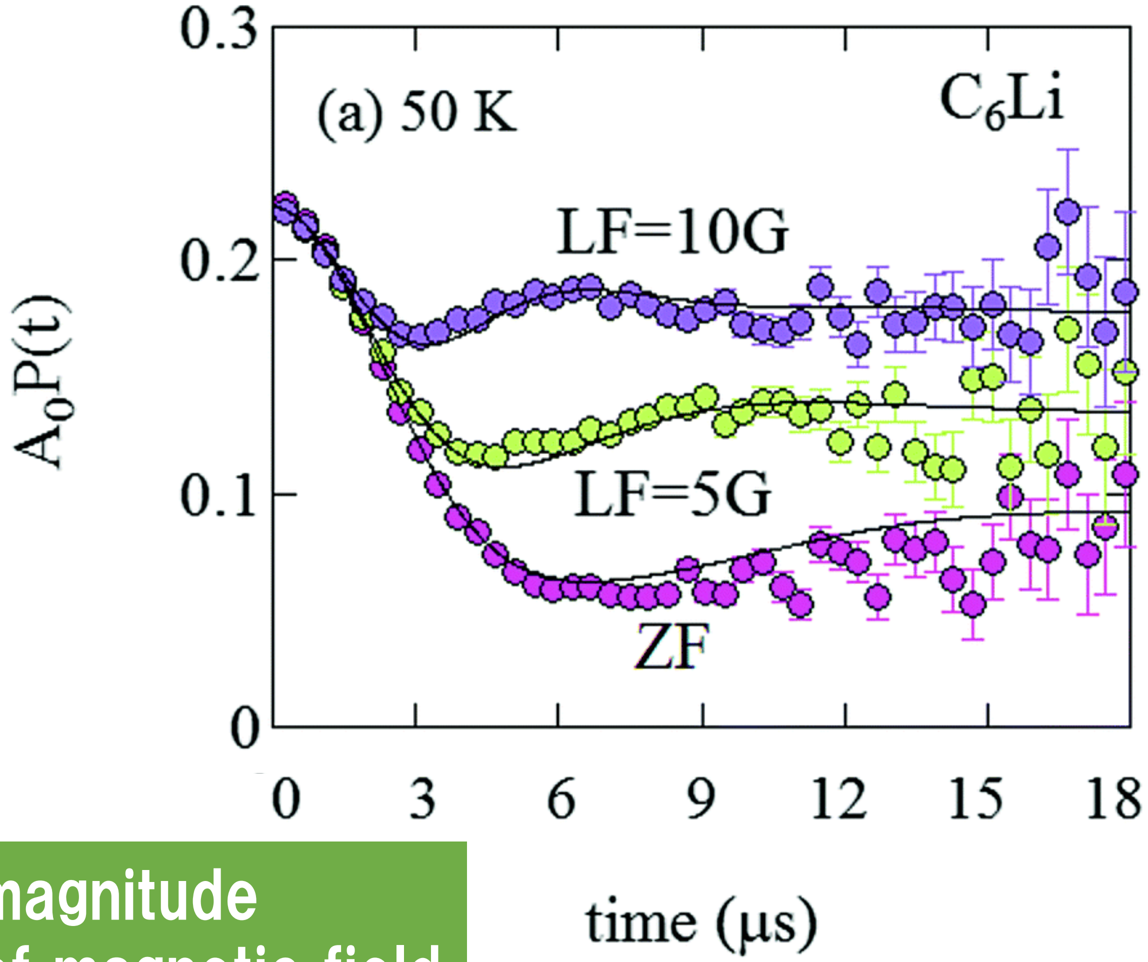
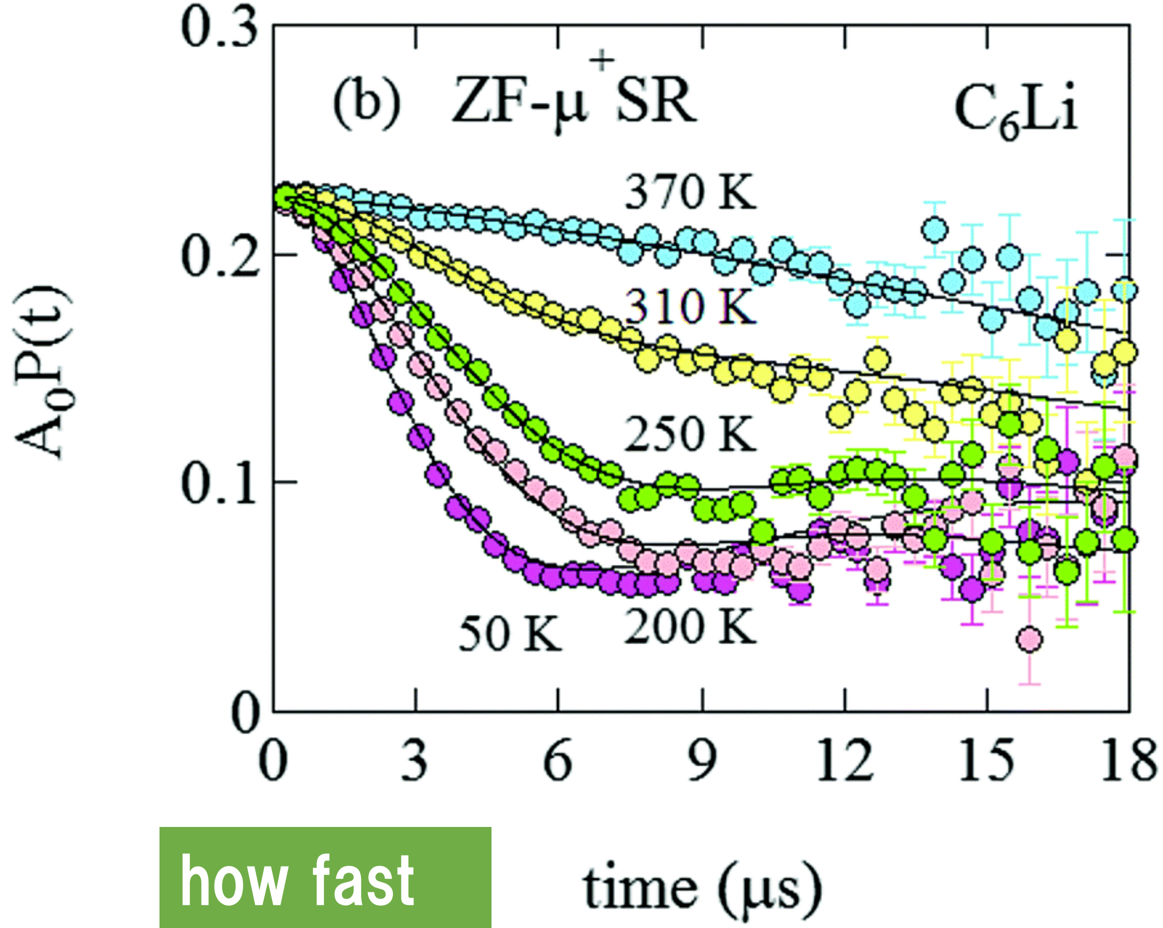
Li ion diffusion in anode observed by μSR



magnitude of magnetic field



how fast Li diffuses

I Umegaki *et al.*, Phys. Chem. Chem. Phys. 19,19058 (2017).

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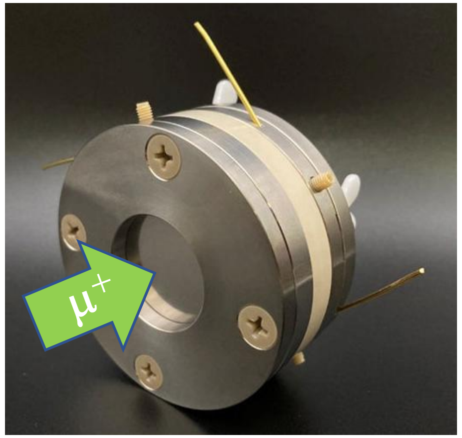
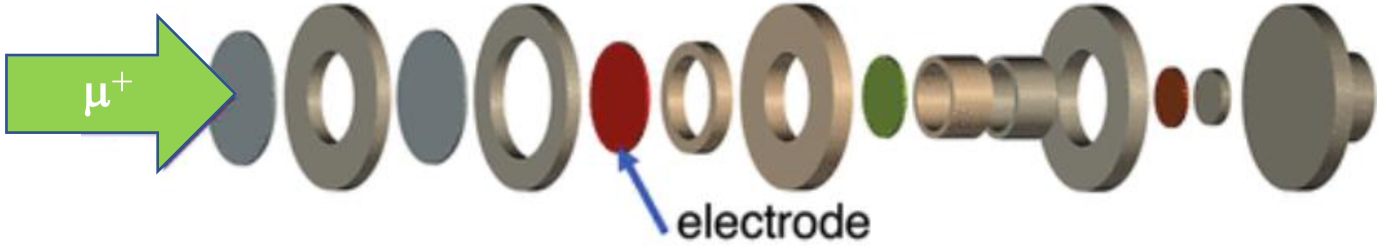
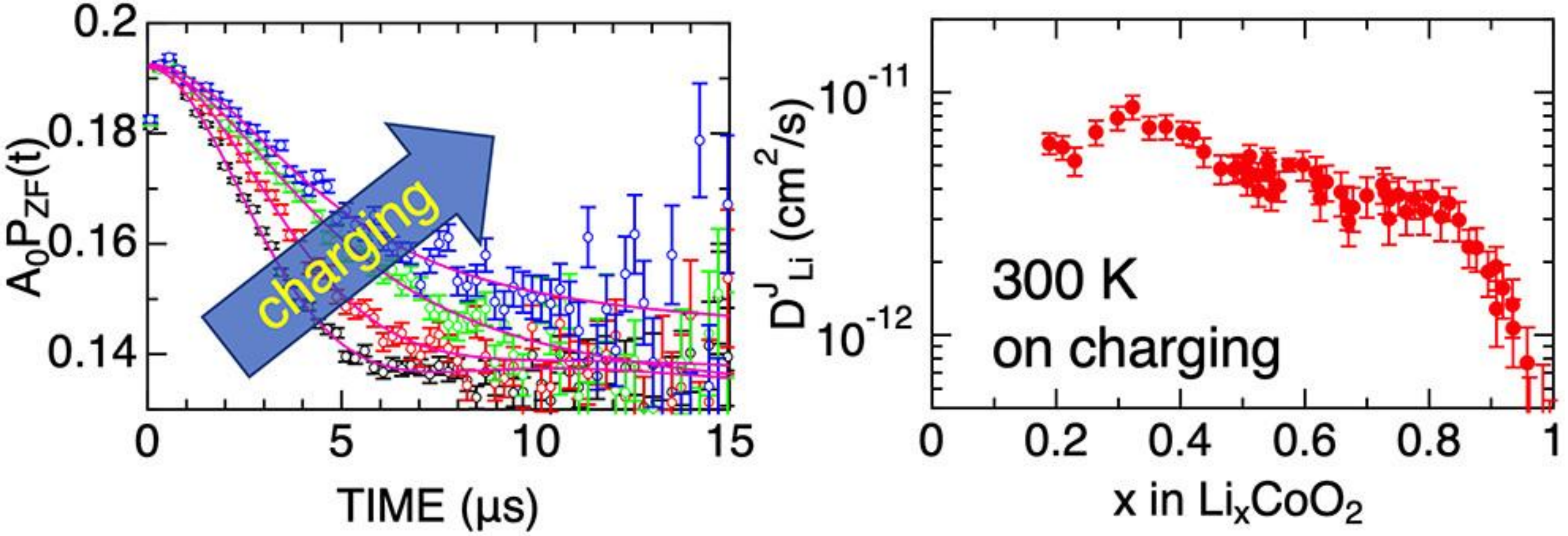
Recent progress of μSR : operando μSR

cell



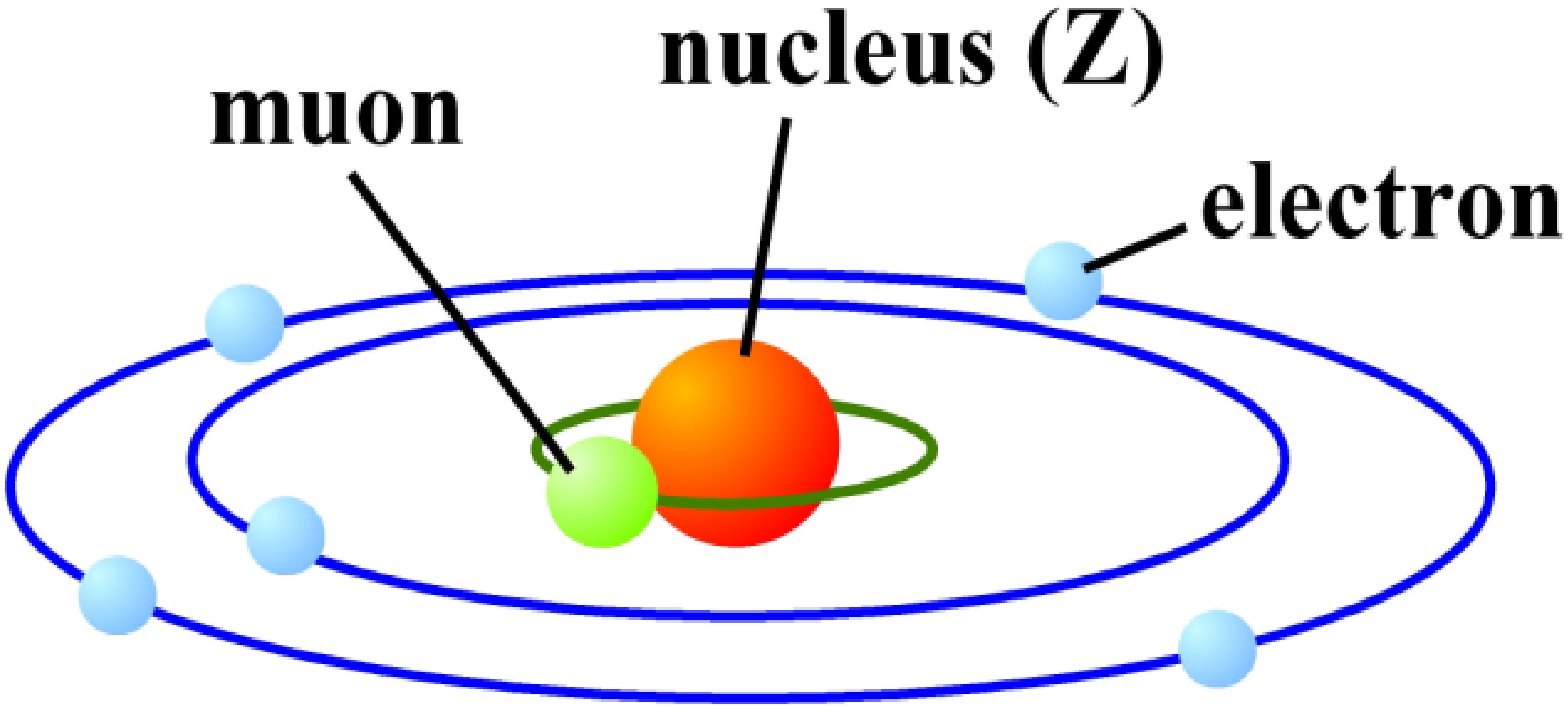




K. Ohishi et al., ACS Appl. Energy Mater. 5, 10, 12538–12544 (2022).

Non-destructive element analysis by negative muonic X ray

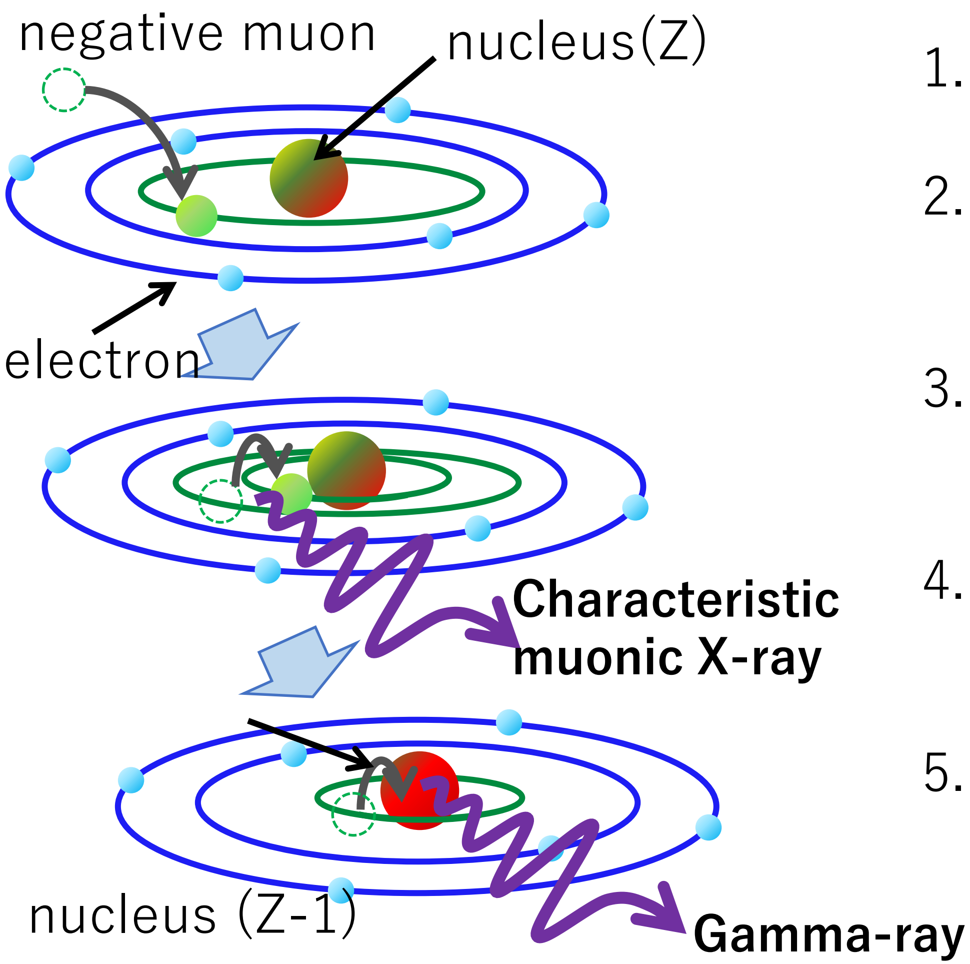
Muonic Atom (negative muon)



m_μ : 200 times m_e

Negative muon and muonic atom

Muonic atom formation and following processes



1. Energetic muon slows down and stops in material
2. Muonic atom formation
   Muon capture in atomic muonic orbital
3. Muon cascading process
   Characteristic muonic X-ray emission
4. Muon in muonic 1s state
   Spends several lifetimes (50-2000 ns)
5. Natural decay or muon capture
   in the nucleus
   Gamma-ray emission

Composition analysis with negative muons

- **Emission of characteristic muonic X-ray with specific energy to the element**
  - Applicable to every element except for hydrogen
    multi-elemental, simultaneous
  - No need of previous knowledge
  - High energy (0.01- 10 MeV) deep inside, light elements
    Observable from outside of sample
    No need of vacuum huge / porous / bio sample
  - No chemical process non-destructive / damage-less
  - Stopping depth control + beam scan
    depth-selective / 3D mapping
  - More than 1 photons by 1 muon highly efficient

< Capture probability: proportional to *Z* with slight chemical effects >

Improvement of sample environment

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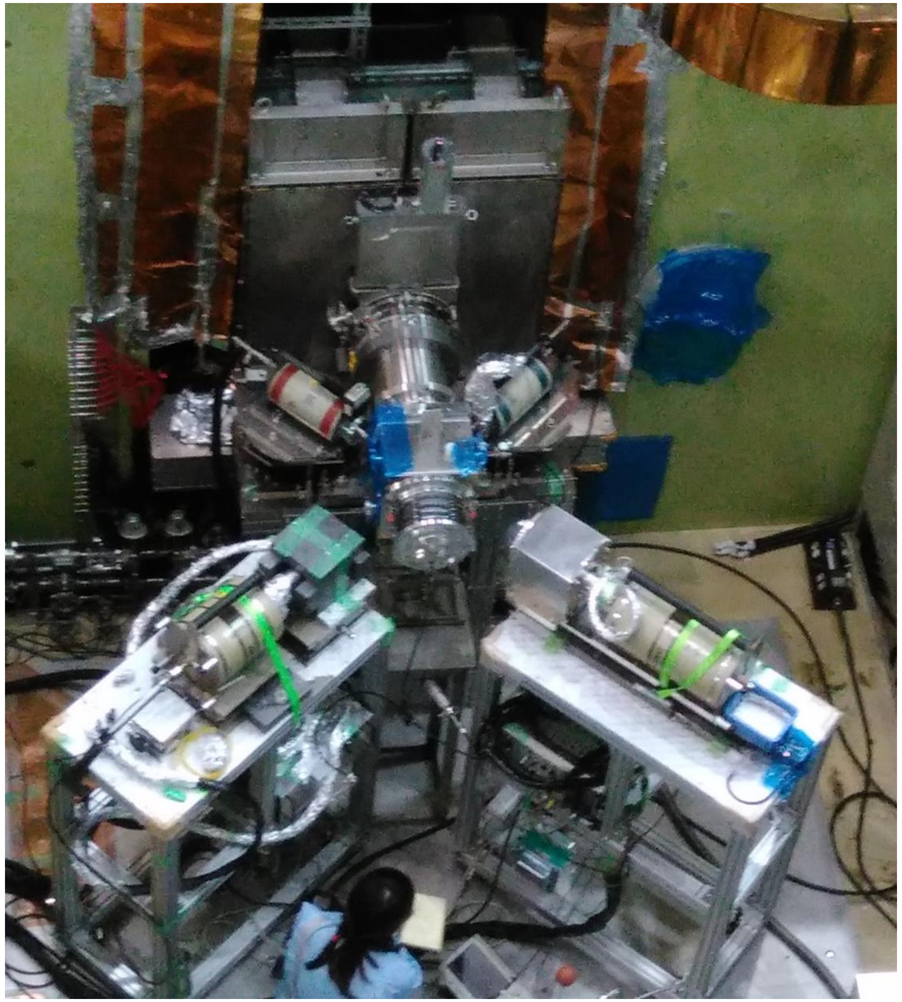
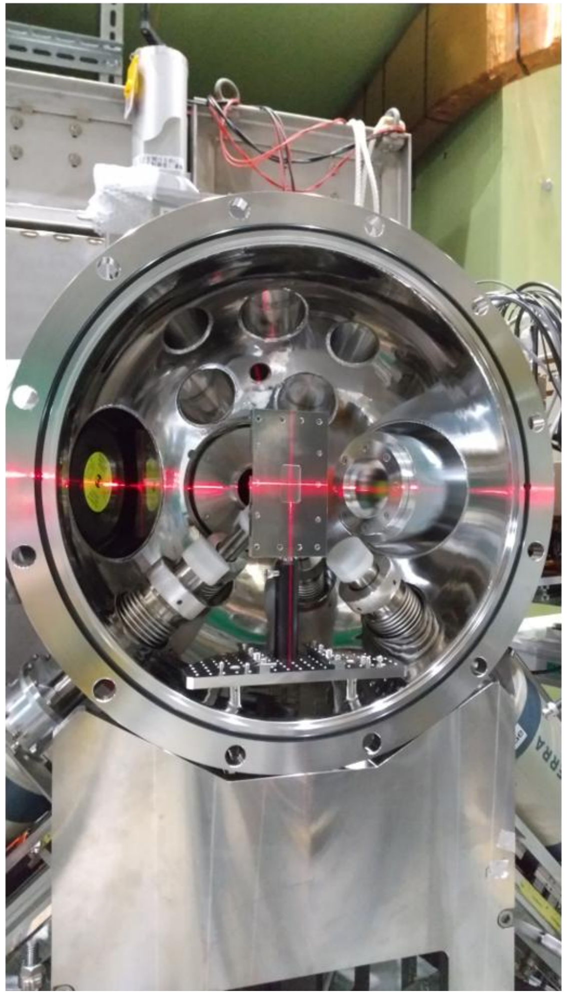
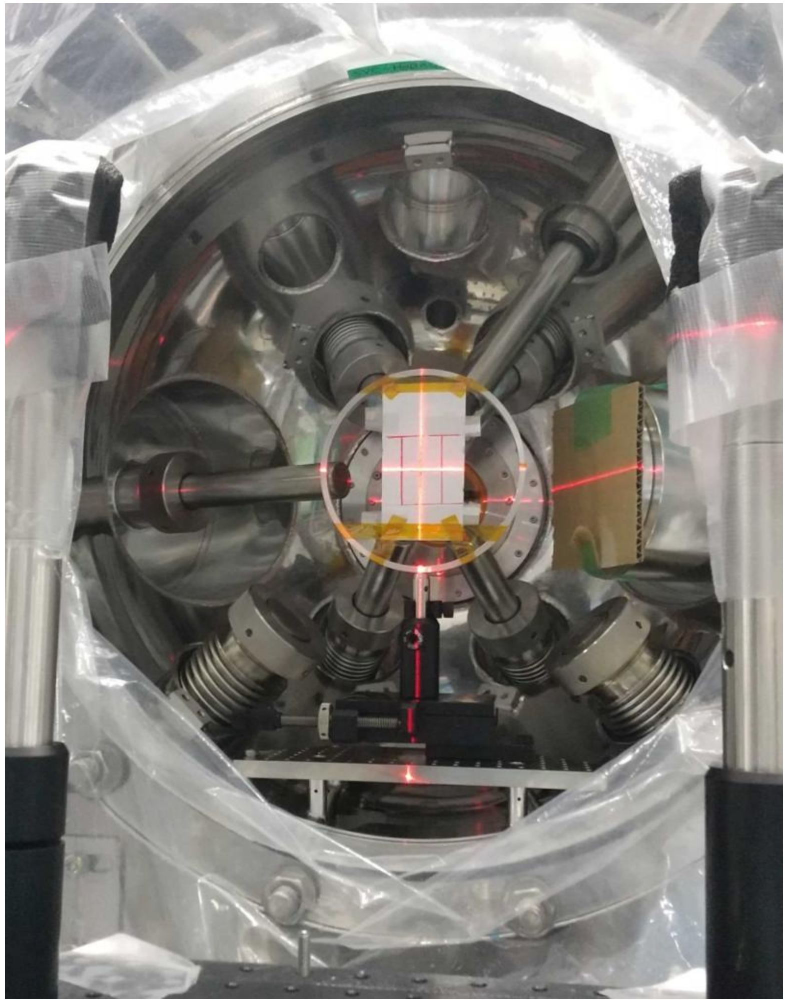


2018.6
2 ports for Ge detectors



2021

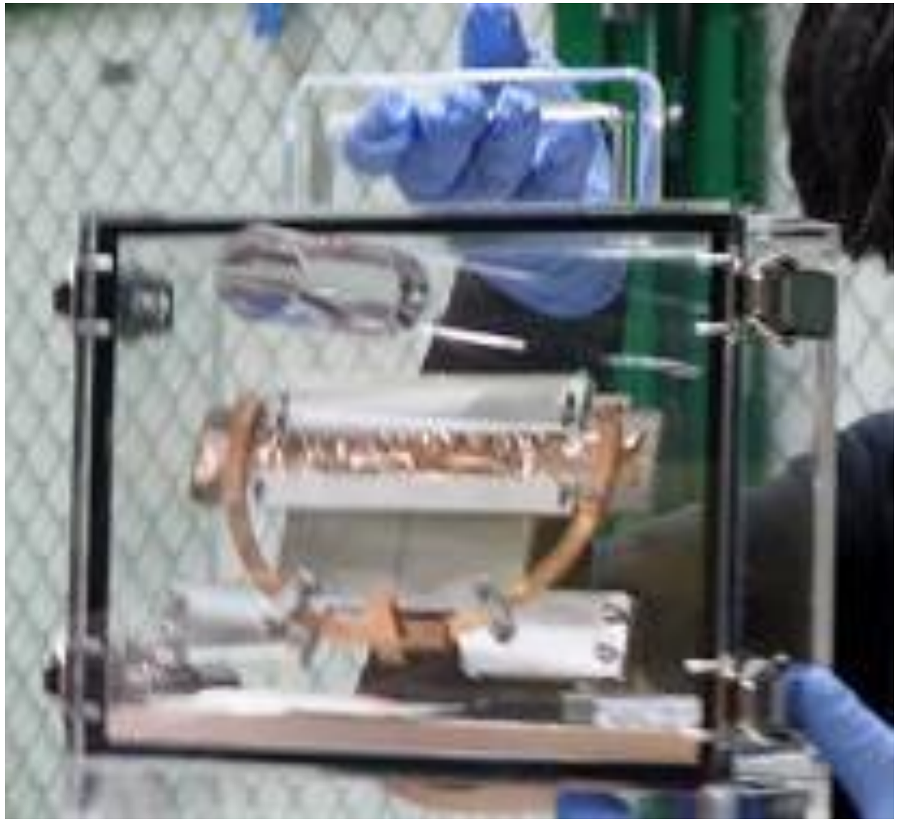


2022
9 ports for Ge detectors

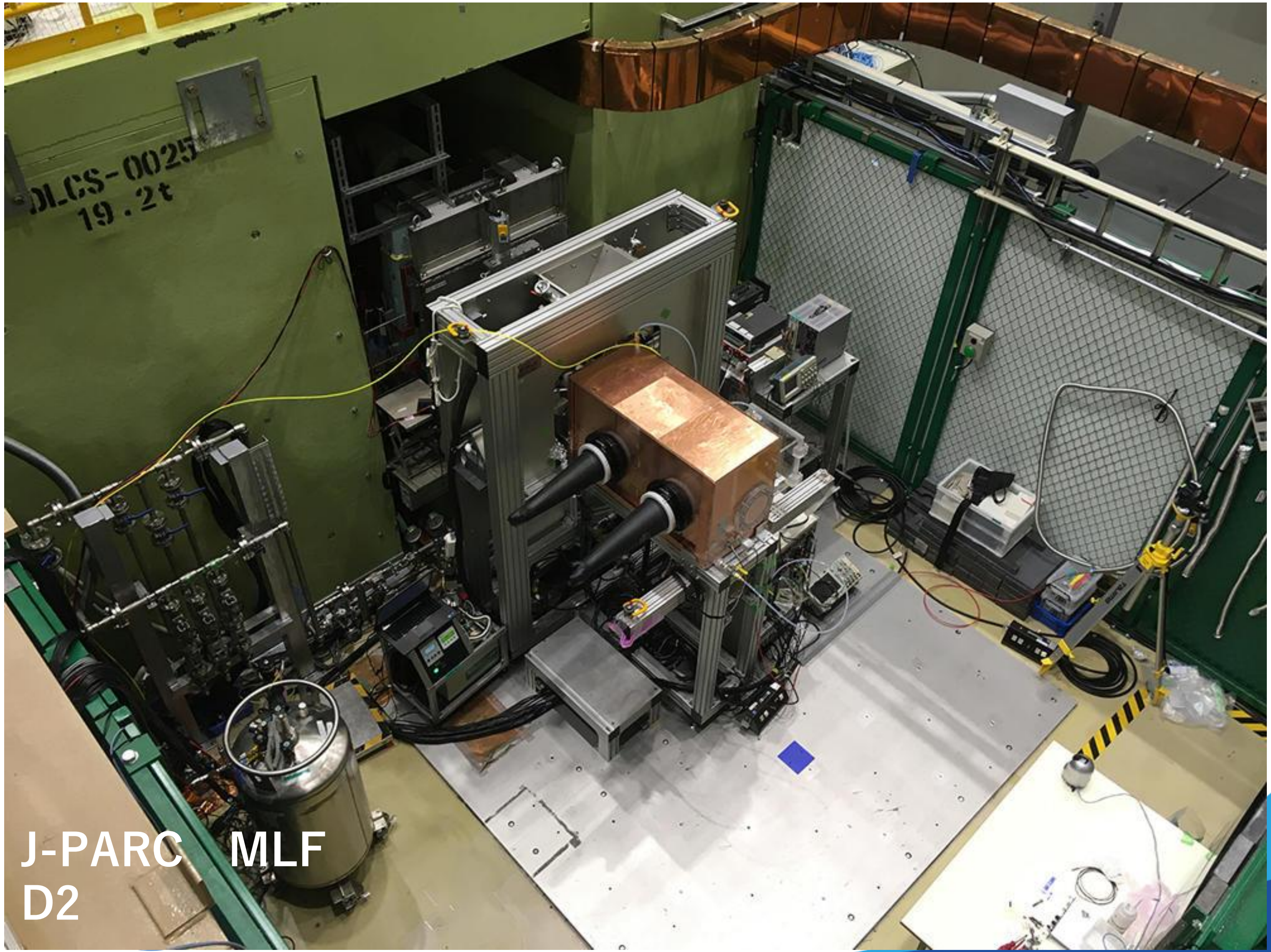
Applications

Analysis of returned sample from asteroid Ryugu

KEK PR dep.



- To prevent the sample form air exposure
- To know average composition of the sample



D2 Instrument (Muon Spectrometer for Basic Sci. Exp.)

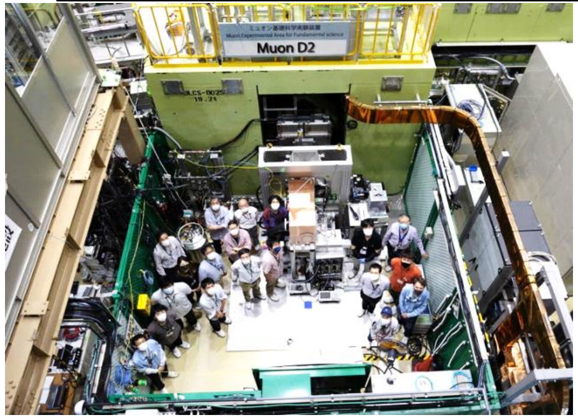
Research & development highlights in 2021

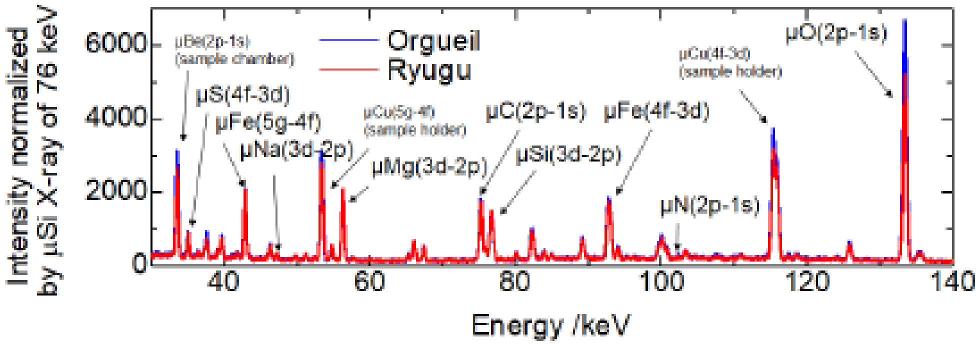
2019MS01

Non-destructive elemental analysis of return samples from asteroid *Ryugu*

- ✓ Need to know the elemental composition of the entire stone, including light elements such as C.
- ✓ Possibility of chemically unstable in the atmosphere

Muonic X-ray elemental analysis was employed as an initial analysis of Ryugu samples.





Ryugu stones could become a new standard representative of the Solar System.

ators.

T. Nakamura *et al.*, *Science* 10.1126/science.abn8671 (2022).

D2 Instrument (Muon Spectrometer for Basic Sci. Exp.)

Research & development highlights in 2021

2014MS01, 2019B0314

Non-destructive elemental analysis of a medicine bottle that cannot be opened

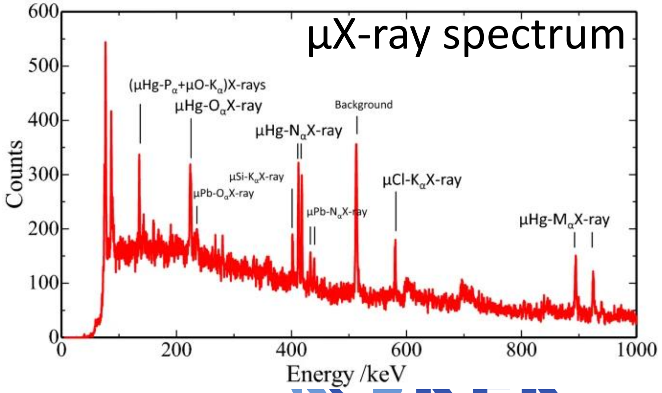
- ✓ The lid is stuck and impossible to open.
- ✓ Possibility of chemically unstable in the atmosphere

Muonic X-ray elemental analysis non-destructively revealed that the material inside the bottle is Hg_2Cl_2.

Kōan's Drug box

The medicine bottle

OGATA Kōan (緒方 洪庵)
1810~1863 (Edo period)
Doctor, *Rangaku* scholar



K. Shimada-Takaura, et al., J. of Natural Medicines 75, (2021) 532.

Significant impact on the public

朝日新聞 DIGITAL

北京五輪 速報 朝刊 夕刊 連載 特集 ランキング コメント

トップ 社会 経済 政治 国際 スポーツ オピニオン IT・科学 文化・芸能

朝日新聞デジタル > 記事

緒方洪庵の「開かずの薬瓶」、中身は…？ 素粒子で透視

小川裕介 2021年3月19日 15時00分

シェア ツイート list ブックマーク 29 メール 印刷

緒方洪庵が晩年に使用していたとされる薬箱。中に薬瓶などが入っている＝大阪大学総合学術博物館の高橋京子・招へい教授提供

大阪大学 などの研究チームが、幕末の蘭（らん）医学者である緒方洪庵（1810～1863）が往診などで使ったとされる薬瓶の中身を突き止めた。瓶が古くフタが開けられないままになっていたが、素粒子 の一種「ミュー粒子」を使った「透視」に成功した。

緒方洪庵は幕末、阪大医学部の源流とされる蘭学塾「適塾」を開き、医療や教育に力を注いだ。研究チームによると、阪大は洪庵が愛用した薬箱二つを所蔵。このうち

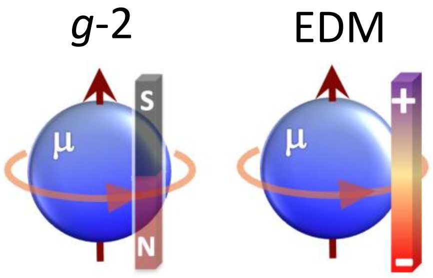
Newspapers (5 major National newspapers etc.)

- *The Asahi Shimbun* (’21/3/19)
- *The Yomiuyri Shimbun* (’21/4/30)
- *The Mainichi Shimbun* (’21/5/12)
- *Nihon Keizai Shimbun* (’21/5/13)
- *The Sankei Shimbun* (’21/5/25)
- *etc.*

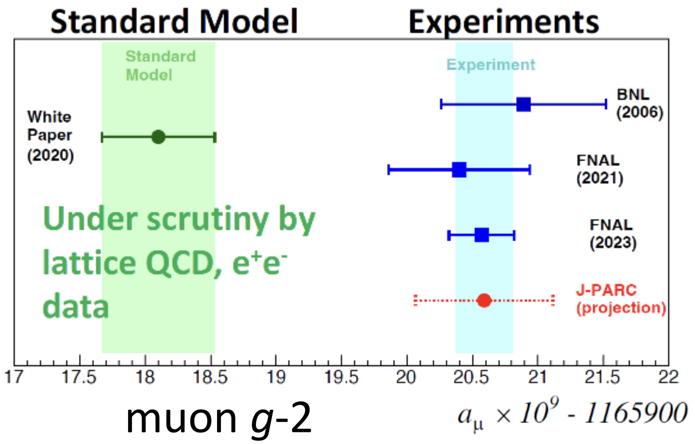
TV news

- *NHK General TV* (’21/6/8)
- *etc.*

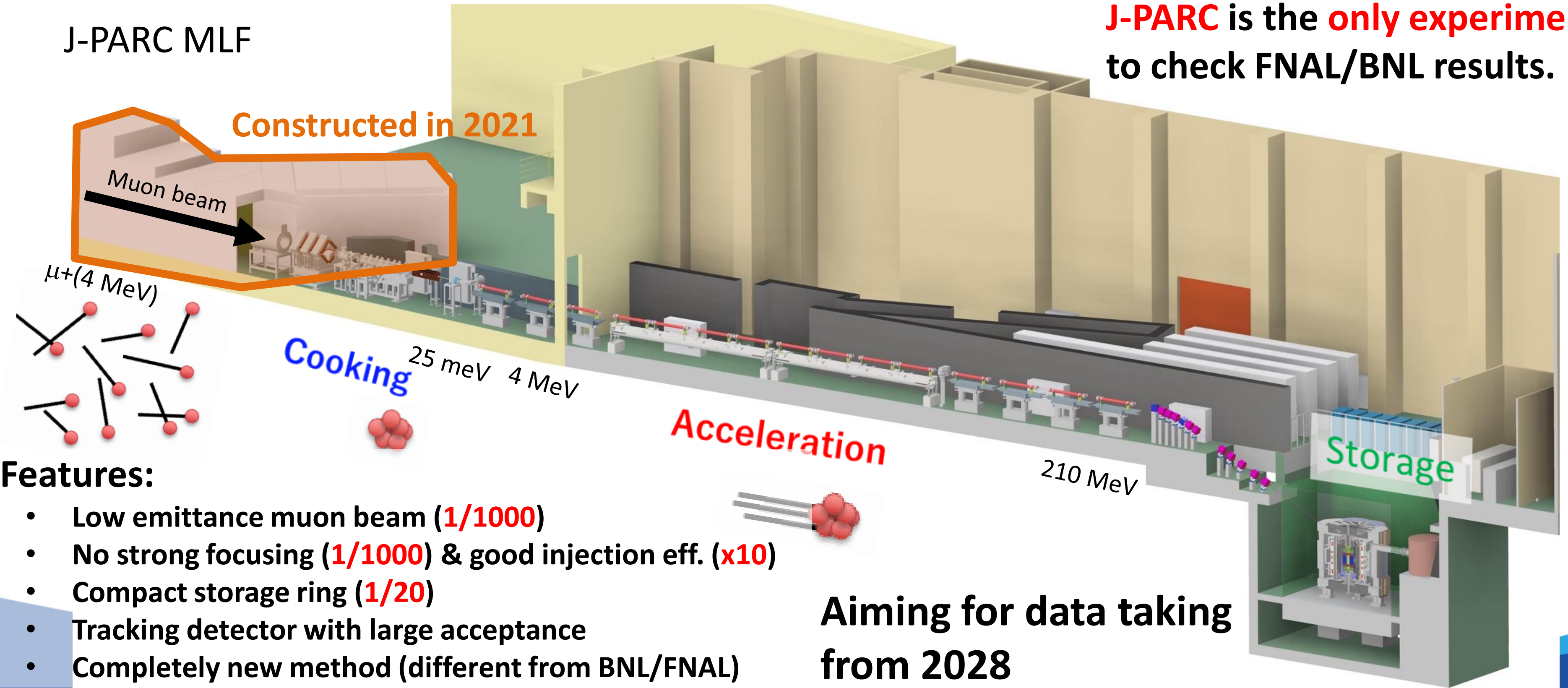
J-PARC muon *g*-2/EDM experiment



- Aim to reach
  - **μ g-2: 450ppb**
  - **μEDM: 1.5e-19**



J-PARC is the only experiment to check FNAL/BNL results.



Features:

- **Low emittance muon beam (1/1000)**
- **No strong focusing (1/1000) & good injection eff. (x10)**
- **Compact storage ring (1/20)**
- **Tracking detector with large acceptance**
- **Completely new method (different from BNL/FNAL)**

Aiming for data taking from 2028

Ultra-cold Muon

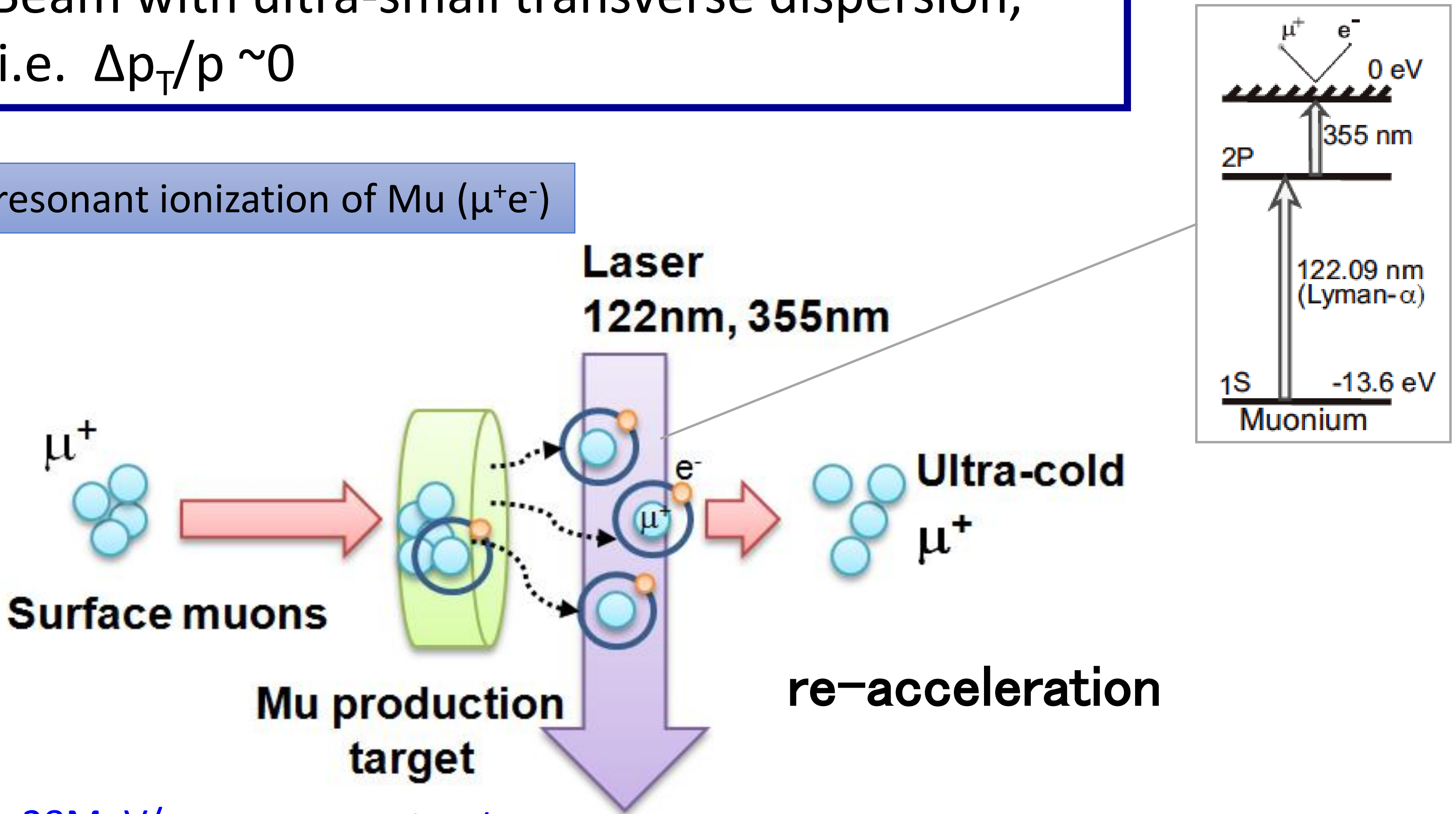
<u>Requirement for zero E-field:</u>

Muons should be kept stored without E-focusing

→ Beam with ultra-small transverse dispersion,

i.e. $\Delta p_T/p \sim 0$

Laser resonant ionization of Mu (μ^+e^-)

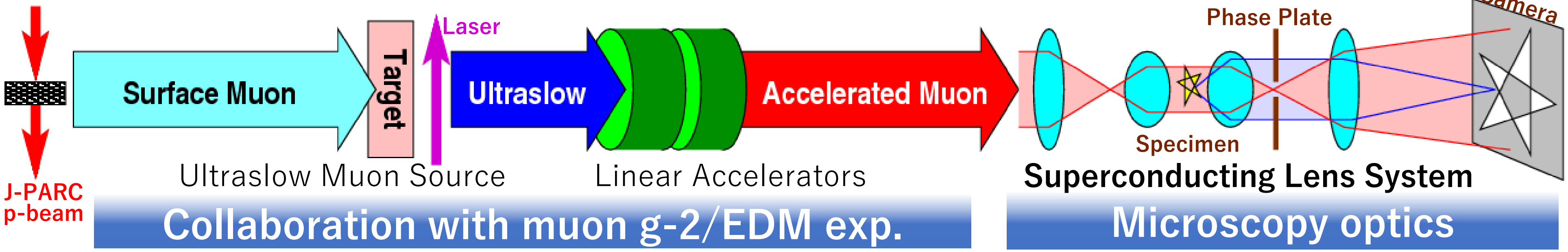


p = 28MeV/c 3 keV/c 300 MeV/c

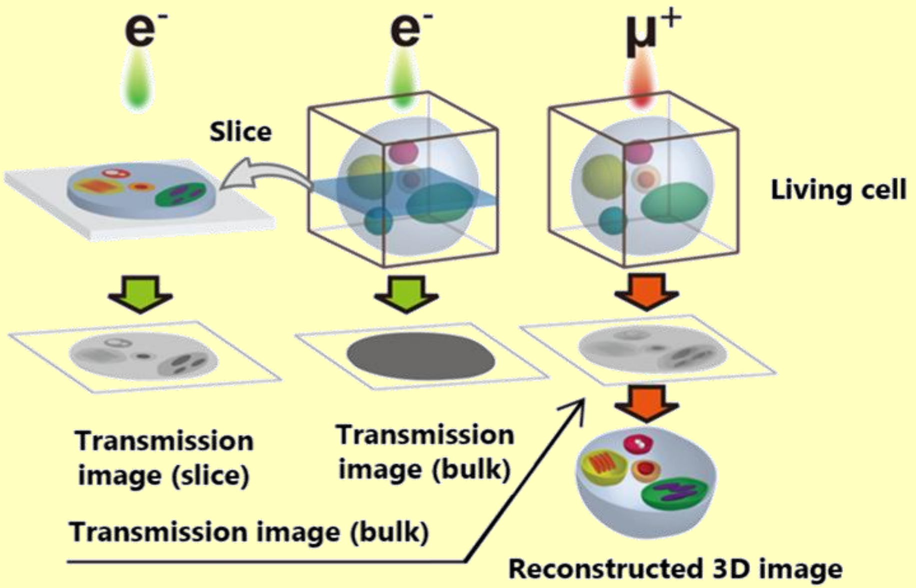
$\Delta p_T/p$ ~3 keV / 300 MeV =1E-5

Concept of Transmission Muon Microscopy

＝ Accelerated Muon : Strong Penetration ＋ Ultraslow Muon : High Luminance / Resolution



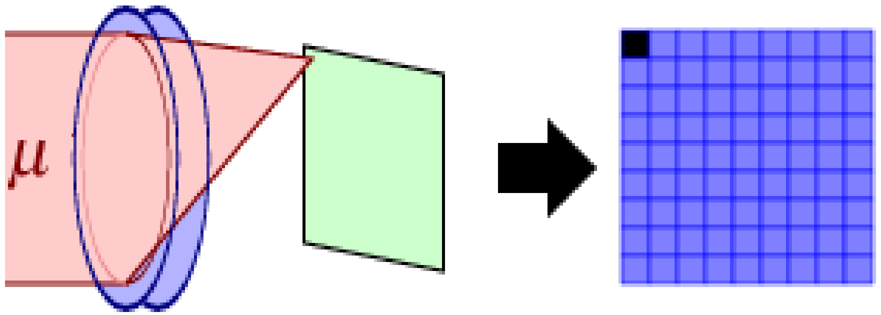
Transmission imaging by μ^+ beam



Nano-resolutional & functional imaging of macroscopic object

Scanning Muon Microscopy as annex

Scanning by focused μ^+ beams,



and detect decay positrons.

It works as a Scanning μSR Microscope:

3-dim mapping of magnetic field and its fluctuation, density of Fermi surface, state of hydrogen, and etc.,

Y.Nagatani

Summary

- In this presentation we have described the basic properties of muons and the fundamentals for various studies using muons.
- There are various muon facilities around the world, and we hope you will make good use of them.
- Of course, J-PARC welcomes you.