Muonic X-ray track density imaging algorithm based on Geant4

Chuntian Feng (冯春添)，Siyuan Luo(罗思远)
Lie He(何列),Xiaodong WANG*(王晓冬)

University of South China
School of Nuclear Science and Technology

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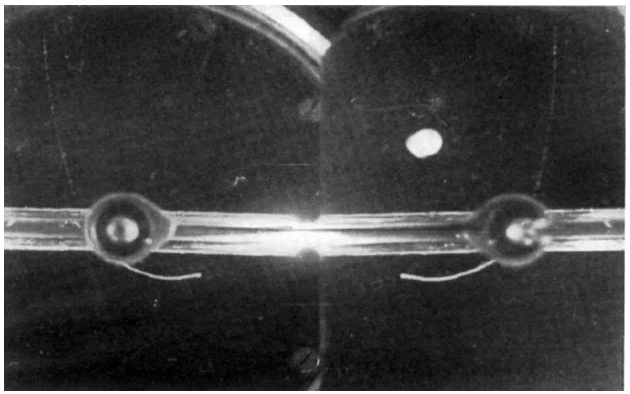
Workshop on Muon Physics at the intensity and Precision Frontiers(MIP2024)

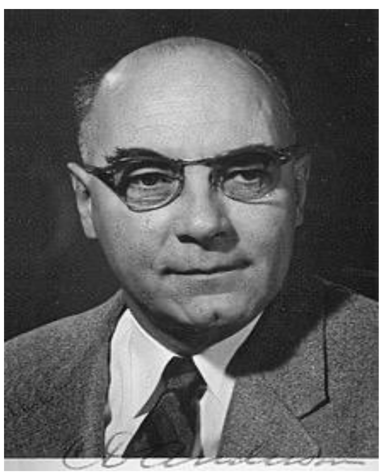

核学楼

1.1 Overview of the Muon

□The discovery of the Muon

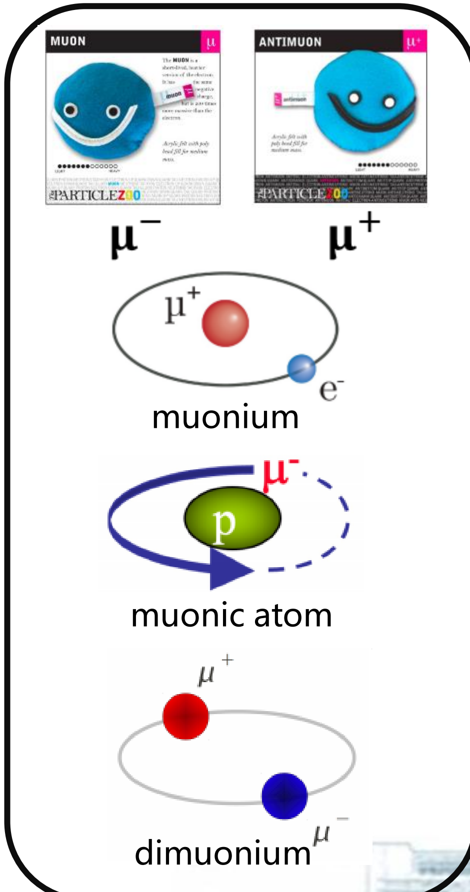
In 1936, C.D. Anderson and S.Anderson Neddermeyer discovered the muon.

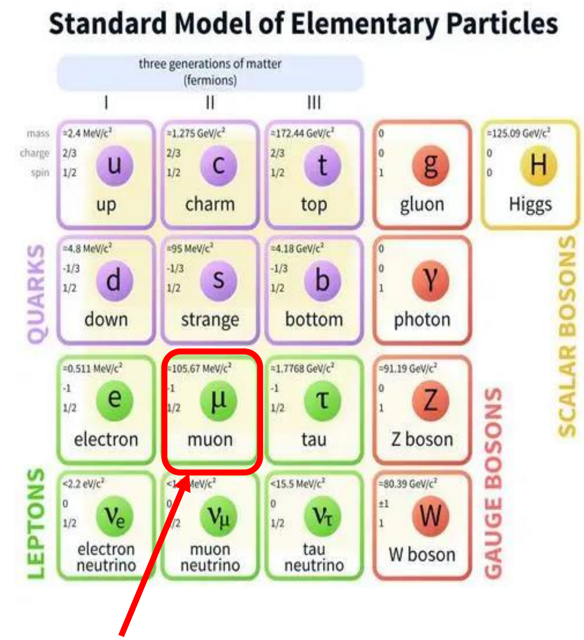




Carl David Anderson (1905-1991)

Muon can exist in various forms





- **Muon is a second generation charged lepton in the SM**
- **Charge +-, spin ½, mμ ~ 206 me, mμ ~ 1/9 mp**
- **the sea level flux is 1 cm^2•min.**

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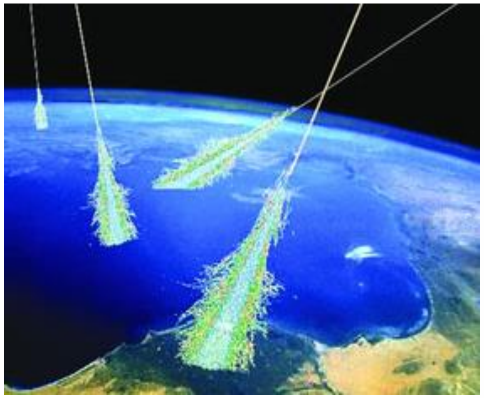
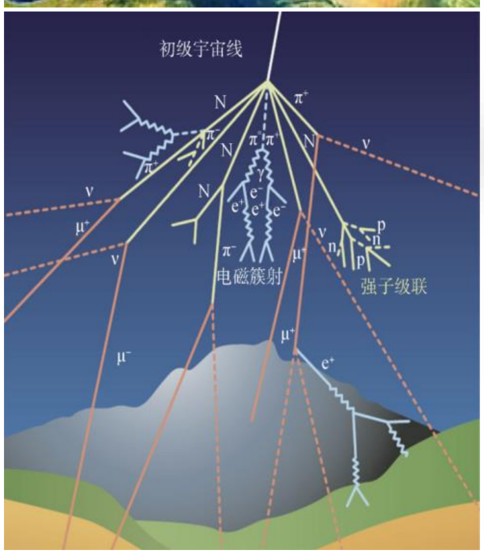
S.H. Neddermeyer, C.D. Anderson, Phys. Rev. 54, 88 (1938)

1.2 The source of muon

□Natural Muon source-background radiation





The muon interacts with matter

Scattering | Transmission | Stopped | Tagged

Wide energy domain

Strong penetrating ability

Background rays

Non-contactremoteNon destructive imaging

1 Scattering imaging technology

Object: Dense high-Z material

2 Transmission imaging technology

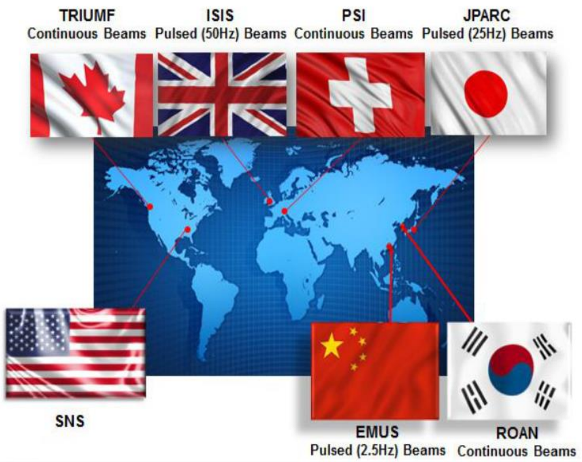
Object: Large size

3 secondary particle imaging technology

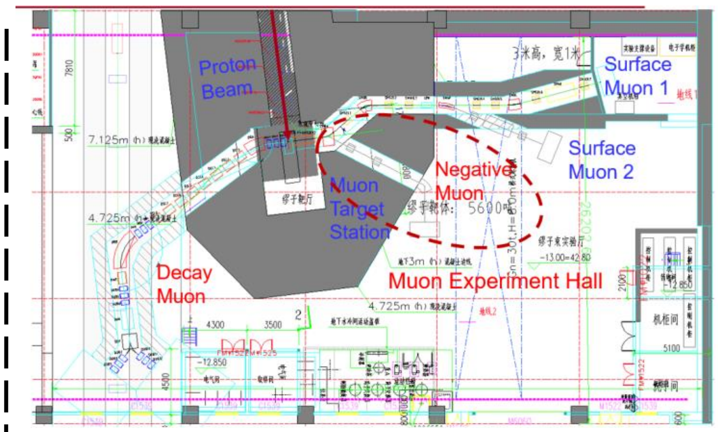
Object: Medium and low Z Small size

1.2 The source of muon

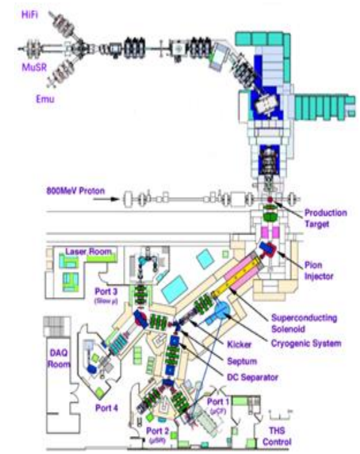
◻The Instruments at muon facilities



muon sources internationally.

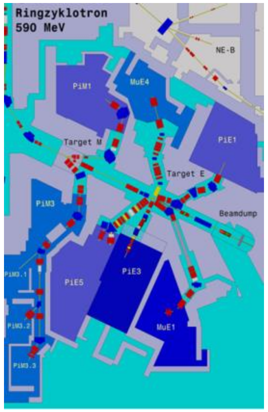


CSNS Melody



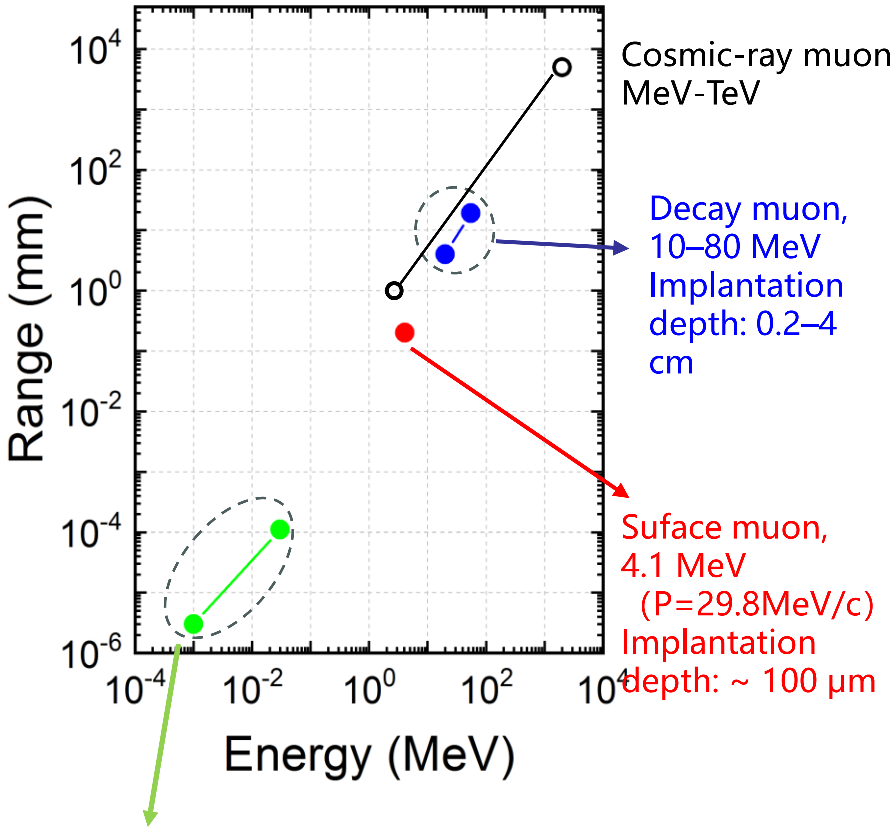
ISIS

J-PARC/MUSE



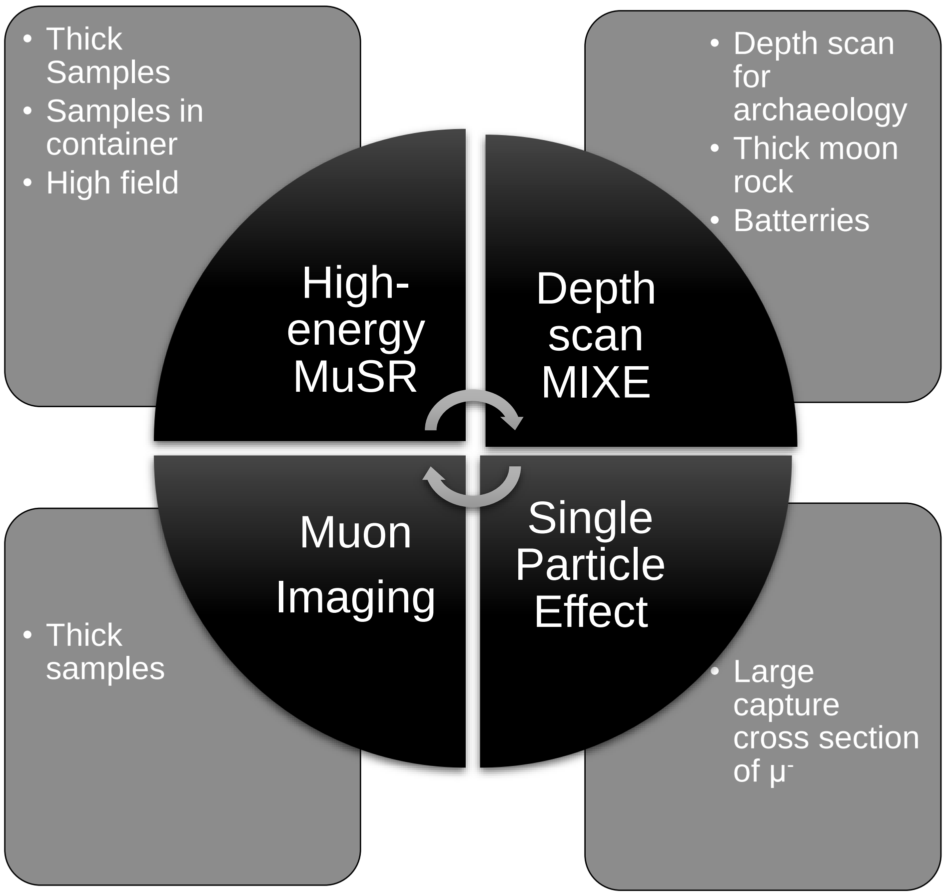
PSI/SμS

1.3 Application range of different energy

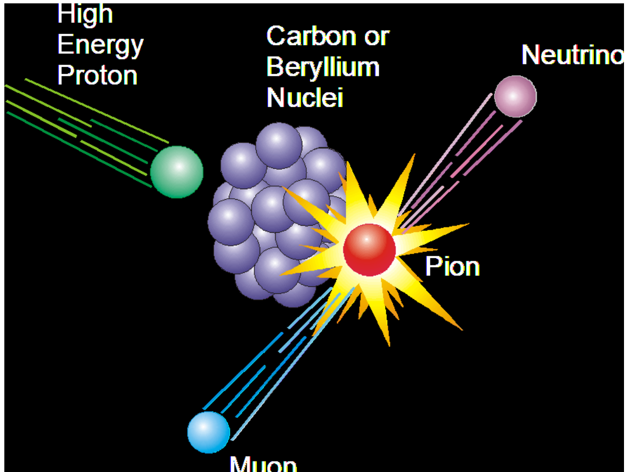


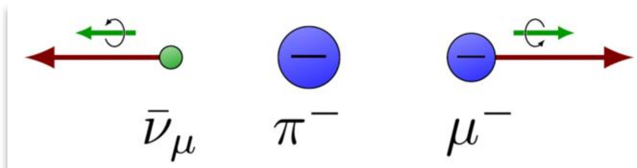
Slow muon, 1–30 keV tunable
Depth: 1–300 nm
Depth sensitive μSR: magnetic spin microprobe for thin films, multilayers, nanomaterials ...

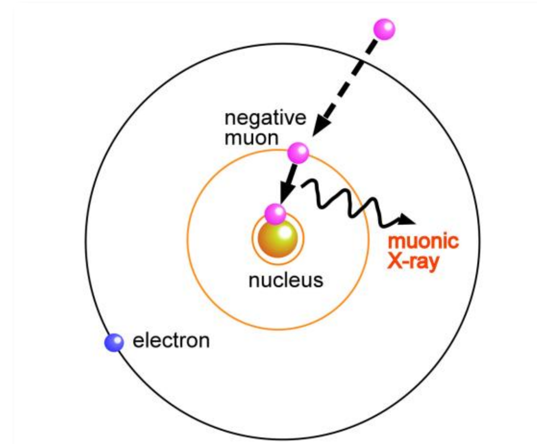
Decay Muon Applications



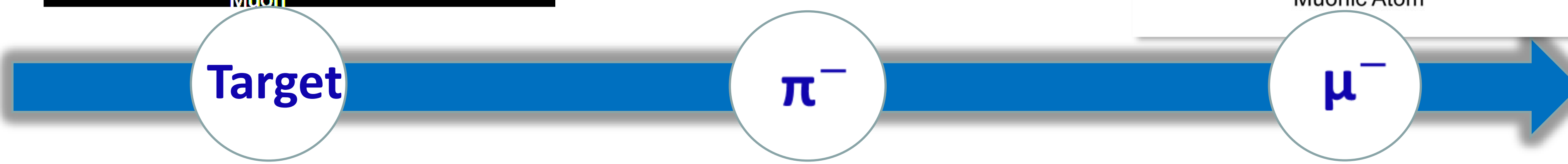
2.1 Generation of negative muon beams

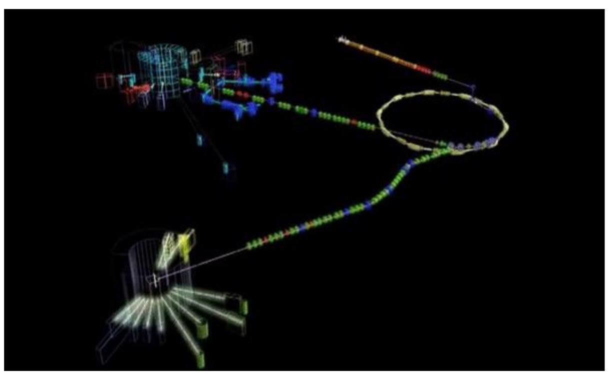


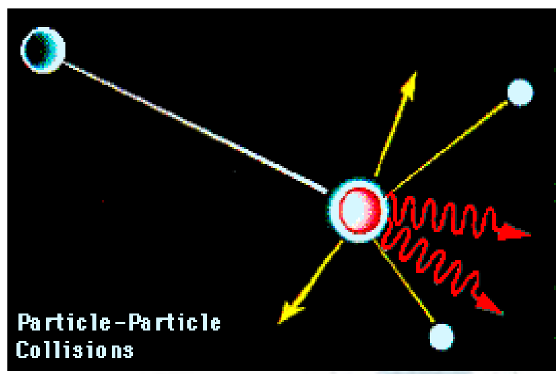


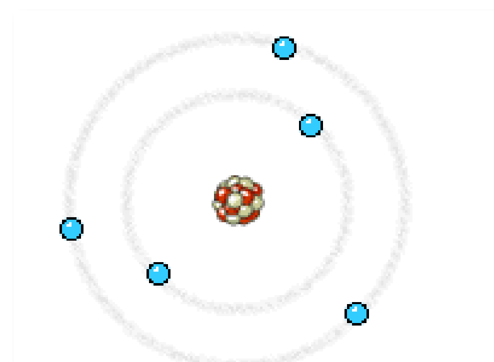


Muonic Atom

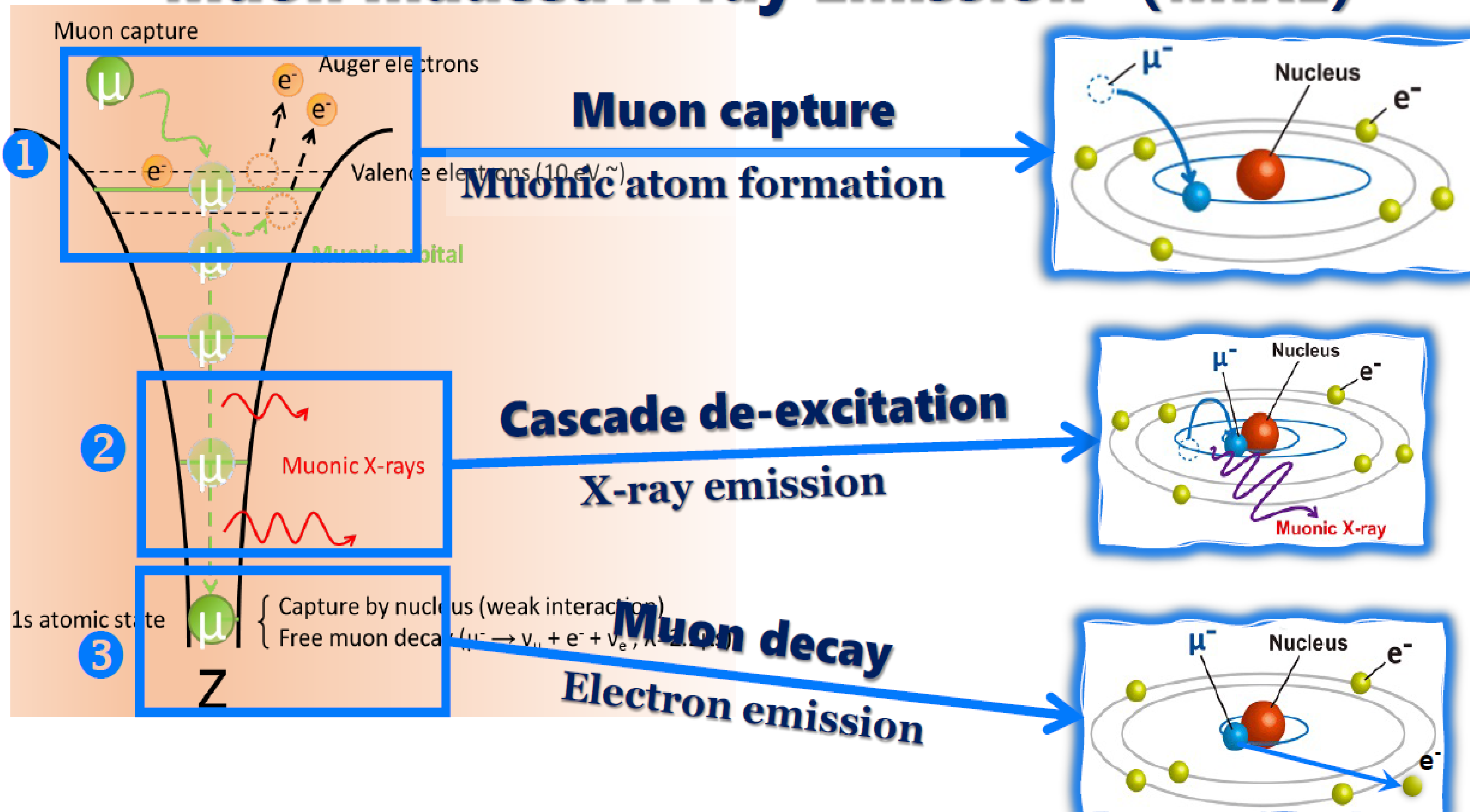








Muon Induced X-ray Emission (MIXE)



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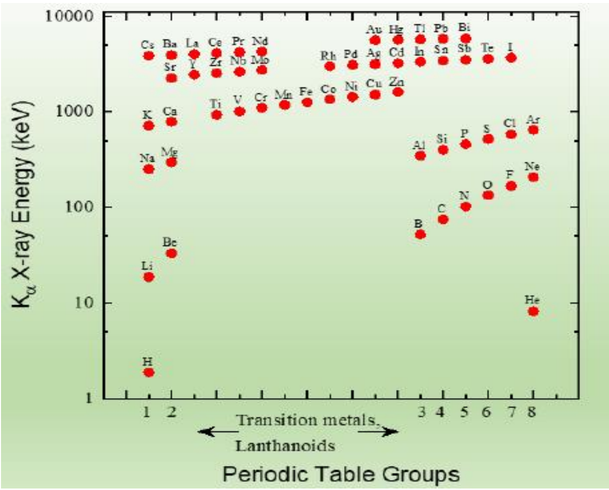
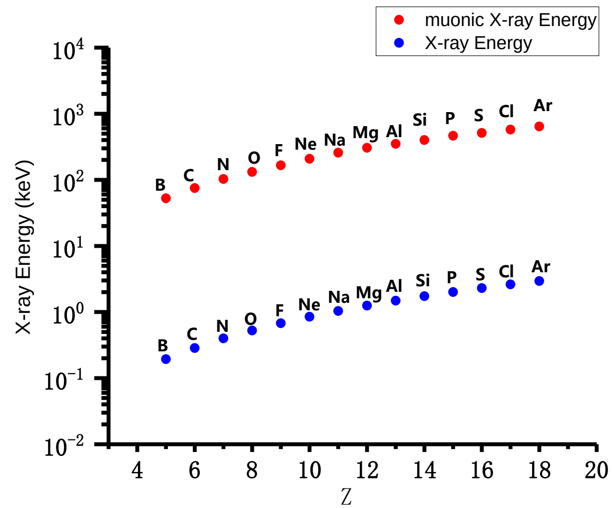
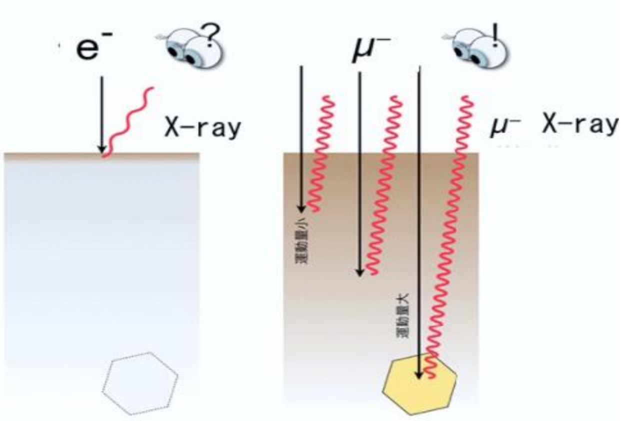
Images Courtesy Z.W.Pan @ USTC

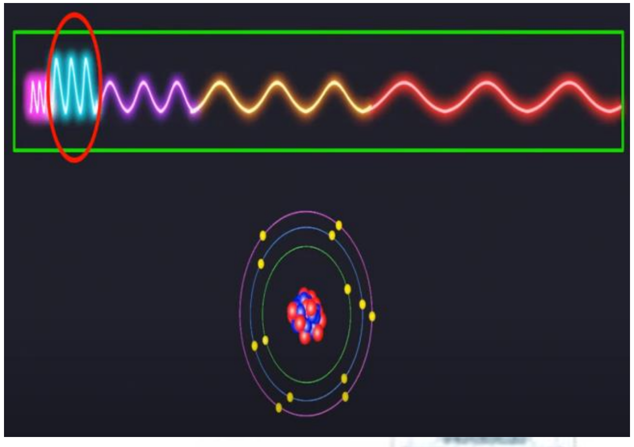
2.3 Advantages of MIXE method





Comparison of two characteristic X-ray energies



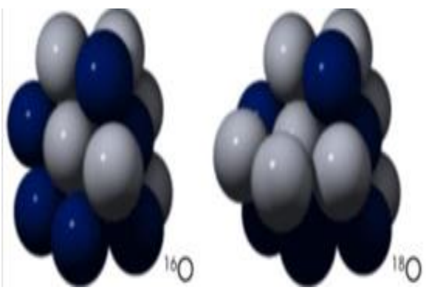


- ☐ **Sensitive to C, N, O, which are not easy to detector in other methods**
- ☐ **High energy,high penetrating capability**
  (Induce X-rays with energy in 10keV-10MeV, 200times of electron.)
- ☐ **Non-destructive measurement**
  (no radiation risk to materials.)
- ☐ **Adjustable Muon beam momentum**
  (depth analysis of elemental distributions.)
- ☐ **Energy dependency on atomic number**
  (multiple atoms/elements distinguishable at one time)

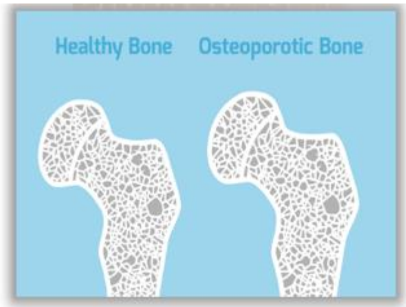
2.4 Multi-field applications

Meteorite

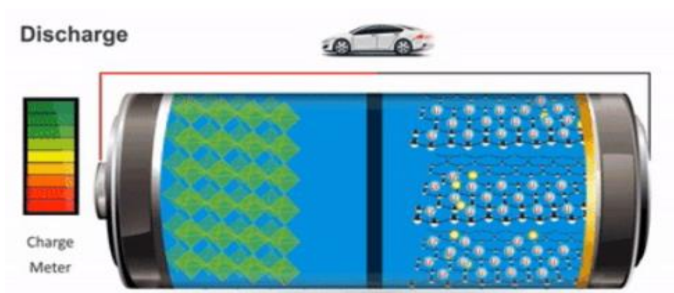
Cultural heritage



Isotope analysis



Biomaterials



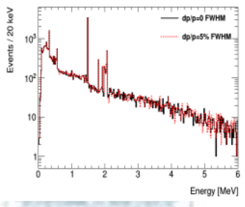
Li-ion battery

PSI MIXE on car bearing

Figure 1. Pictures of (a) a Li-ion battery sample, (b) the sample set in an aluminum holder at the measurement position with cables, and (c) the sample holder and Ge semiconductor detectors and Si drift detectors from the downstream the muon beam at the D2 experimental area.

JPARC on Lithium batteries

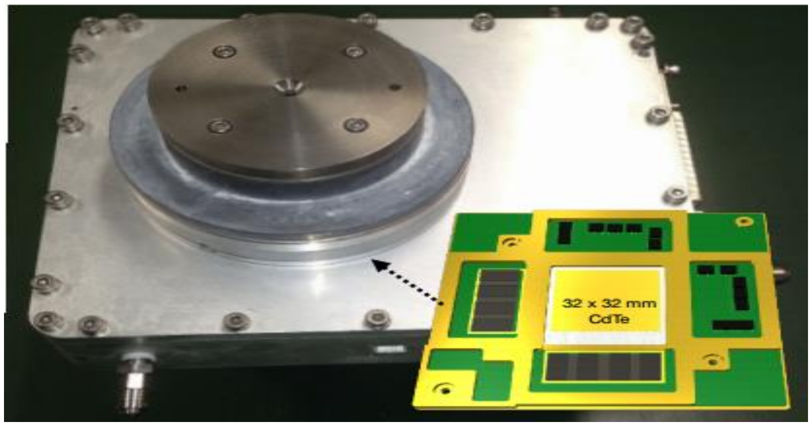
ISIS MIXE on ancient ROME coin

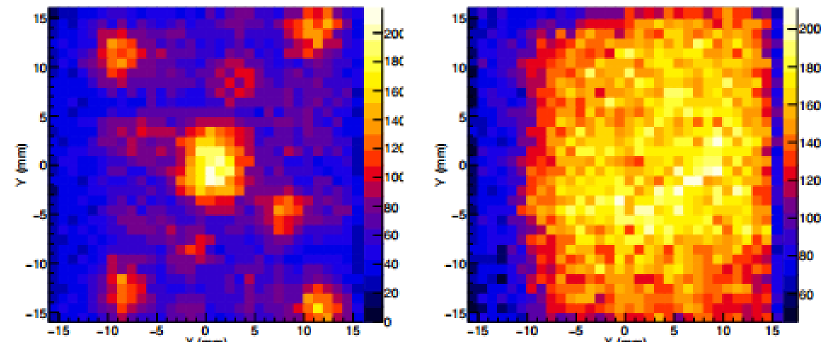


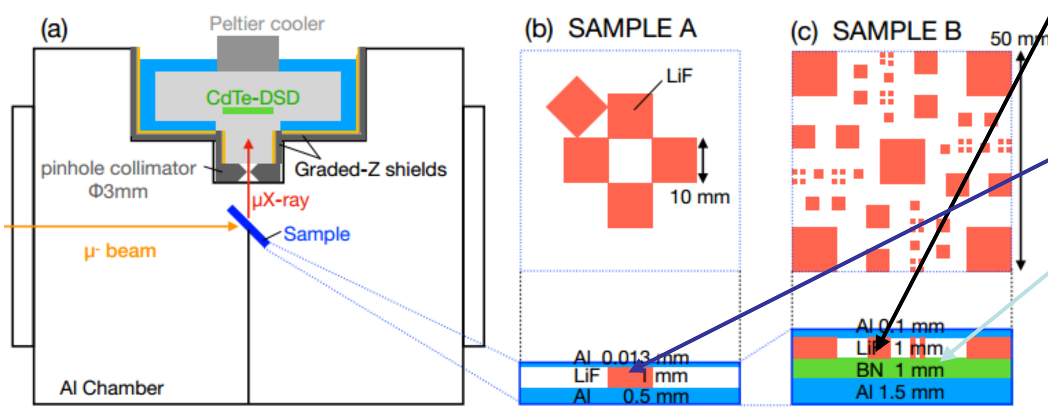
JPARC MIXE on ancient Chinese Mirror

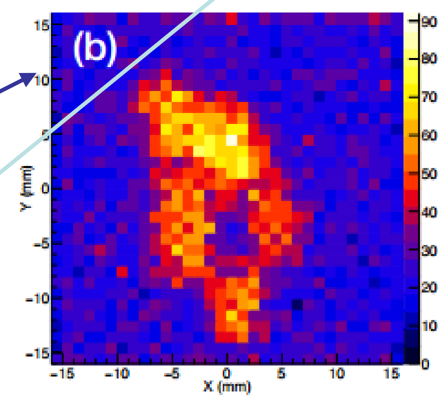
2.5 Current imaging methods

Single Depth+ 2D imaging





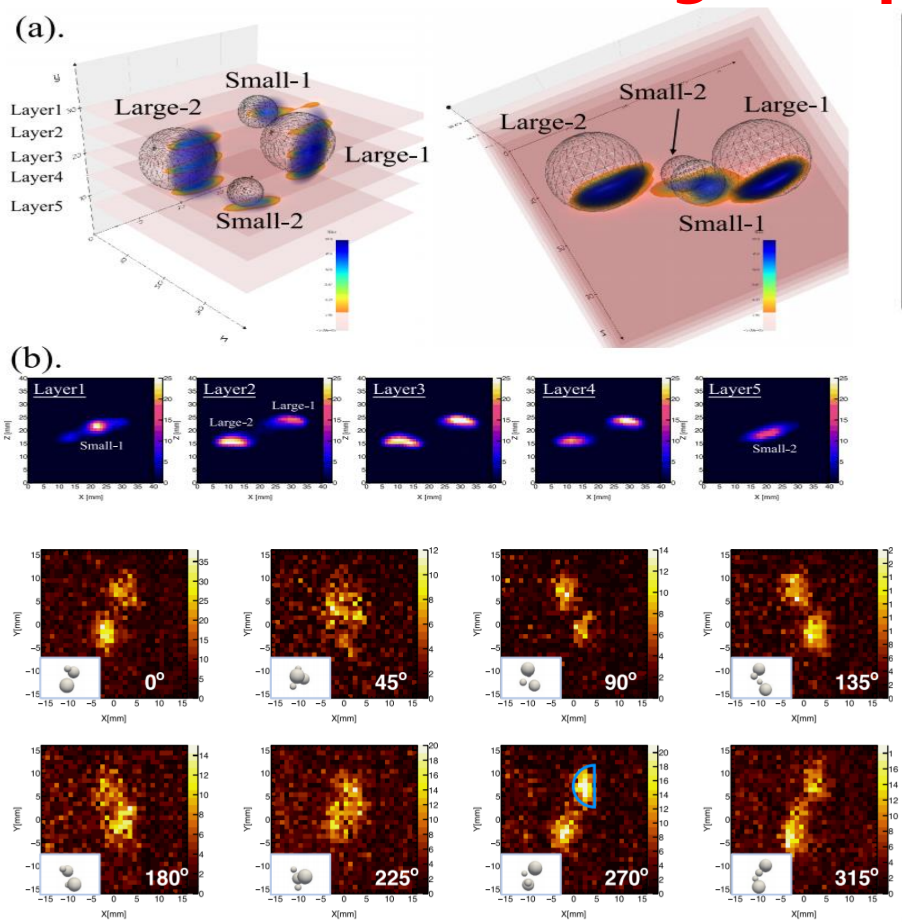


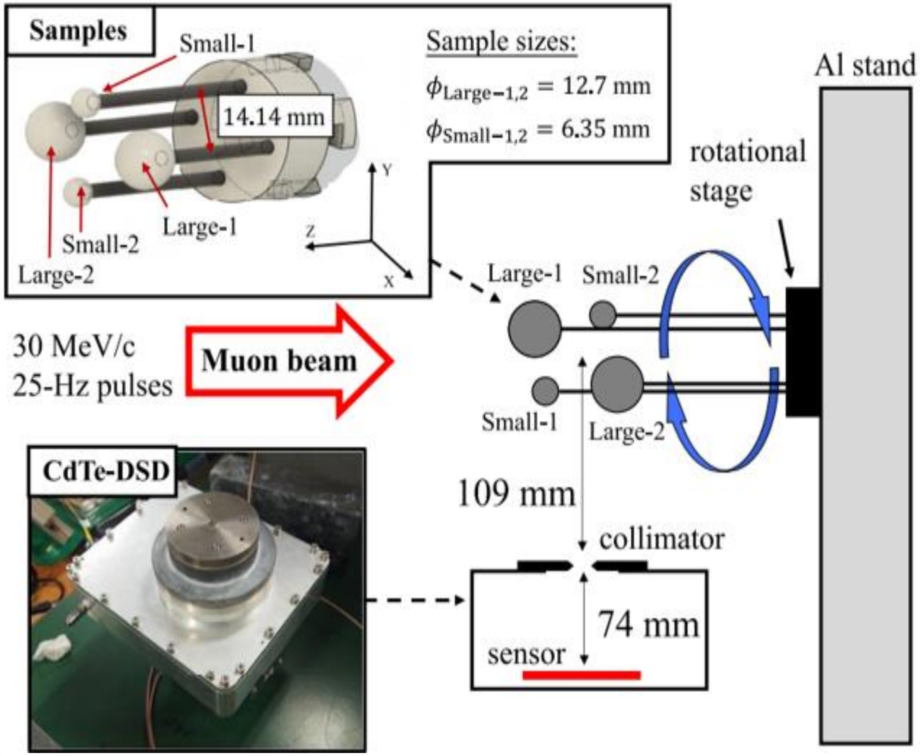


J-PARC MLF

M. Katsuragawa et al., NIMA 912 (2018) 140

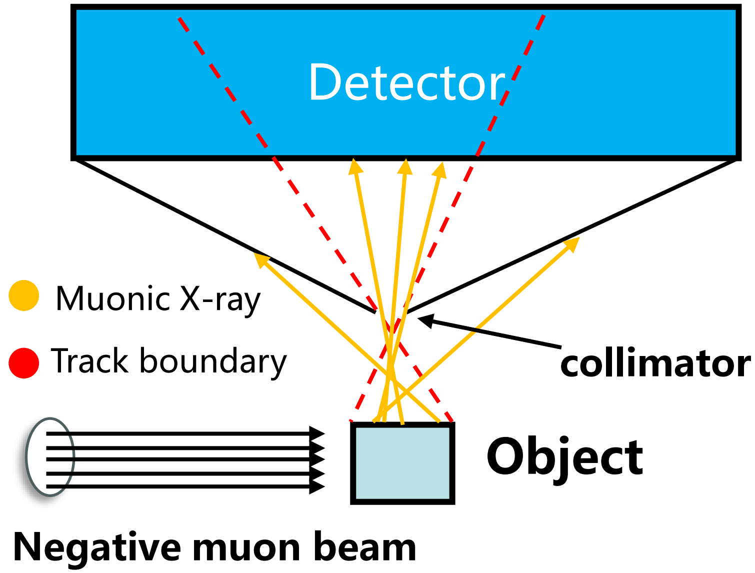
Single Depth+CT

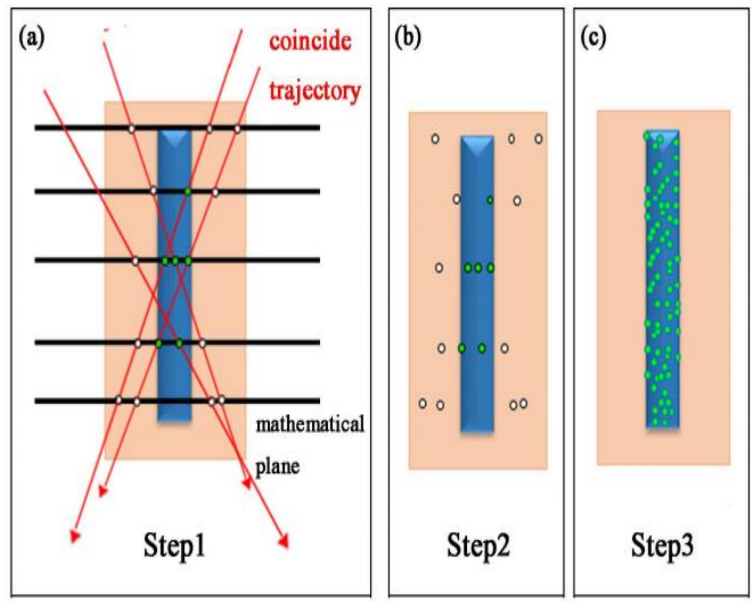


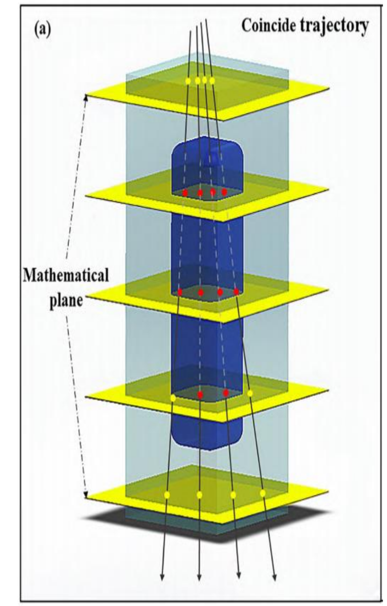


I. Chiu et al., Sci. Rep. 12 (2022) 5261

3.1 Track density imaging algorithm







Step 1

Collect photon tracks through the pinhole collimator

Step 2

Every photon trail is the same as every mathemat the face produces an intersection.

Step 3

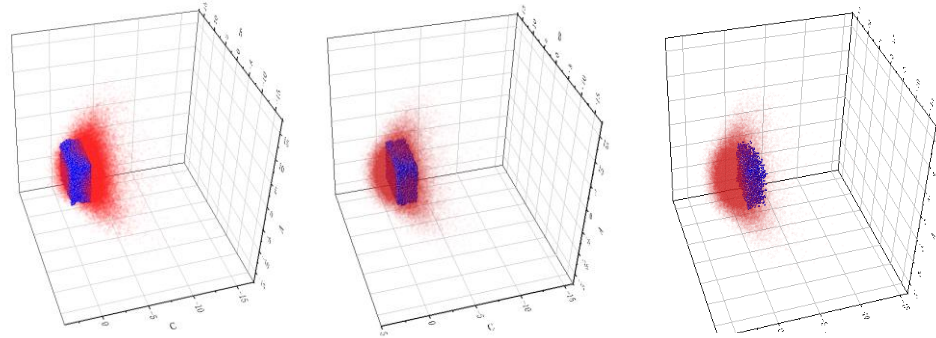
By setting a threshold, pick the one with the most dense intersections region.

Step 4

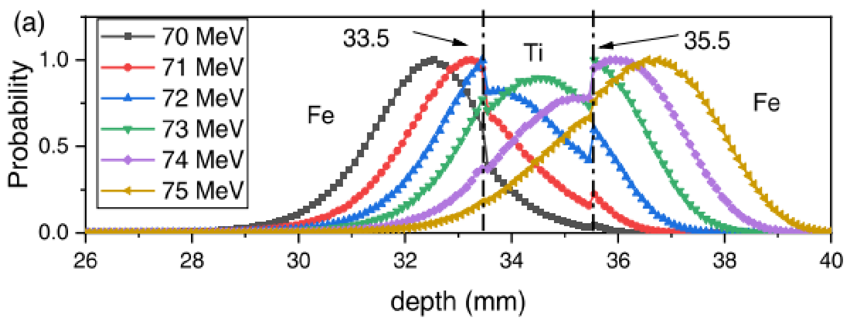
Converts the number of intersections within a region to voxels Assign values to reconstruct the image of the object to be measured.

3.2 Sample A Imaging result

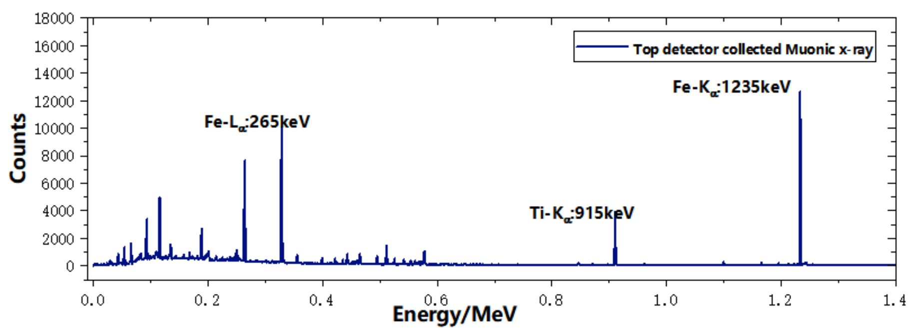
Single energy 2D imaging

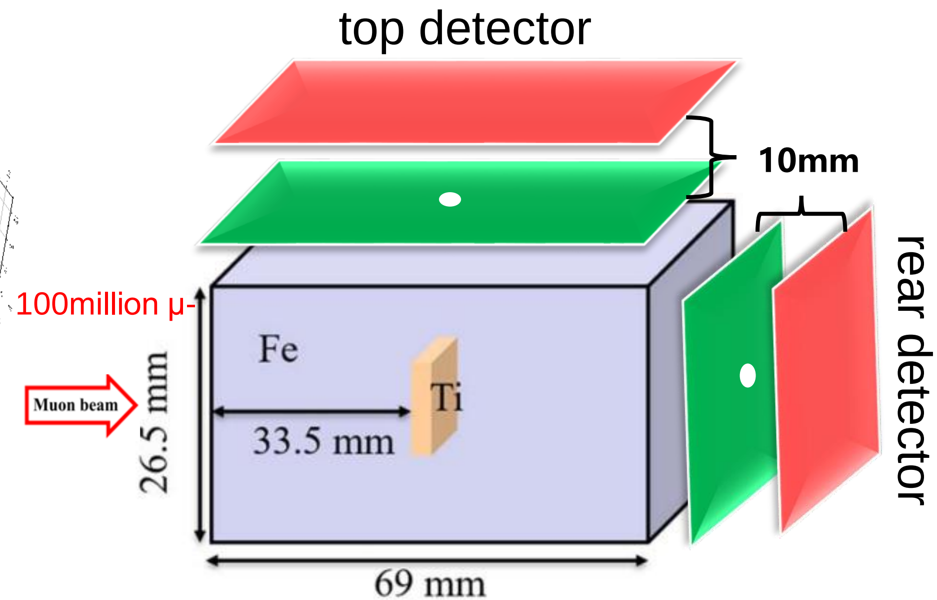


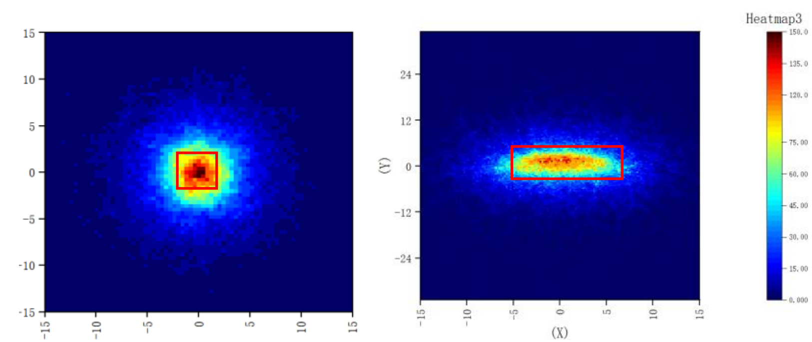
71MeV　73MeV　75MeV



Distribution of longitudinal diffusion of the μ-







Density plot of photon trajectories in the xoy，xoz direction

3.3 Three-dimensional reconstruction methods

Step1

Adjust the muon beam energy to determine the depth of the substance under test

The detector collects photon trajectories of specific energy at different depths

Step2

photon trajectories collected by the detectors

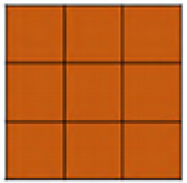
fictitious mathematical plane

Intersection

Step3

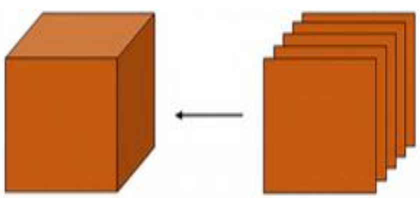
Collect intersection points obtained from all detectors

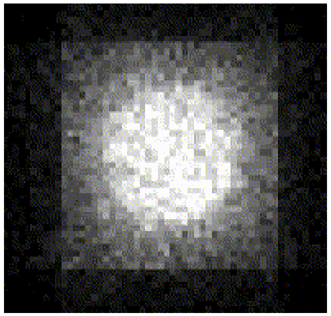
Generate a two-dimensional heat map at regular intervals



Step4

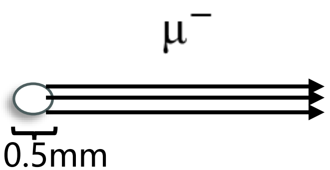
stack multiple 2D images to create a 3D reconstruction image



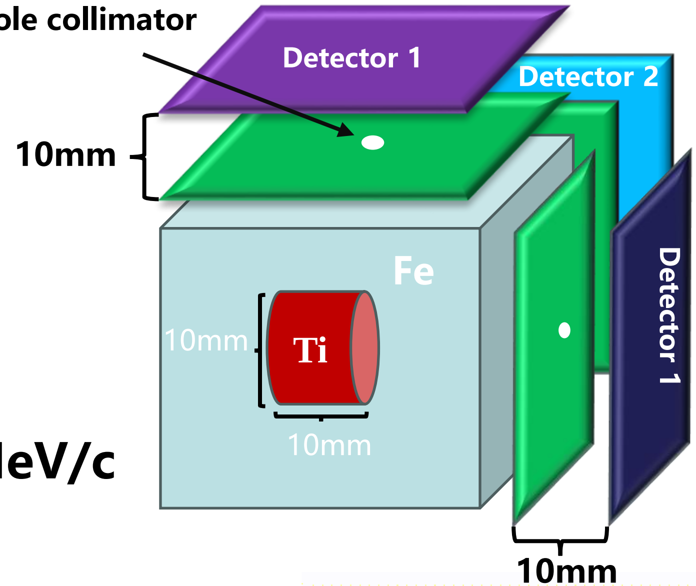


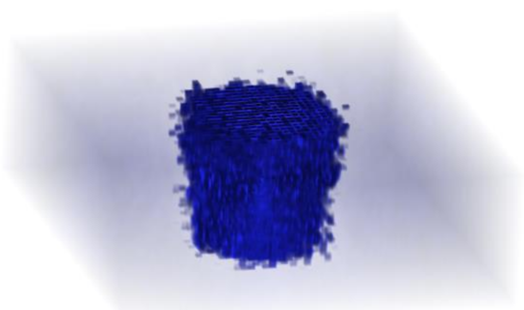
3.4 Sample B imaging result

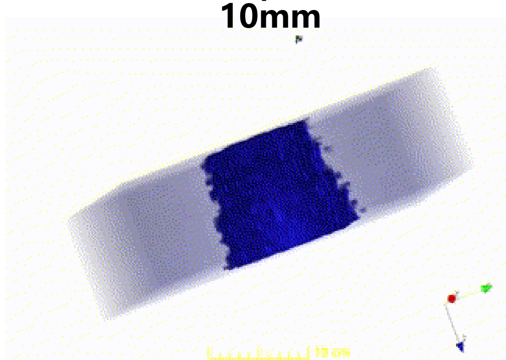
Single-object track density imaging



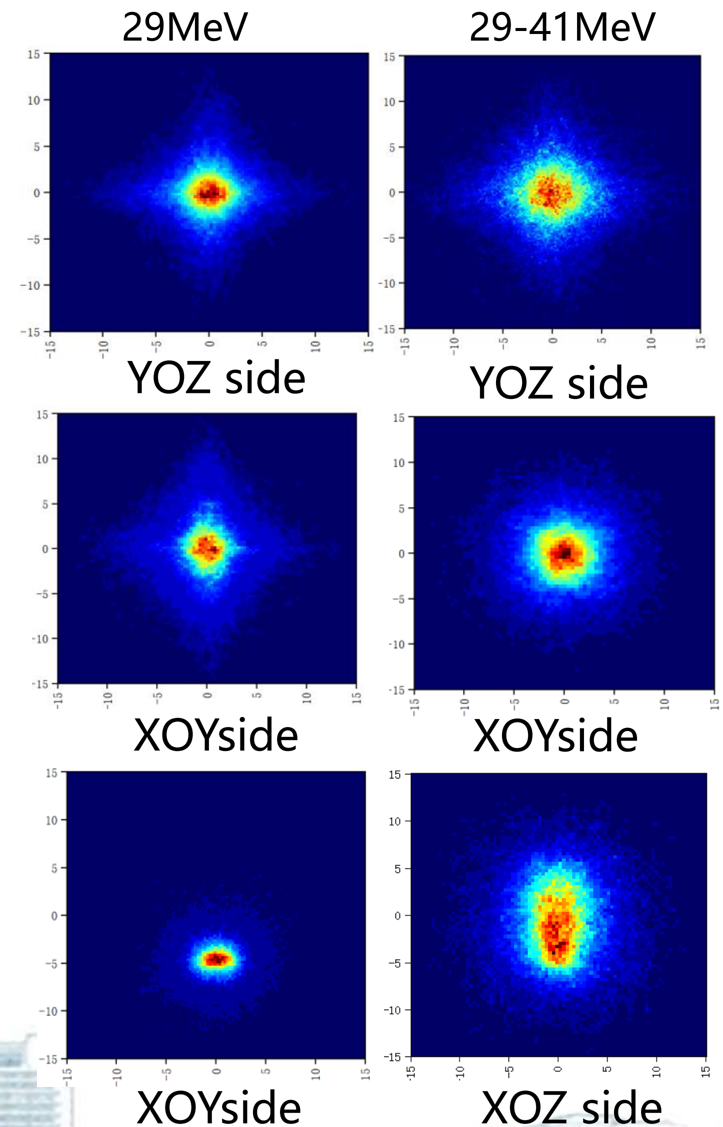
Muon:29-41MeV/c





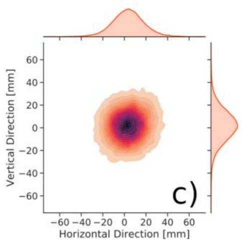


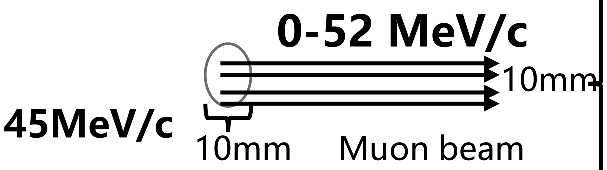
3D reconstruction image

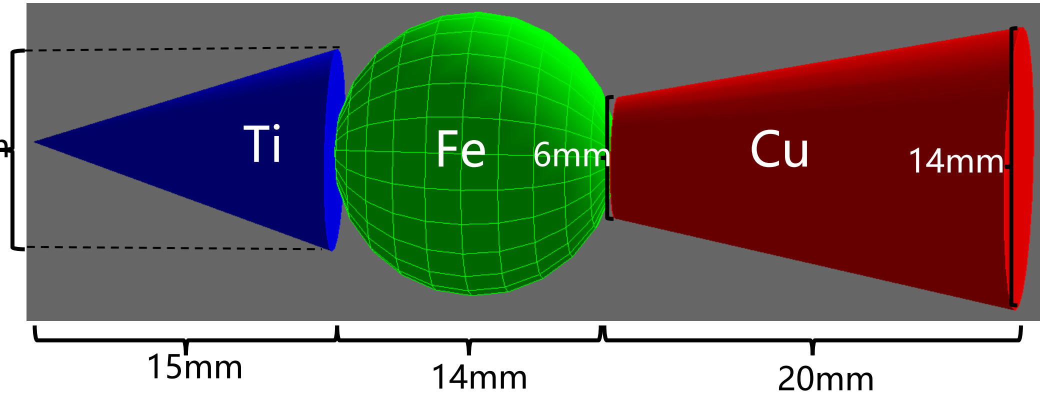


3.5 Sample C imaging result

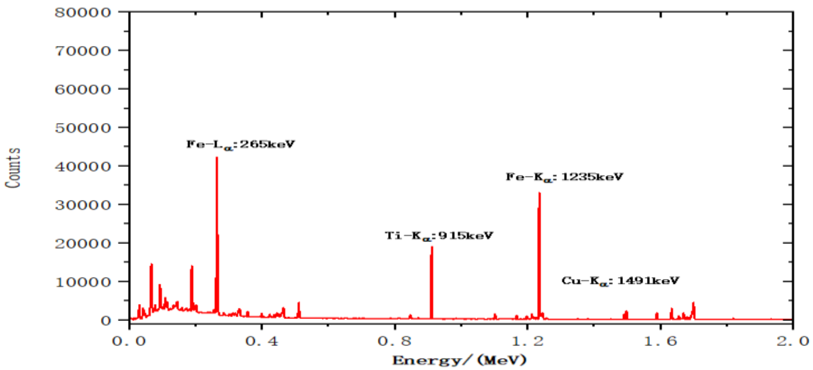
Multi material complex model imaging

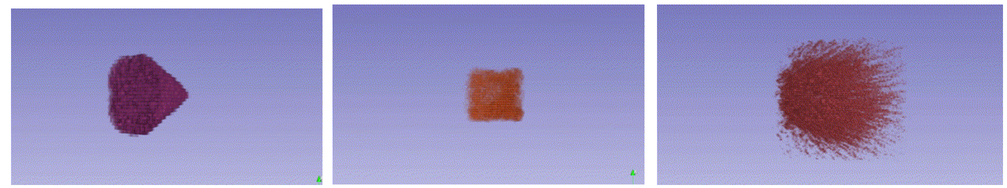


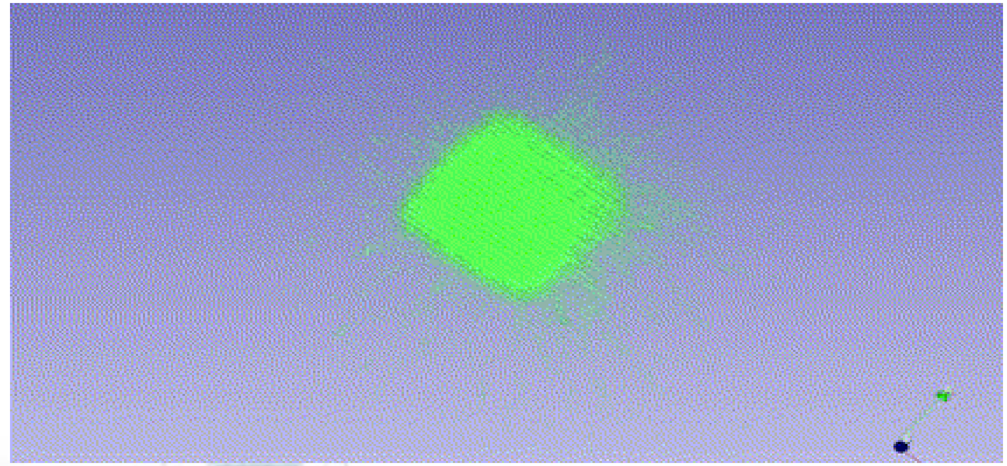




PSI πE1.2 beam spot character



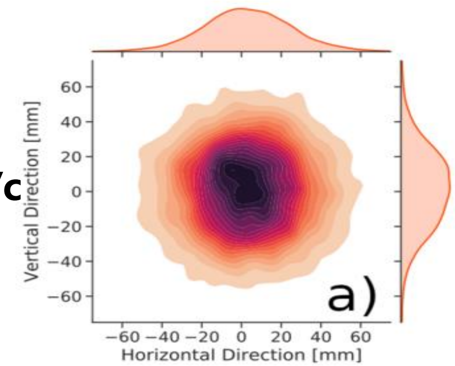




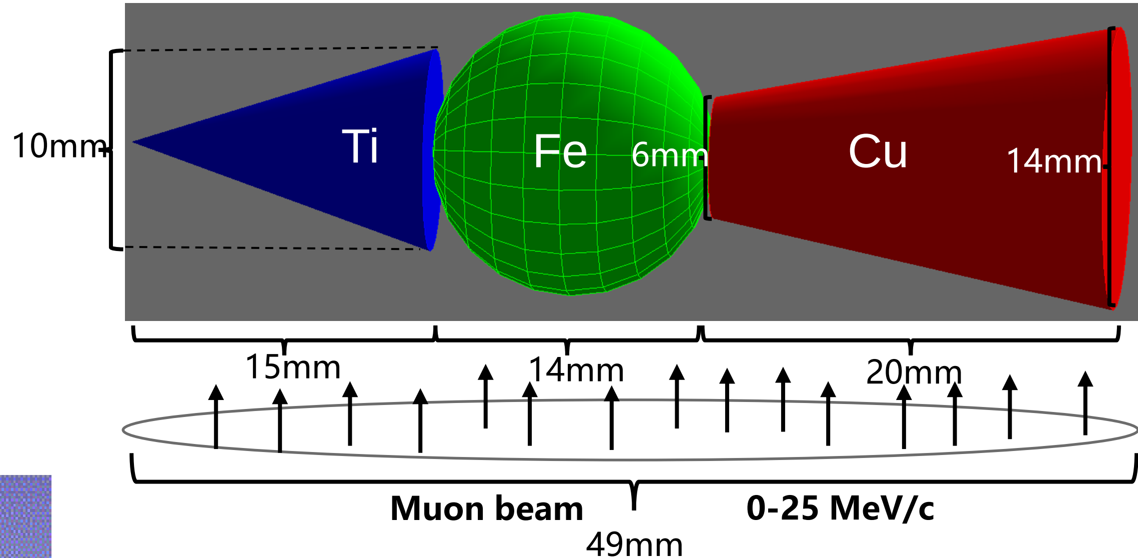
- Photons inside high z objects are not easily ejected .
- The front object causes the muon beam angle deviate resulting in insufficient data when hitting the rear object.
- Muon beam has limited area smaller imaging area so the imaging quality of the rear object is poor .

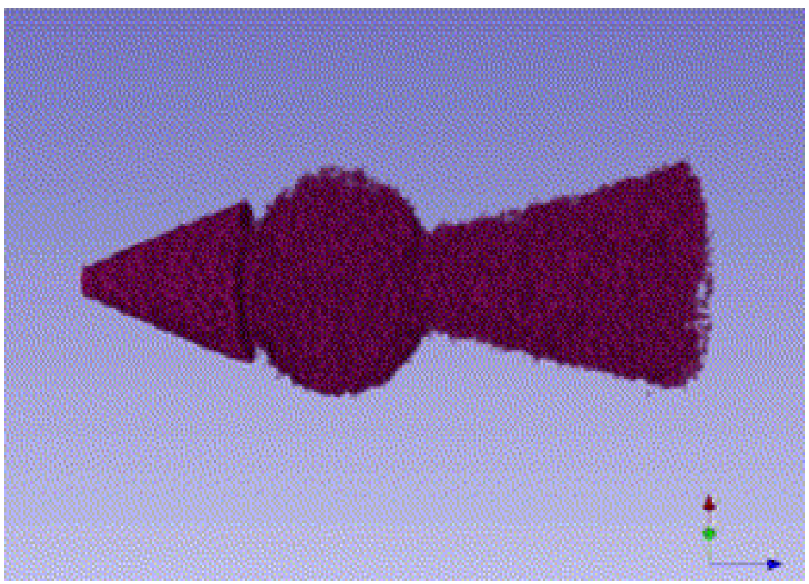
3.5 Sample C imaging result

25MeV/c

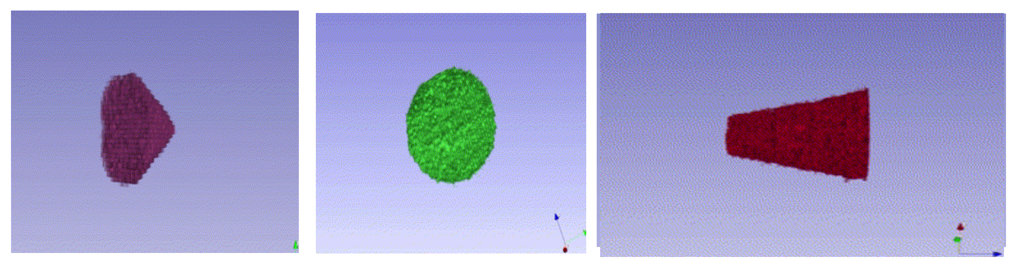


PSI πE1.2 beam spot character





The three objects were rebuilt together



Titanium cone, iron ball, copper table reconstruction

4 Summary and Outlook

Achievement

- The feasibility of using the track density algorithm for imaging has been confirmed in simulations using imaging methods in the MIXE field.

Insufficient:

- Changing the muon energy multiple times to control its depth of capture requires a longer irradiation time, which increases the actual cost,
- In the future, we plan to use a combination of scattering imaging and Moonic X-ray imaging to improve imaging quality.

Future:

- The use of detectors in three locations can only prove the preliminary feasibility of using this algorithm, and additional detectors should be added later to increase the number of collected photon tracks and improve imaging quality.

Thank You！
Welcome any critical comments!