Data related to Muon nuclear capture

as a new demand for nuclear data

Shoichiro Kawase

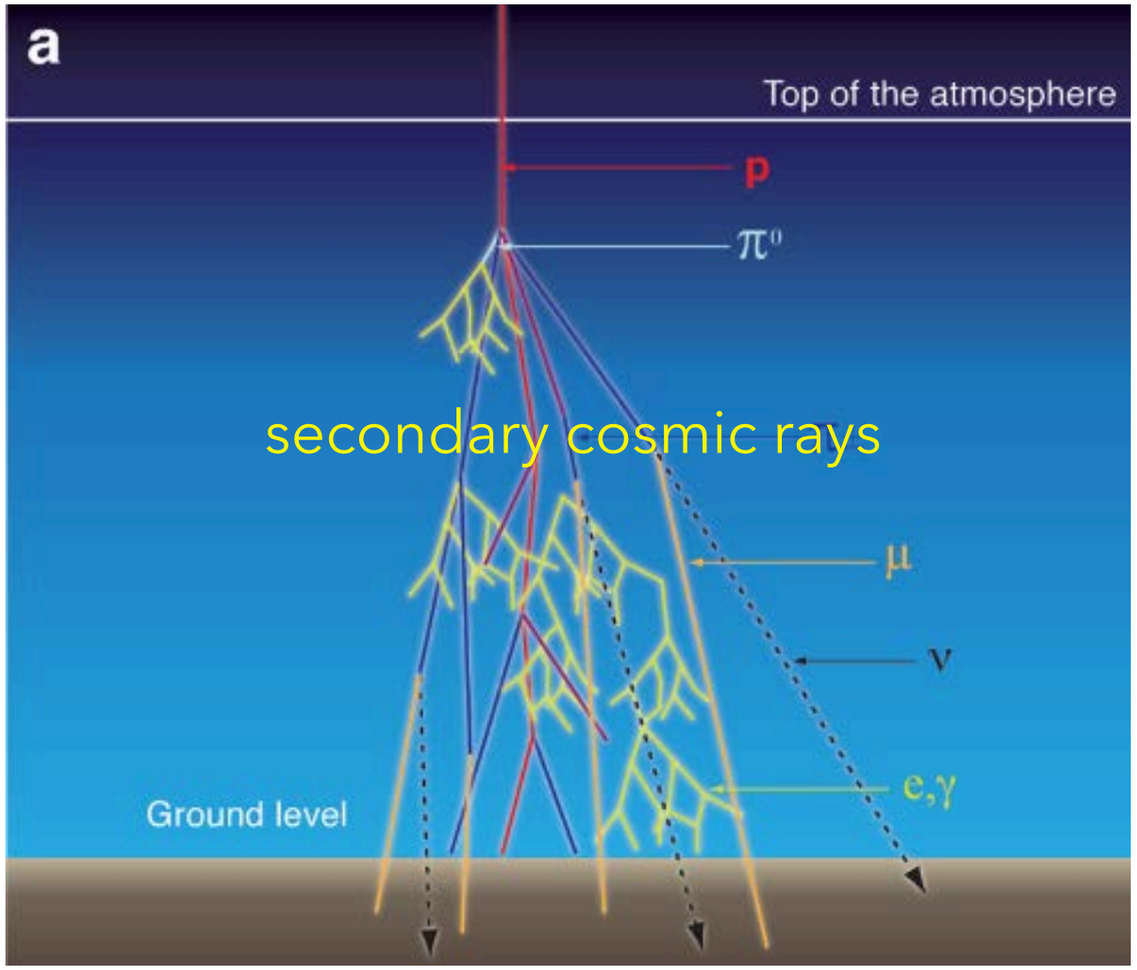
Faculty of Engineering Sciences, Kyushu University

Contents

- Reaction process of muon nuclear capture (μNC)
- Muon nuclear data project
- Recent measurements related to muon nuclear data

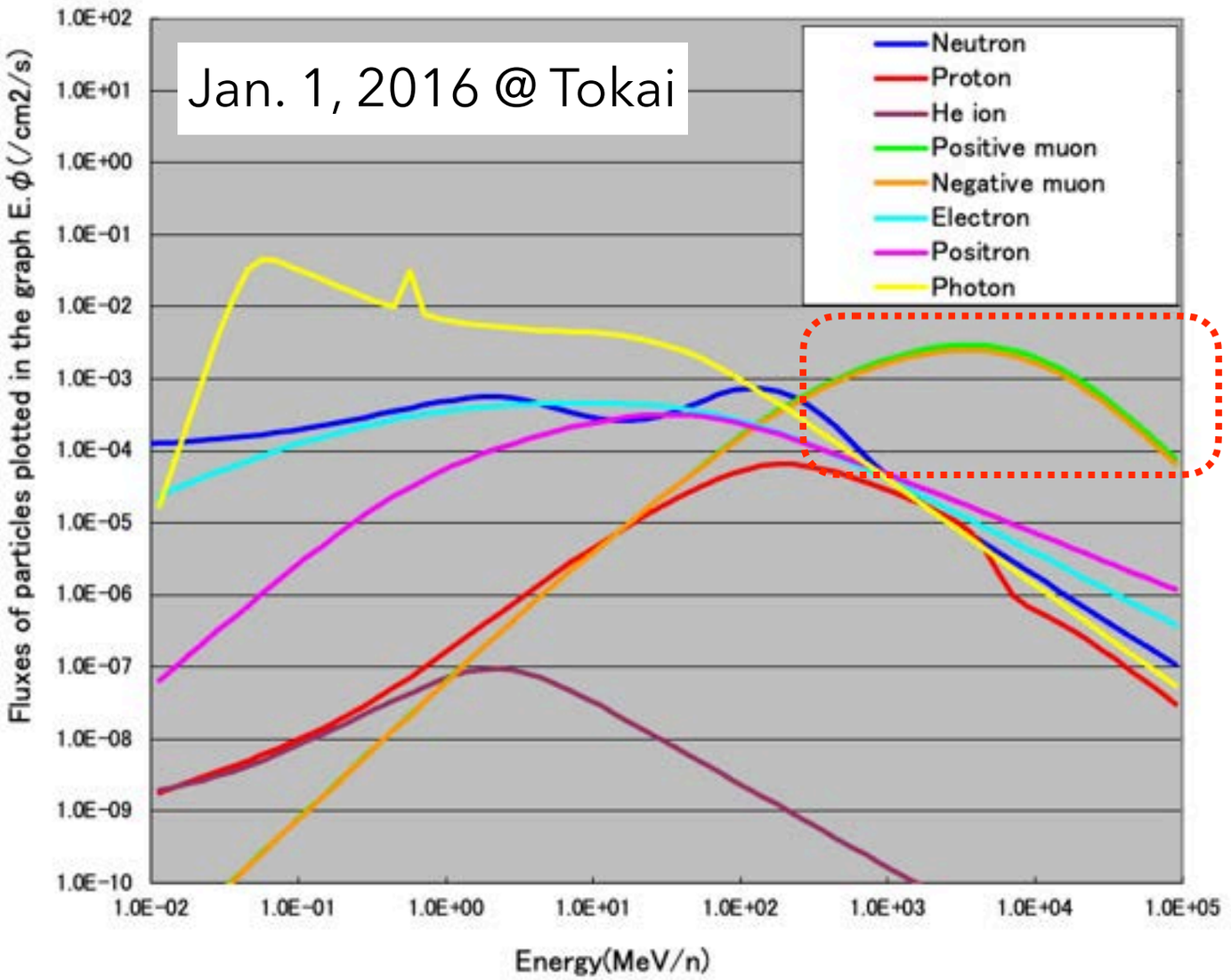
Muons in cosmic ray

primary cosmic ray (p, heavy ions)



secondary cosmic rays

K-H. Kampert, Physics **1**, 37 (2008)

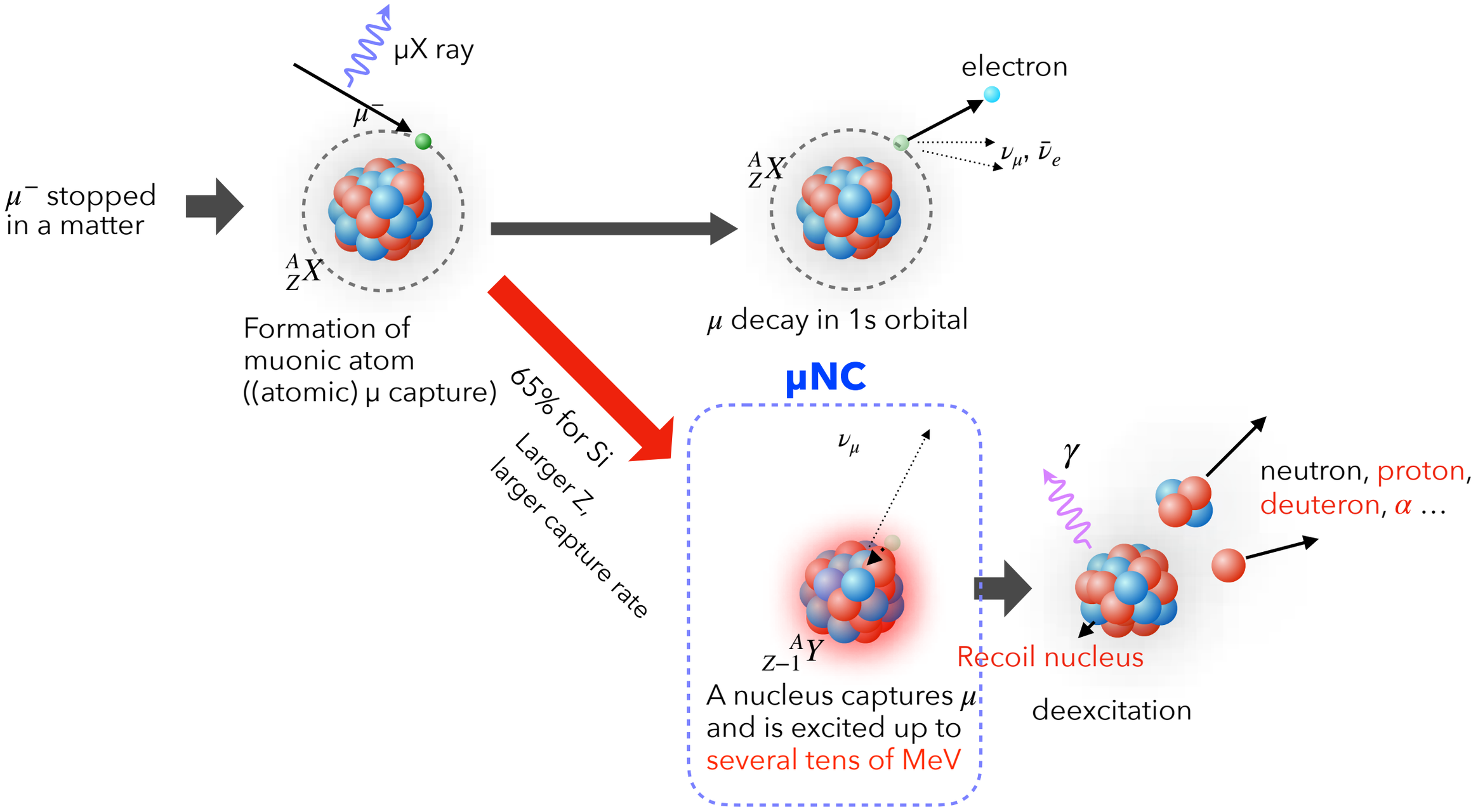


EXPACS: http://phits.jaea.go.jp/expacs/
T. Sato, PLOS ONE 10(12), e0144679

flux ~ 1/cm^2/min ~ 1/s on your palm

Muons are the main component of cosmic rays that bombards us everywhere on the ground

Muon Nuclear Capture (μNC)



μNC is one of "common" nuclear reactions that happens everywhere around you!

μNC's importance in nuclear physics

μNC data is helpful in understanding …

- dynamics through nuclear processes with different timescales:

  direct ($< 10^{-20}$ s), preequilibrium ($< 10^{-18}$ s), and compound ($< 10^{-16}$ s) process

- nuclear reactions induced by the weak interaction

  - *e.g.* β-decay, electron capture,

    neutrino-nucleus reaction (cf. background eval. @ Super-Kamiokande)

higgstan.com

- what happens to nucleus if large excitation energy with small momentum transfer are given

- exotic elementary process involving a nucleon pair: meson exchange current

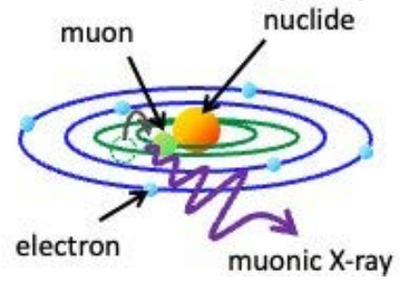
- α-decay and cluster decay process

μNC can provide information on nuclear structure and reactions from a different perspective than conventional reaction probes.

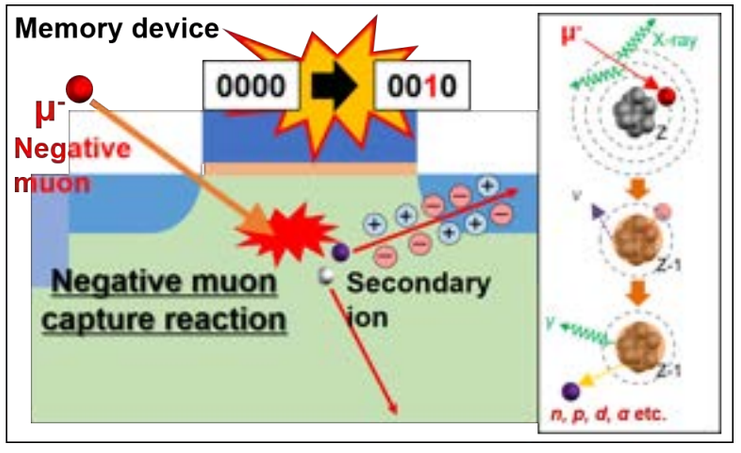
Not just for nuclear physics

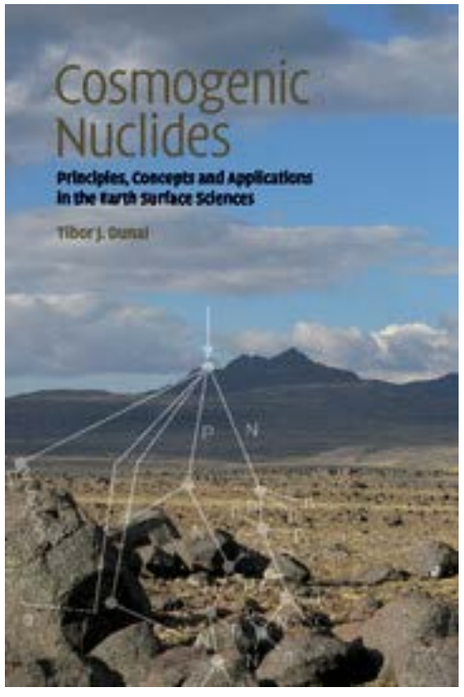
μNC data is also valuable for applications beyond nuclear physics such as…

- Elemental analysis using μX-rays
- Radiation safety at accelerator facilities
- Medical RI production via μNC
- Geochronology using cosmogenic nuclides
- Muon-induced soft errors in semiconductor devices
- and others …



A sample from Ryugu (near earth object)



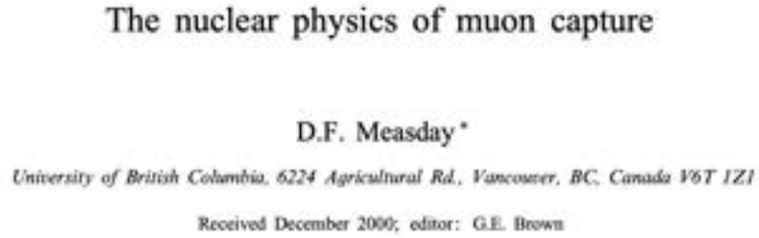


However, available data are limited and not organized…

- Intensive nuclear physics studies using negative muons until ~1980s
- After that, μNC became a ***"forgotten field of research"*** for some reason…

- A comprehensive review article by Measday in *2001* shows incomplete and sometimes contradicting experimental data sets…

D. Measday, Phys. Rep. **354**, 243 (2001)


The nuclear physics of muon capture

D.F. Measday*

University of British Columbia, 6224 Agricultural Rd., Vancouver, BC, Canada V6T 1Z1

Received December 2000; editor: G.E. Brown

- In addition, μNC data is **not standardized** or **even not included** in conventional nuclear data
  - ENSDF: we found 4 entries, but…

    all stand for the same reaction but each is tagged differently!

    B ^{48}Ca(MU,nγ): AT REST

    I ^{127}I(μ$^-$,νnγ)

    O ^{197}Au(μ$^-$,nγ)

    H ^{207}Pb(μ$^-$,γ)
  - EXFOR: **no reaction identifier for muon reactions**

Muon nuclear data (μND) project

For comprehensive understanding of μNC and contribution to its application

M. Niikura et al., JAEA Conf. 2024-02 (2024), pp. 29-34, in press (arXiv:2403.19965).

Development team as of Nov 2024:
M. Niikura (RIKEN), S. Abe (JAEA), H. Iwamoto (JAEA), S. Kawase (Kyushu U),
N. Kawamura (KEK), D. Tomono (Osaka U/KEK), T. Matsuzaki (RIKEN)
R. Mizuno (U Tokyo), F. Minato (Kyushu U), Y. Yamaguchi (JAEA), Y. Watanabe (Kyushu U)
A. D. Hillier (RAL), S. Biswas (RAL)

μND will consist of both experimental and evaluated data of …

(1) Energies and intensities of the muonic X rays

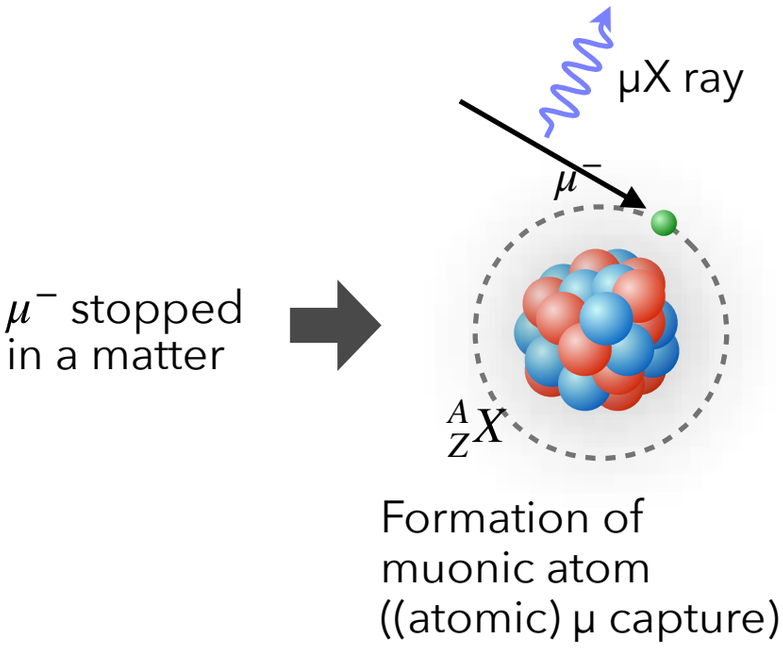
(2) Lifetimes of muonic atoms (μNC probability)

(3) Isotopic production probability through muon nuclear capture

(4) Energy spectra of nuclear fragments emitted after muon nuclear capture

μND Sublibraries

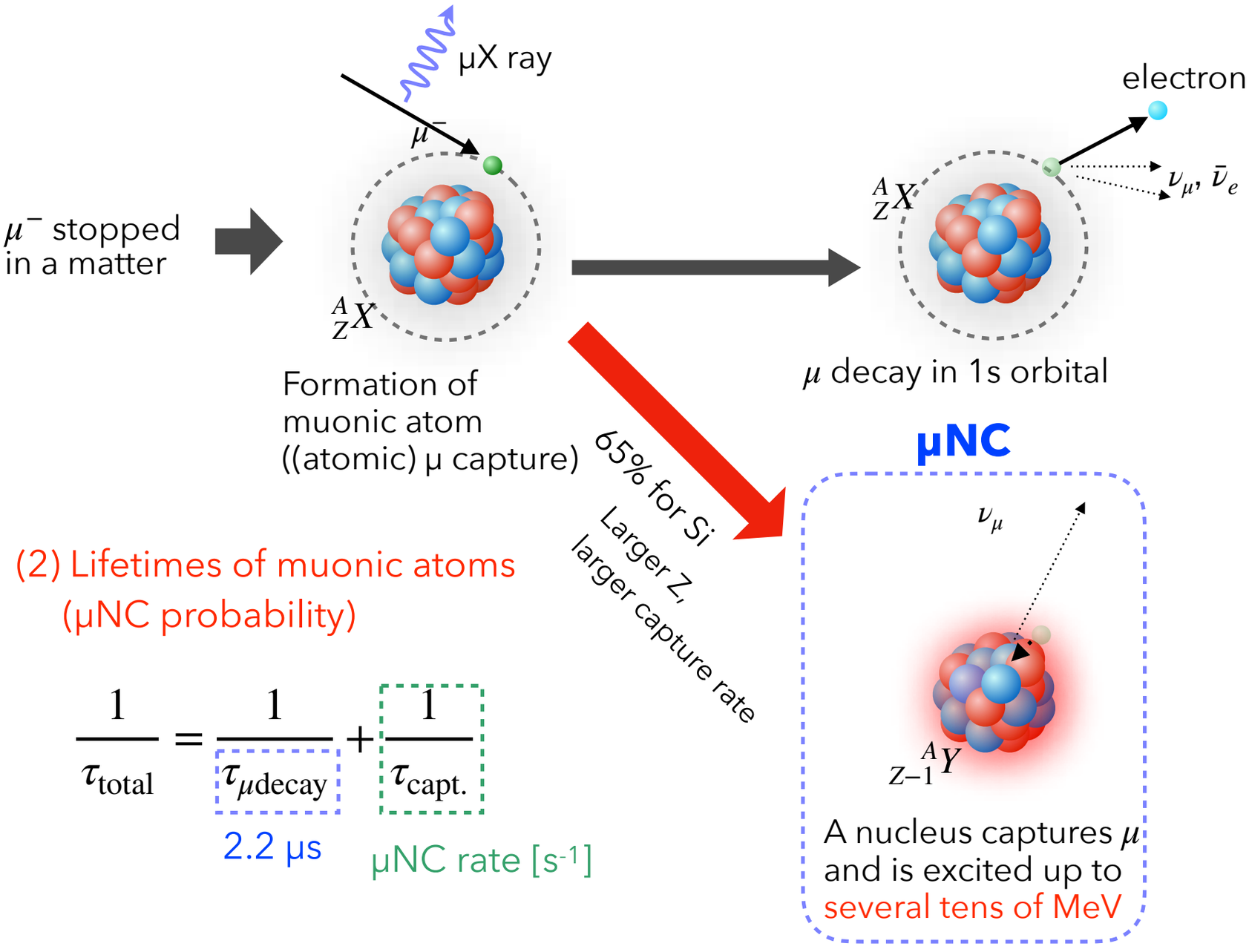
(1) Energies and intensities of the muonic X rays



necessary for elemental analysis w/ μX-rays

μND Sublibraries

(1) Energies and intensities of the muonic X rays



(2) Lifetimes of muonic atoms (μNC probability)

$$\frac{1}{\tau_{\text{total}}} = \frac{1}{\tau_{\mu\text{decay}}} + \frac{1}{\tau_{\text{capt.}}}$$

2.2 μs

μNC rate [s^{-1}]

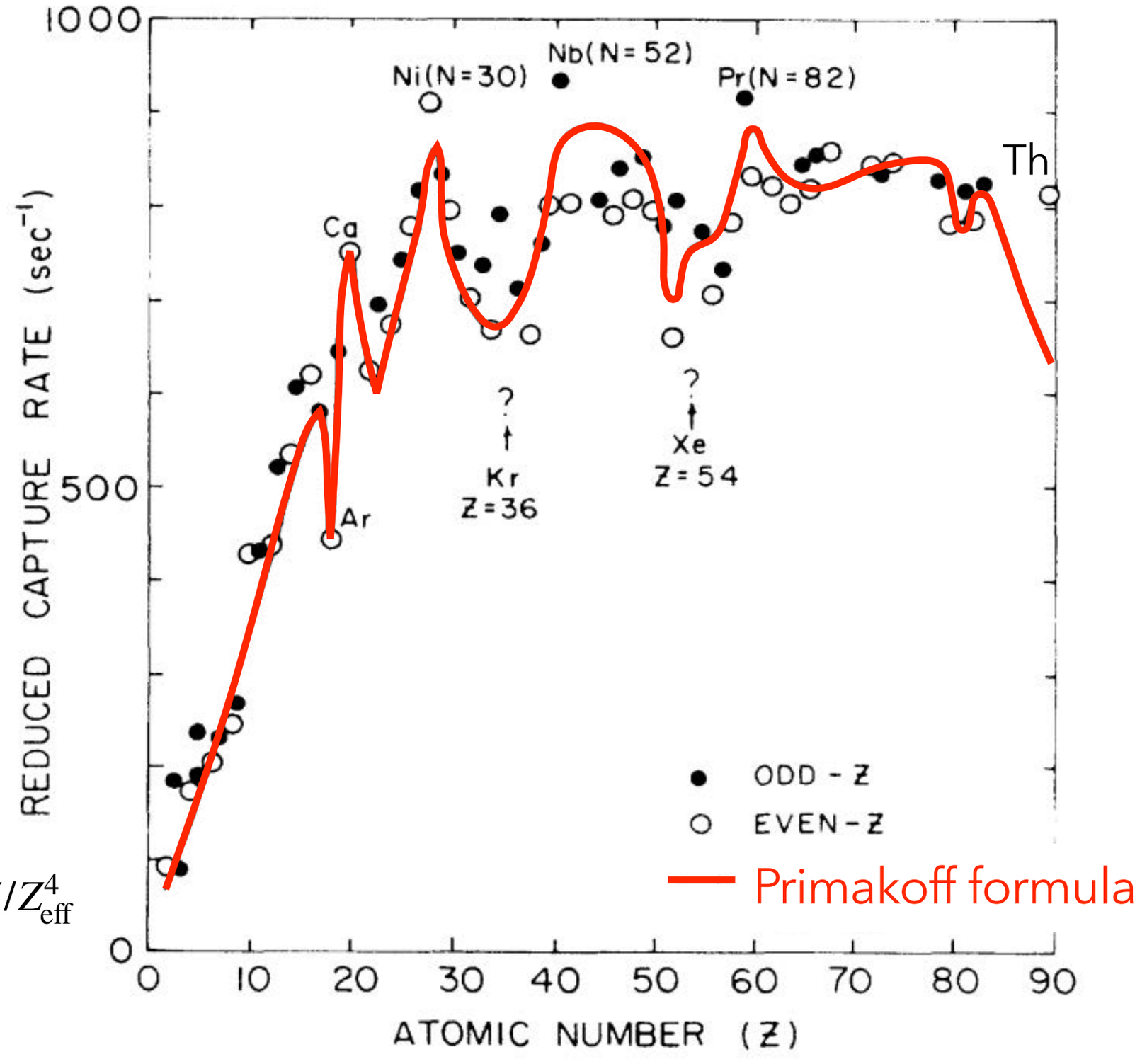
necessary for elemental analysis w/ decay electrons

Lifetime of muonic atoms

Systematic data on the lifetime of muonic atoms have been taken across a wide range of elements

Overall trend can be reproduced by the Primakoff formula but the fluctuation is not fully understood.

$$= \Lambda_{\mathrm{capt}}^{\mathrm{exp}} Z / Z_{\mathrm{eff}}^{4}$$

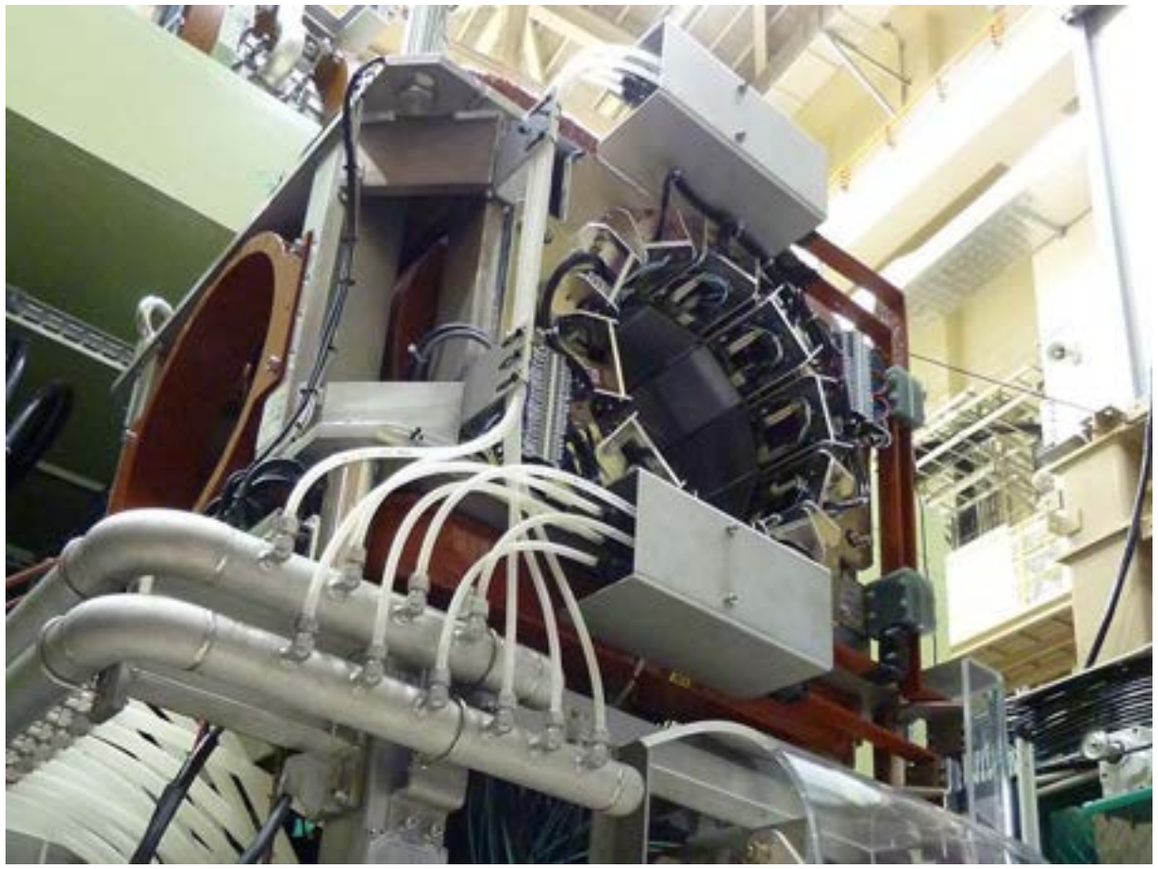


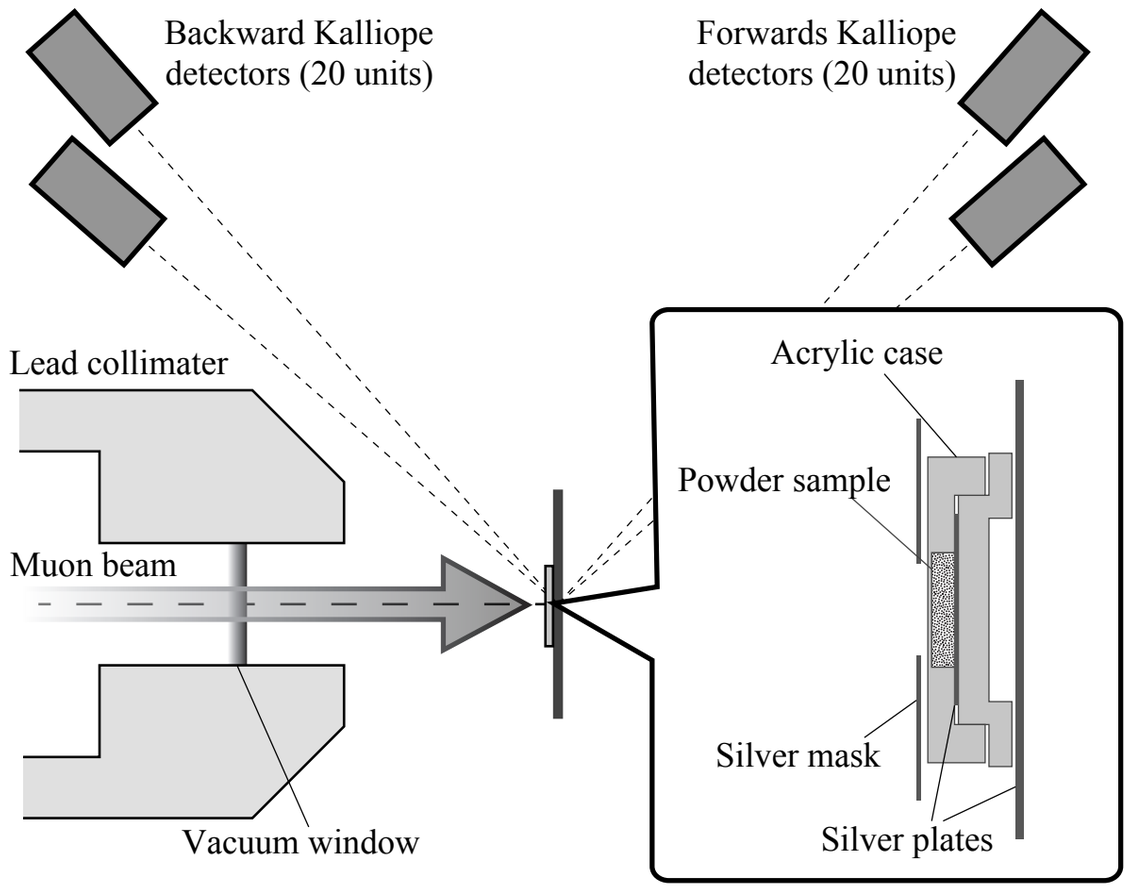
T. Suzuki, D.F. Measday, and J.P. Roalsvig, Phys. Rev. C 35, 2212 (1987).

Lifetime of muonic atoms: recent progress

R. Mizuno et al., in preparation

Kalliope μSR spectrometer @ J-PARC MLF D1

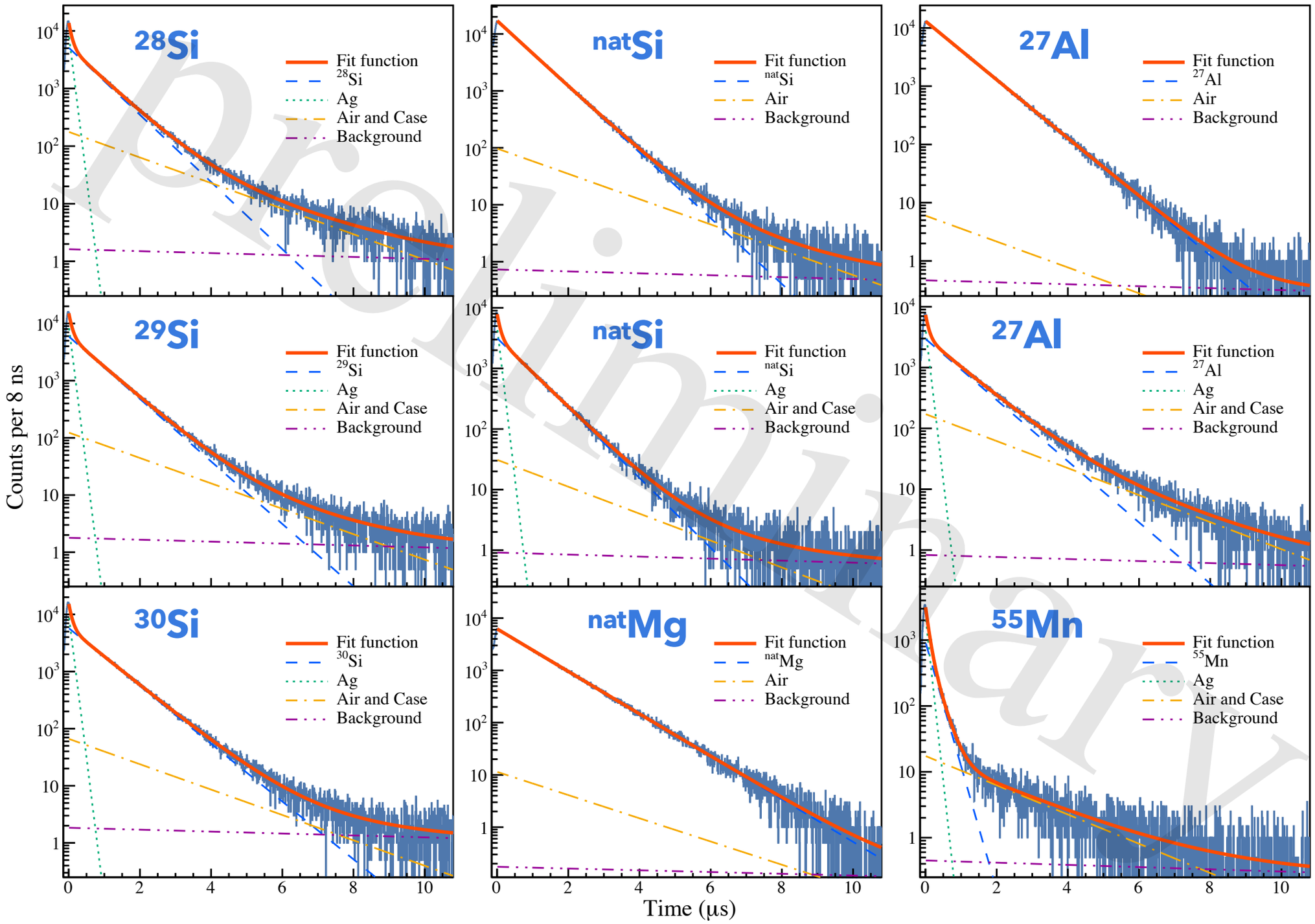




- Lifetime of μ-Mg, -Al, -**Si** (w/ enriched targets) and -Mn were measured.
  for observation of the isotopic effect

Lifetime of muonic atoms: recent progress

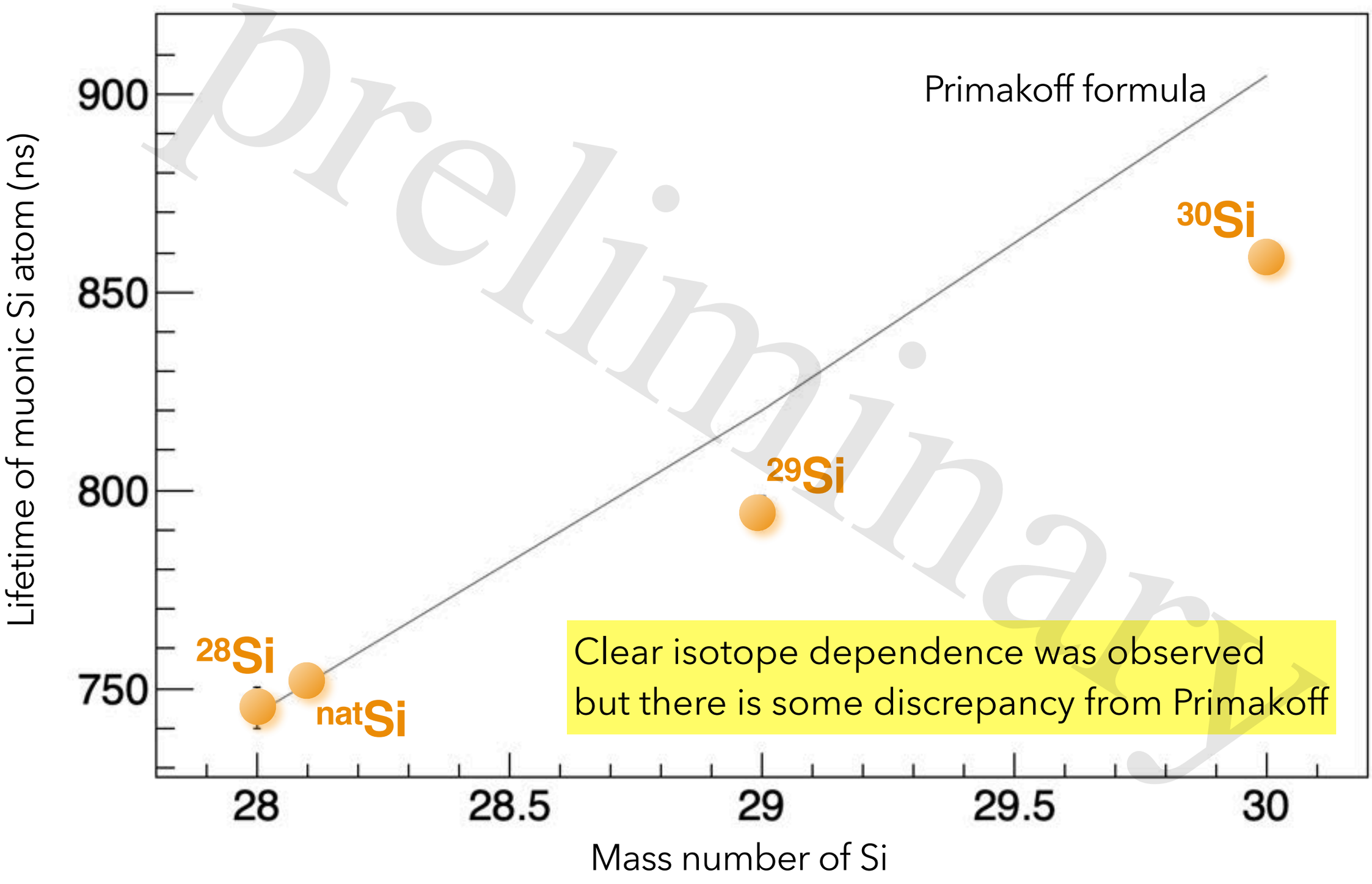
R. Mizuno et al., in preparation



Timing spectra of decay electrons

Lifetime of muonic atom of Si isotopes

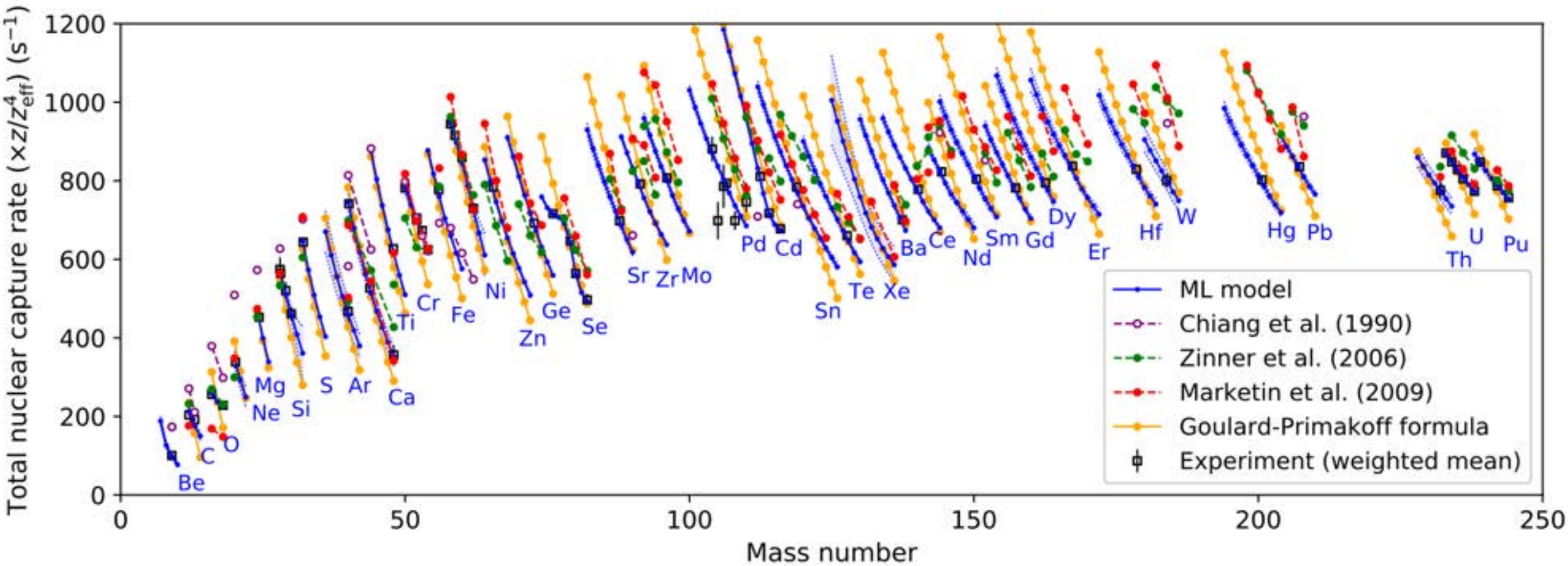
R. Mizuno et al., in preparation



Evaluation of capture rates using Gaussian process regression

H. Iwamoto (JAEA), submitted to PRC

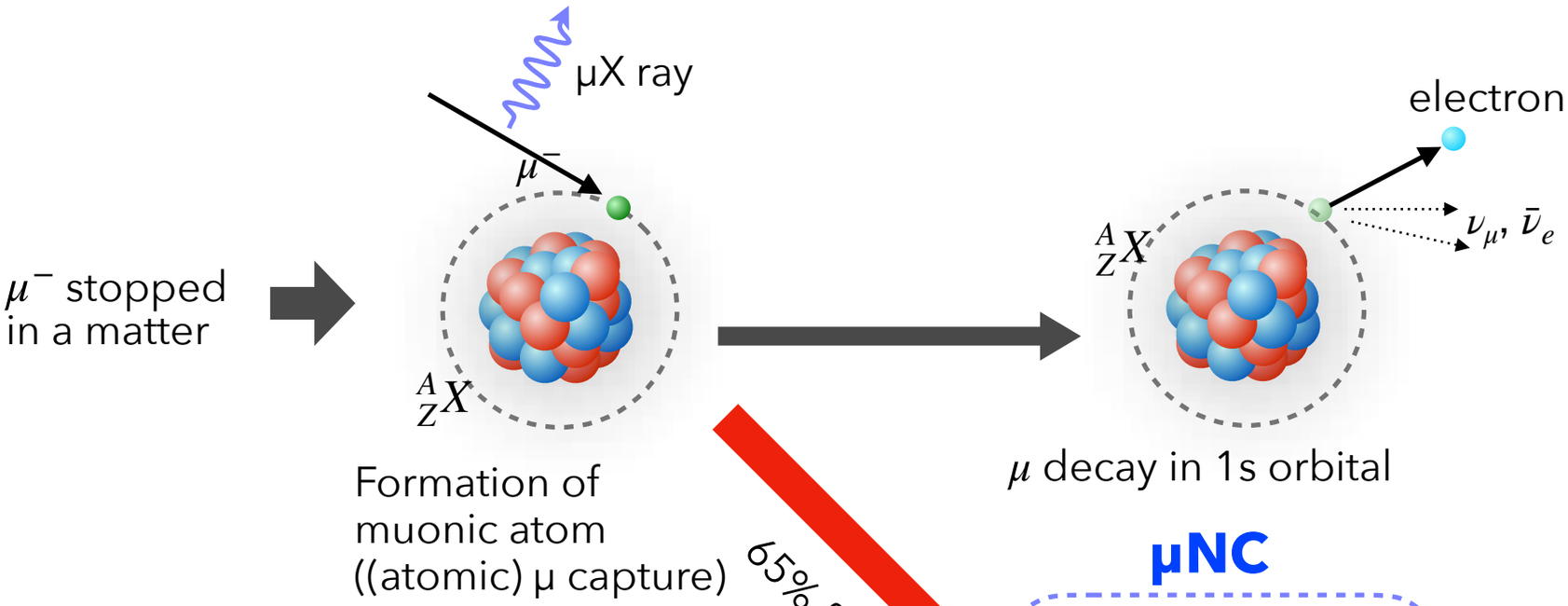
The muon capture rates for wide range of elements were evaluated with uncertainties using Gaussian process regression.



it seems promising…

μND Sublibraries

(1) Energies and intensities of the muonic X rays



(2) Lifetimes of muonic atoms (μNC probability)

$$\frac{1}{\tau_{\text{total}}} = \frac{1}{\tau_{\mu\text{decay}}} + \frac{1}{\tau_{\text{capt.}}}$$

2.2 μs

μNC rate [s^{-1}]

(3) Isotopic production probability through muon nuclear capture

unit: /μ-capture

Branching ratio: ex) 0p1n: 30%, …

necessary for radiation safety, geochronology

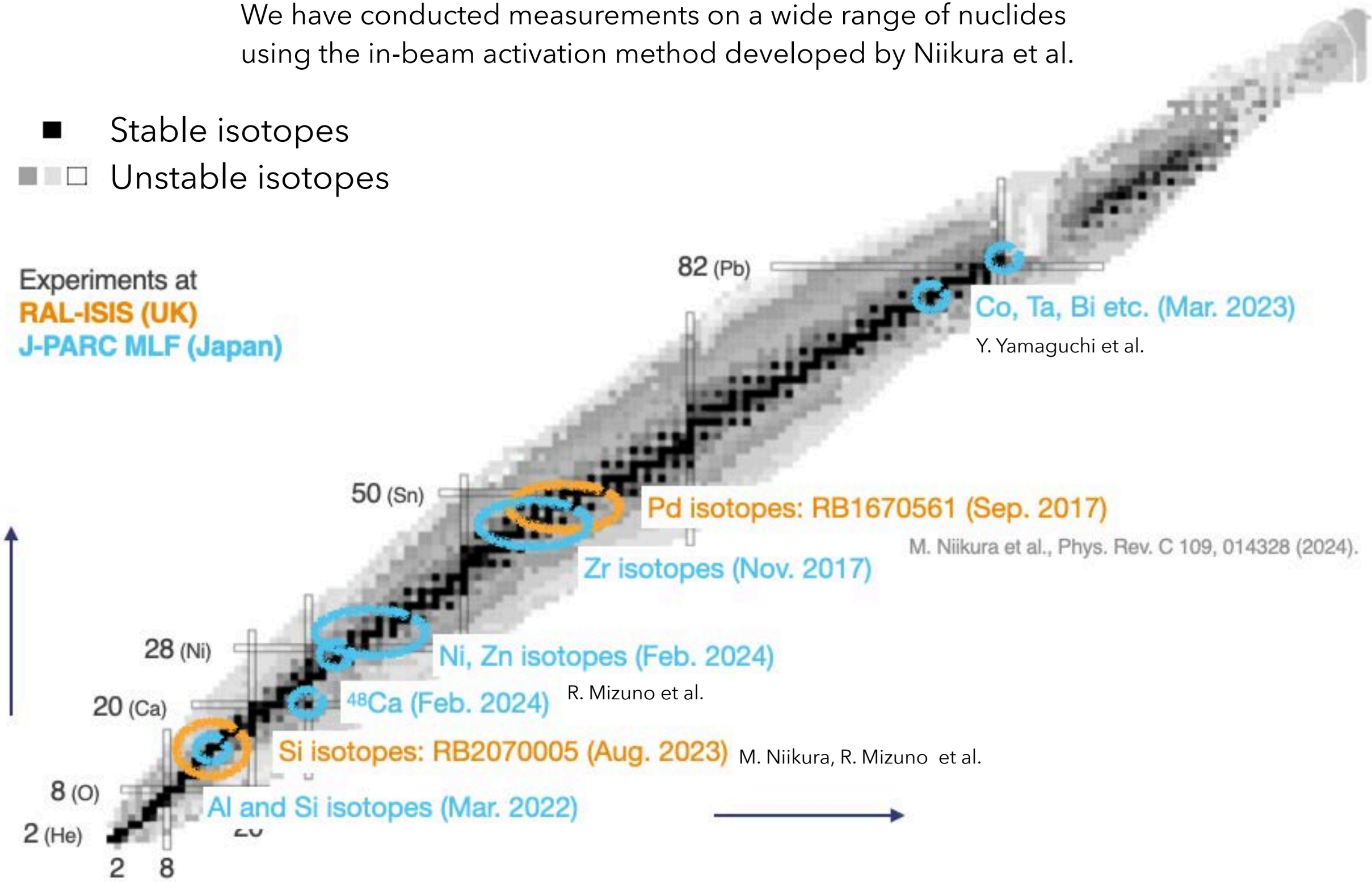
Isotopic production probability through muon nuclear capture

We have conducted measurements on a wide range of nuclides
using the in-beam activation method developed by Niikura et al.

■ Stable isotopes

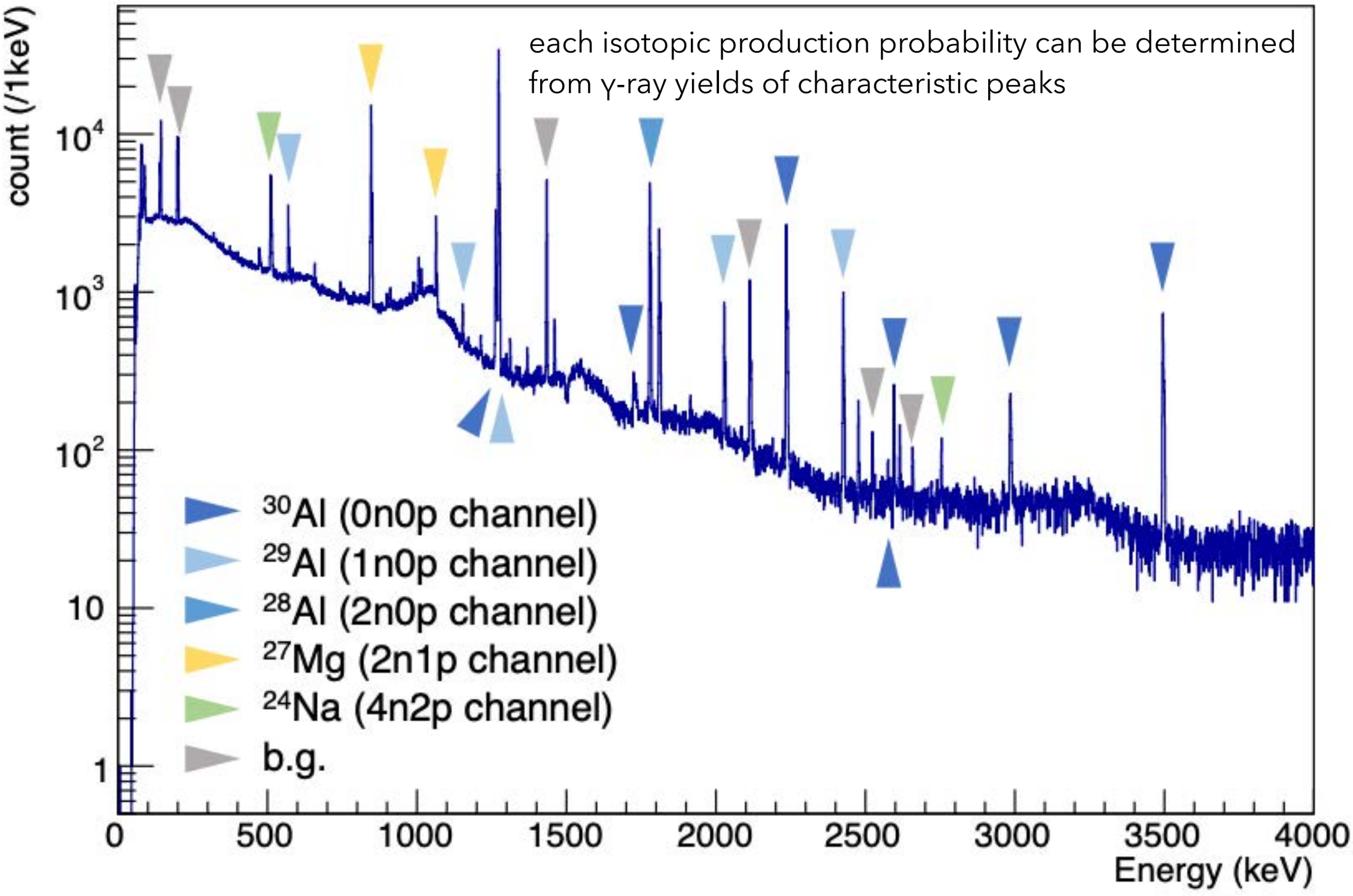
■ ■ □ Unstable isotopes

Experiments at
RAL-ISIS (UK)
J-PARC MLF (Japan)



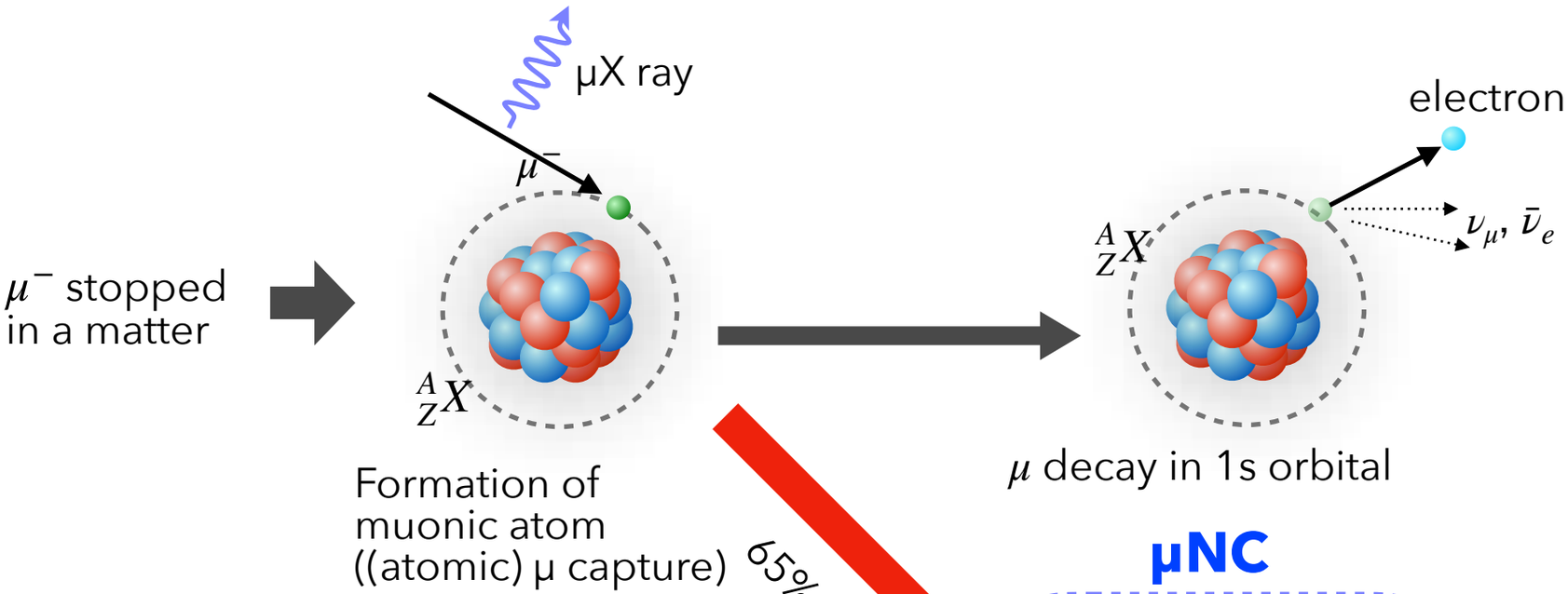
Beta-delayed gamma-ray spectrum from residual of μNC @ ^{30}Si

by R. Mizuno (U Tokyo)



μND Sublibraries

(1) Energies and intensities of the muonic X rays



necessary for μ-induced soft error evaluation

unit: /μ-capture/MeV

(4) Energy spectra of nuclear fragments emitted after muon nuclear capture

(2) Lifetimes of muonic atoms (μNC probability)

$$\frac{1}{\tau_{\text{total}}} = \frac{1}{\tau_{\mu\text{decay}}} + \frac{1}{\tau_{\text{capt.}}}$$

2.2 μs

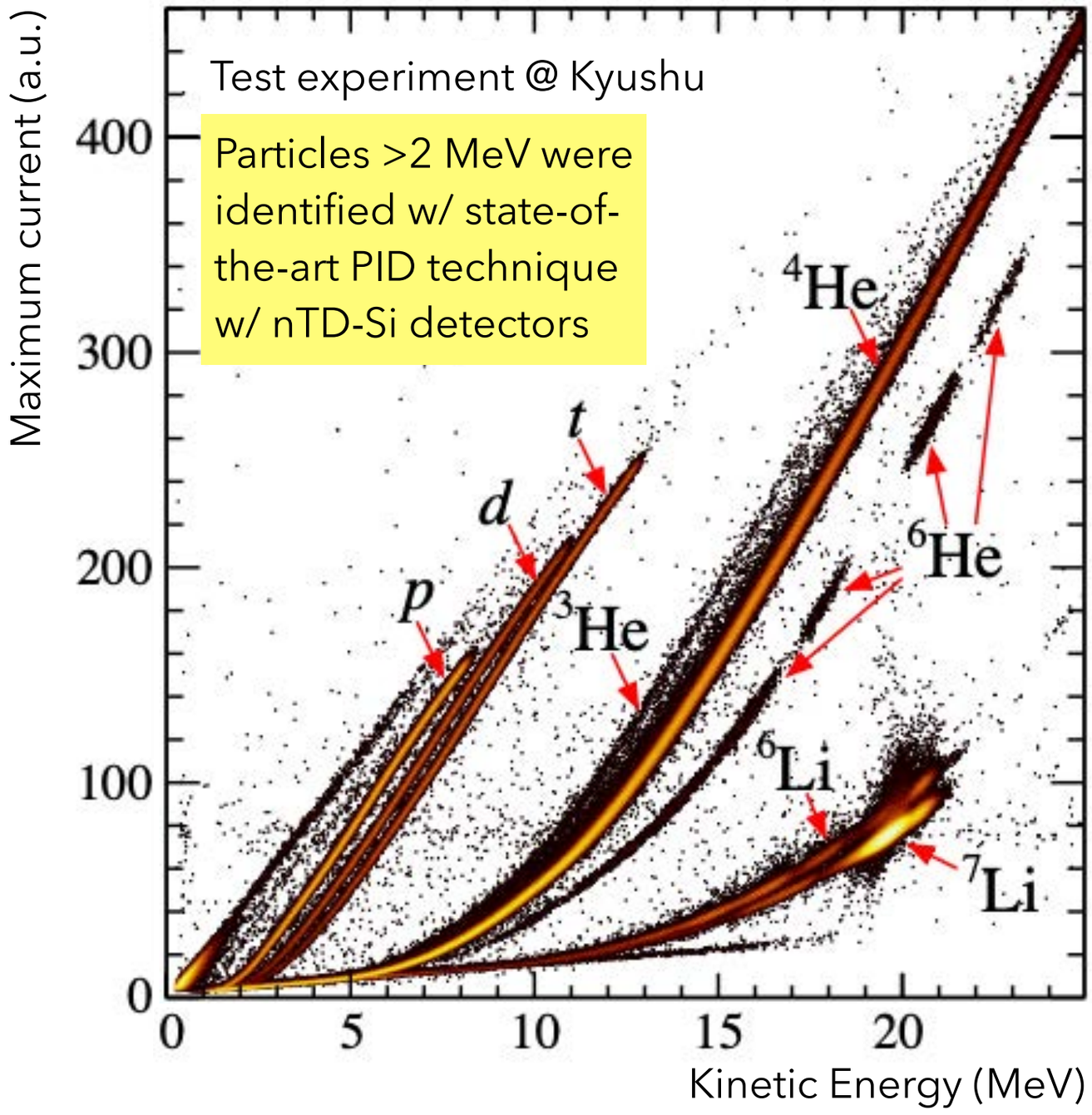
μNC rate [s^{-1}]

(3) Isotopic production probability through muon nuclear capture

Energy spectra of nuclear fragments emitted after muon nuclear capture

Telescope consists of
Si and CsI detectors

setup @ RAL (Jul 2024)

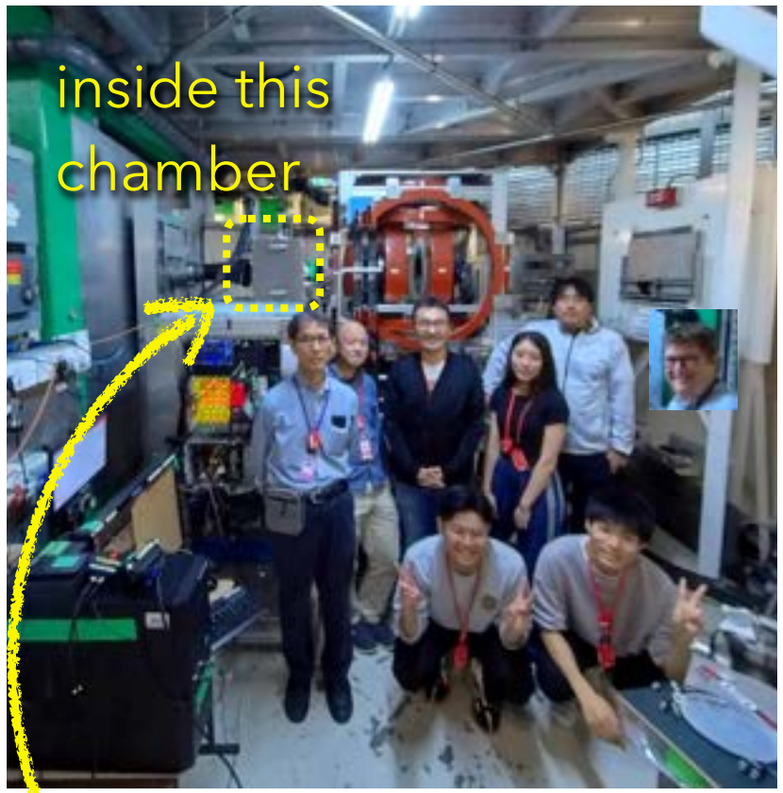


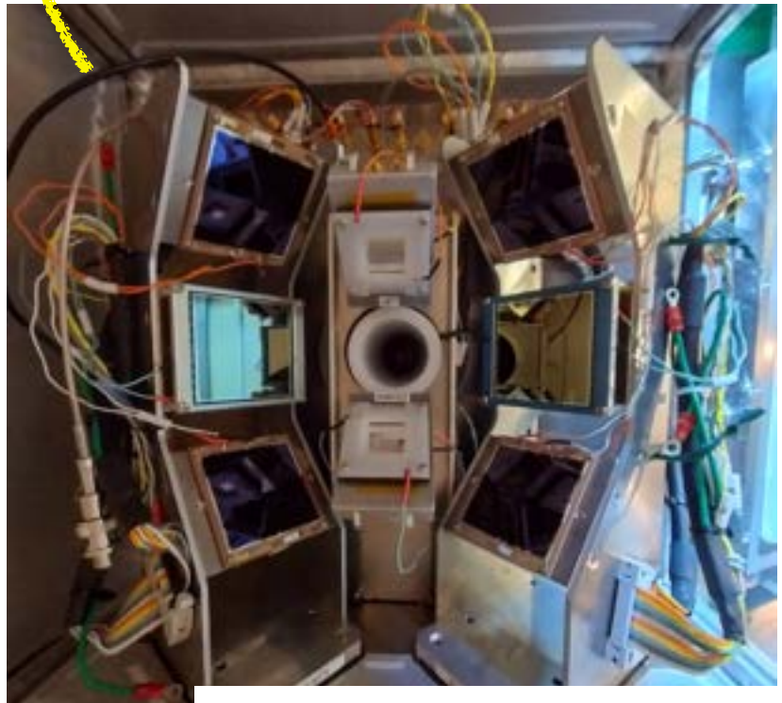
S. Kawase et al., Nucl. Instrum. Meth. A **1059**, 168984 (2024).

A dedicated detector system for charged particle emission from μNC were developed.

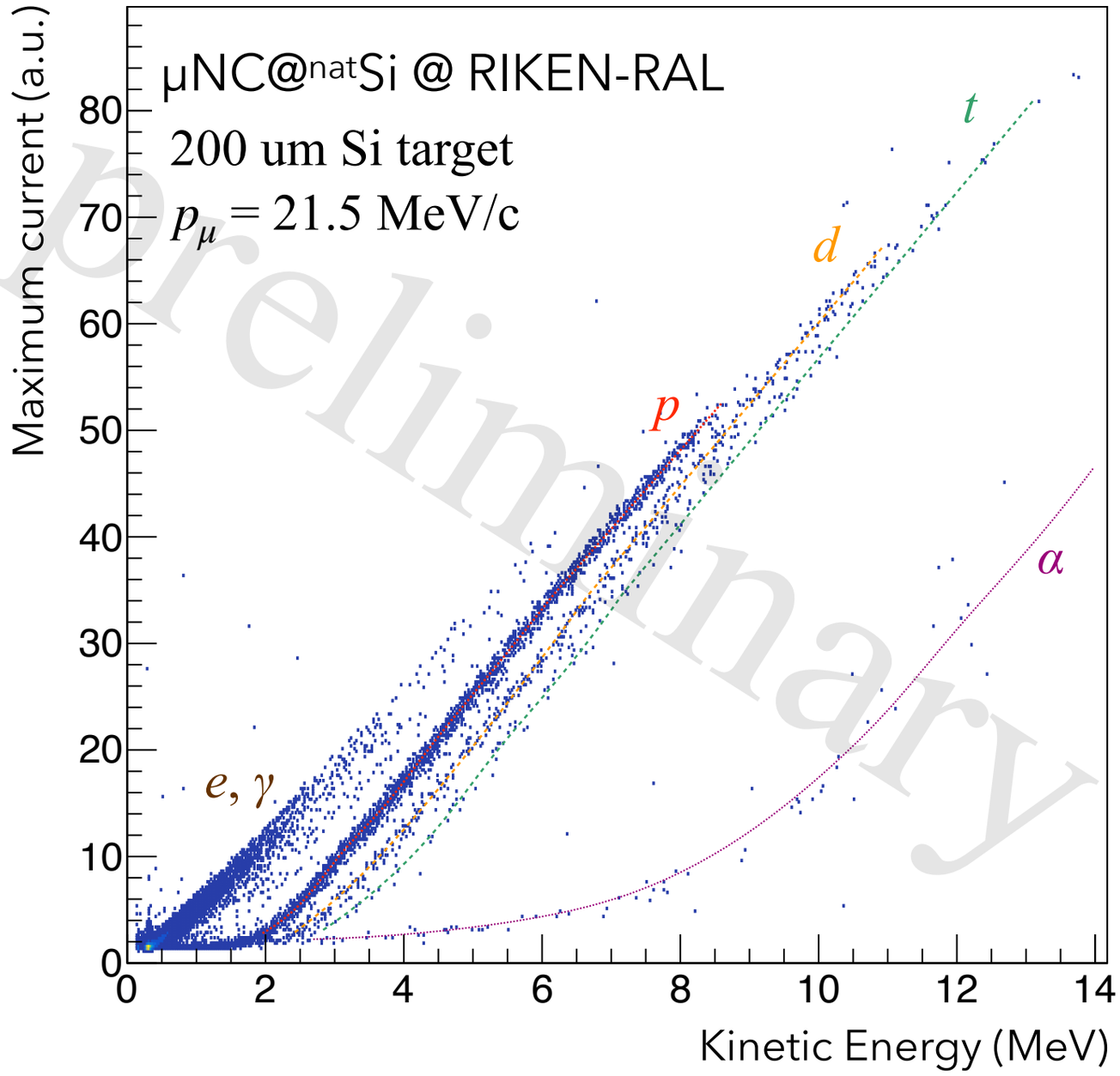
Energy spectra of nuclear fragments emitted after muon nuclear capture

SK, K. Kawata, K. Kitafuji, Y. Watanabe, M. Niikura, R. Mizuno, K. Ishida, T. Matsuzaki, D. Tomono, A. D. Hillier





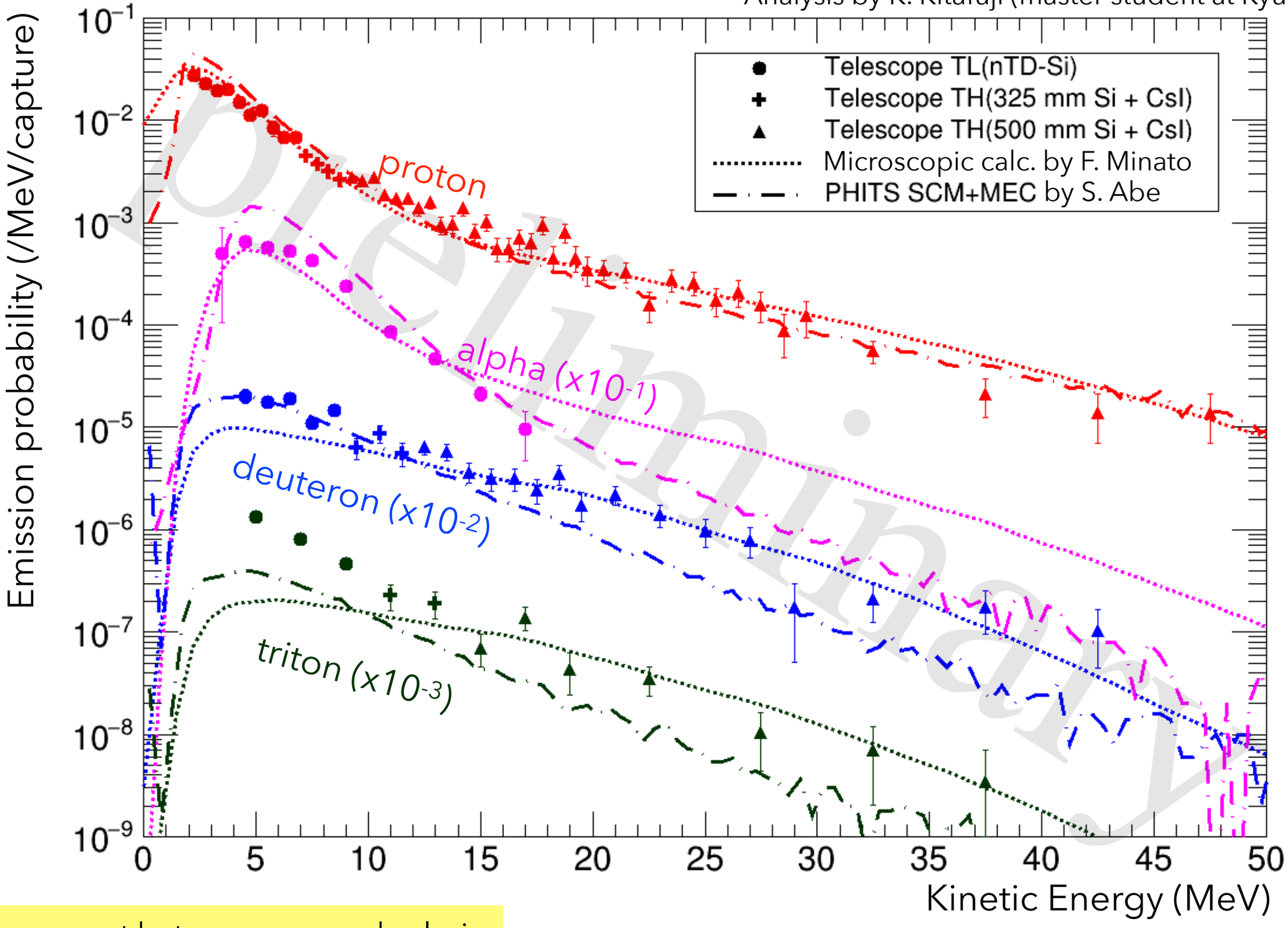
setup @ RAL (Jul 2023)



Low energy nuclear fragments emitted from μNC @ Si were successfully identified.

Energy spectra of nuclear fragments emitted after muon nuclear capture

Analysis by K. Kitafuji (master student at Kyushu U)



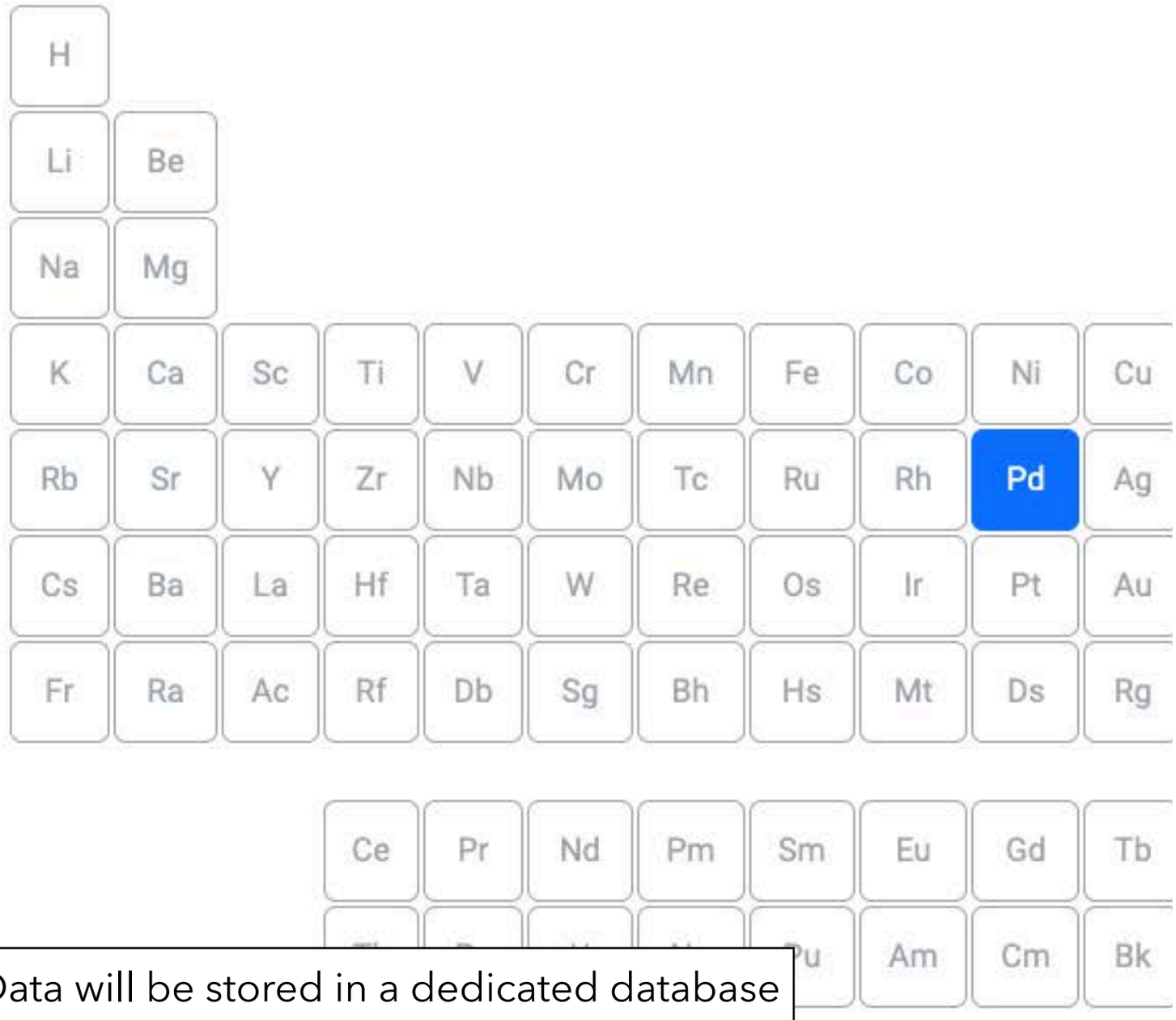
Agreement between exp. and calc. is remarkably good for p and α.

Future: other targets, multi-particle measurement

Muon nuclear data web page (WIP)

not published yet

Muon Nuclear Data



Data will be stored in a dedicated database and convert it to some formats as needed.

muND for Pd (Z=46)

^{nat}Pd

Natual aboundance

Atomic mass: 106.42

^{102}Pd	^{104}Pd	^{105}Pd	^{106}Pd	^{108}Pd	^{110}Pd
1.02%	11.14%	22.33%	27.33%	26.46%	11.72%

Muonic X-ray energy

Mesoroentgen Spectra Catalogue (JINR)

Lifetime of muonic atom

Huff factor	0.927
Mean life	96.0(6) [ns]
Capture rate	10.00(7) [10^6/s]
Capture probability	95%

^{104}Pd$_{58}$

Lifetime of muonic atom

Mean life	87(3) [ns]
Capture rate	11.1(4) [10^6/s]
Capture probability	95%

Production branch of residual nuclei

M. Niikura et al., Phys. Rev. C 109, 014328 (2024).

Summary

- **Muon nuclear capture (μNC) is one of "common" nuclear reactions** that happens everywhere around you!
- μNC can provide **information on nuclear structure and reactions** from a new perspective than conventional reaction probes.
- μNC data is also valuable for some **applications** such as radiation safety, soft error evaluation, and geochronology. *What's coming next?*
- Since currently available data sets are limited and not organized, we have launched a project to develop **muon nuclear data**, compiling both experimental and evaluated data relevant to μNC, independently from conventional nuclear data.
- We will advance comprehensive studies including experimental measurements and theoretical model analyses on μNC.

Thank you for your attention!