Measurement of charged particle spectra emitted following muon nuclear capture in Si nuclei

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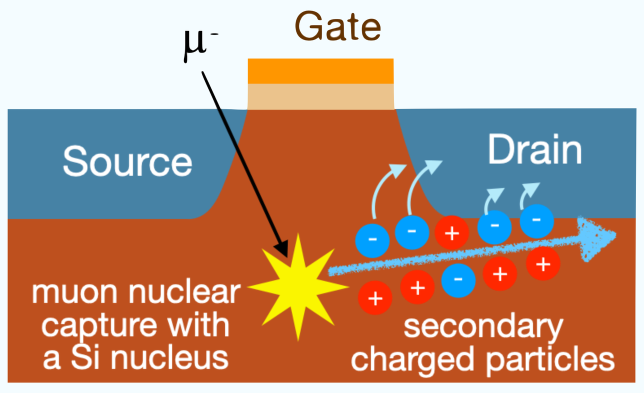
Muon induced soft error

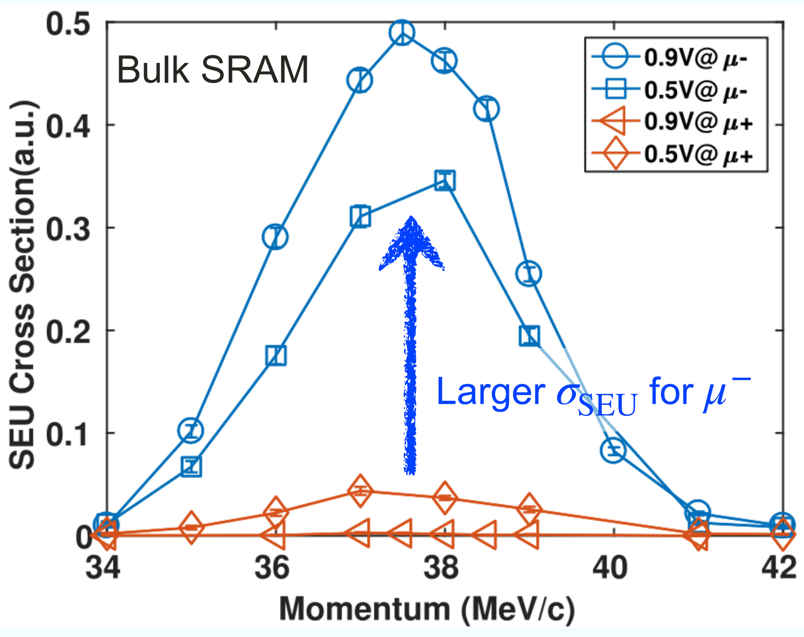
When radiation enters a semiconductor device, soft errors can occur. The impact of cosmic-ray muons is expected to increase with the miniaturization of semiconductor processes.

B. D. Sierawski et al, IEEE Trans. Nucl. Sci. **57**, 3273 (2010)



Secondary charged particles emitted following the (negative) muon nuclear capture in Si, increase the soft-error cross section.

W. Liao et al., IEEE Trans. Nucl. Sci., **65** (8), 1734 (2018).

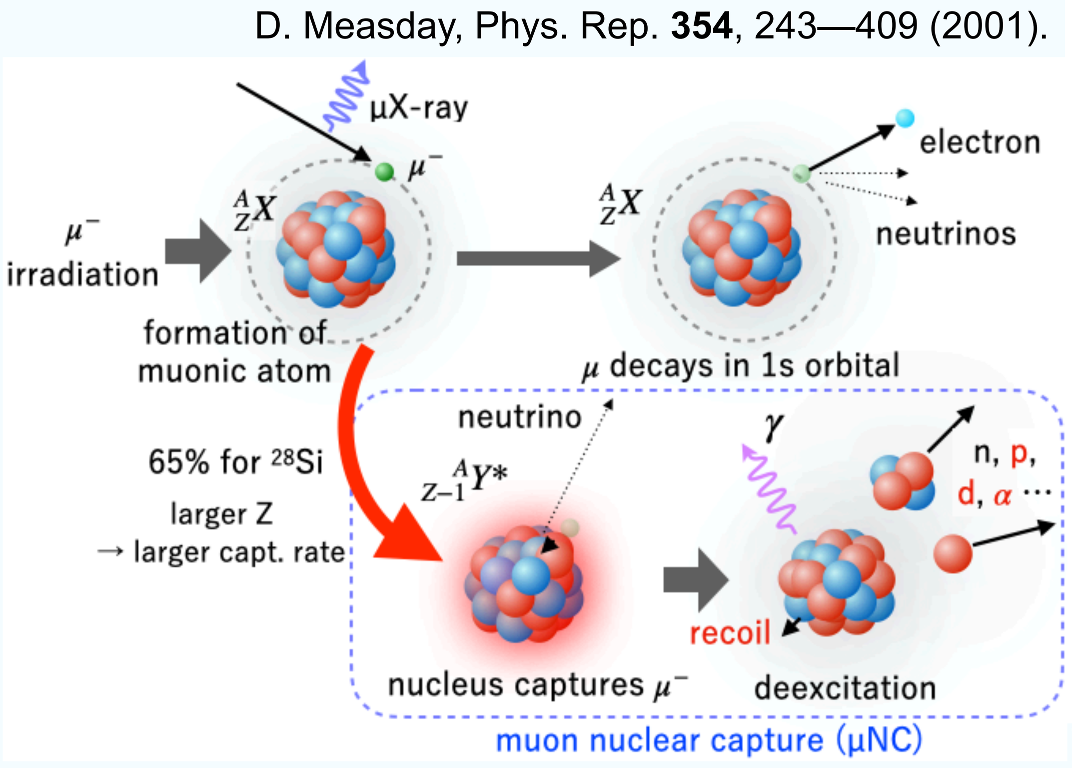


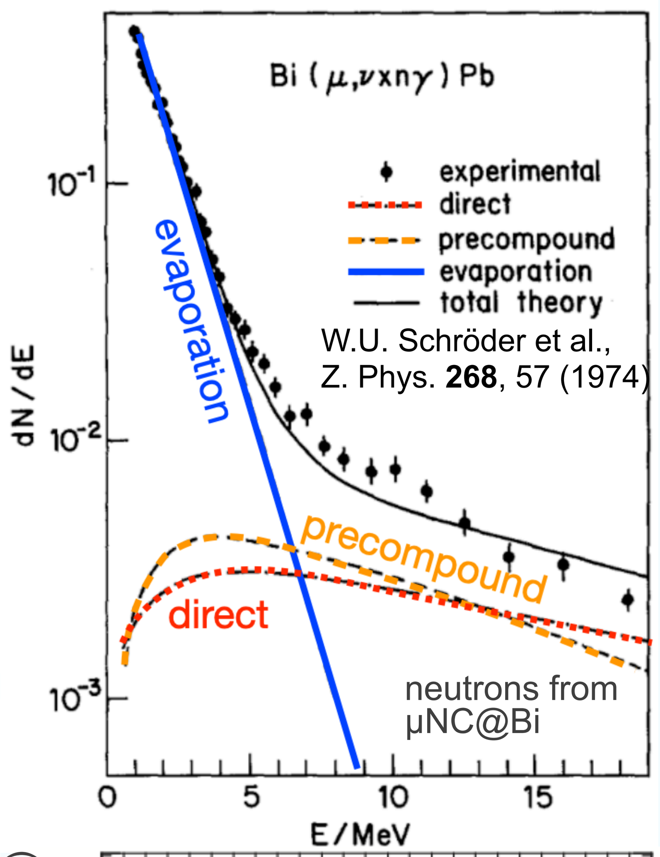
Energy spectra of charged particles emitted after muon nuclear capture in Si is crucial for the evaluation of cosmic-ray-muon-induced soft-error rate for advanced semiconductor devices.

Muon nuclear capture (μNC)

When negative muons come to stop in a material, muon nuclear capture (μNC) occurs.

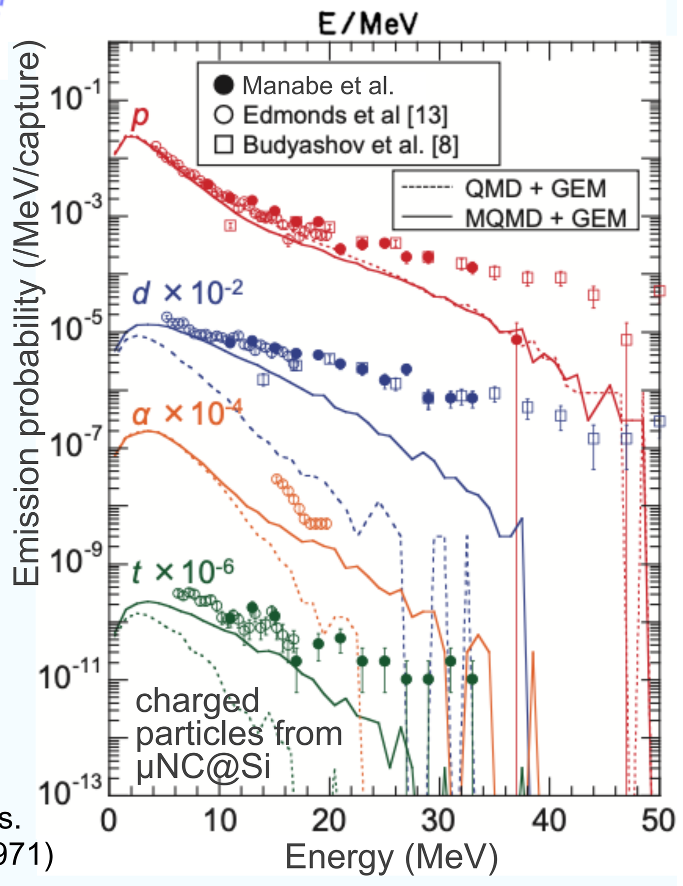
D. Measday, Phys. Rep. **354**, 243—409 (2001).





- Part of muon's rest mass energy (105.658 MeV) is used to excite the nucleus.
- Mostly, it de-excites with γ or neutron emission but sometimes it emits charged particles.
  - This particle emission involves two processes: **preequilibrium** and **compound formation**.
- However, experimental data is insufficient to comprehensively understand the emission process, particularly on the low-energy compound particles.

We aim to obtain charged particle spectra from μNC@Si over a wide energy range.



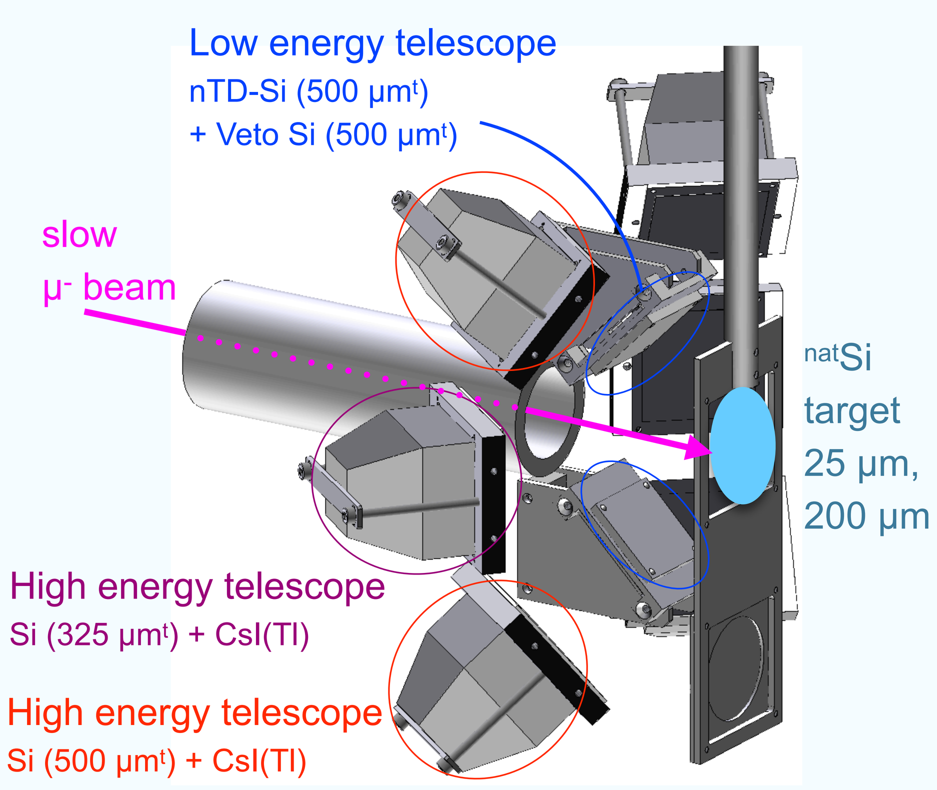
S. Manabe et al., EPJ Web. Conf. **284**, 01029 (2023), A. Edmonds et al., Phys. Rev. C **105**, 035501 (2022), Yu. G. Budyashov et al., Sov. Phys. **33**, 11-15 (1971)

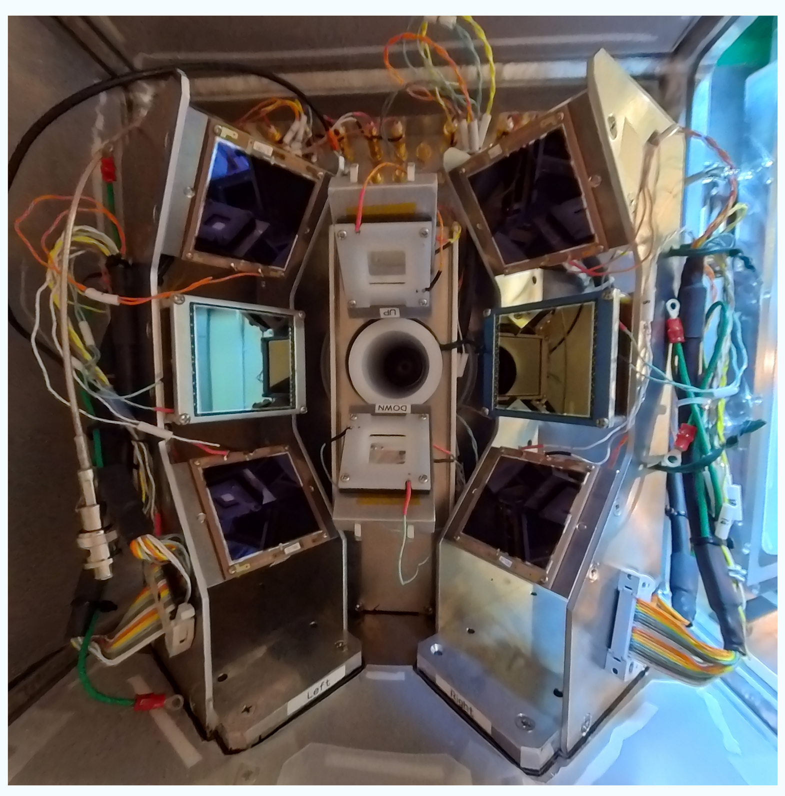
Experiment @ RIKEN-RAL

The experiment was conducted at the RIKEN-RAL muon facility at the Rutherford Appleton Laboratory, England.

RIKEN-RAL: A. D. Hillier et al., Phil. Trans. R. Soc. A 377, 20180064 (2019).

Slow negative muon beam (18.5 and 21.5 MeV/c for 25 and 200 μm targets) was stopped in a thin Si target to induce μNC. The particle identification and energy measurement of emitted charged particles were performed.

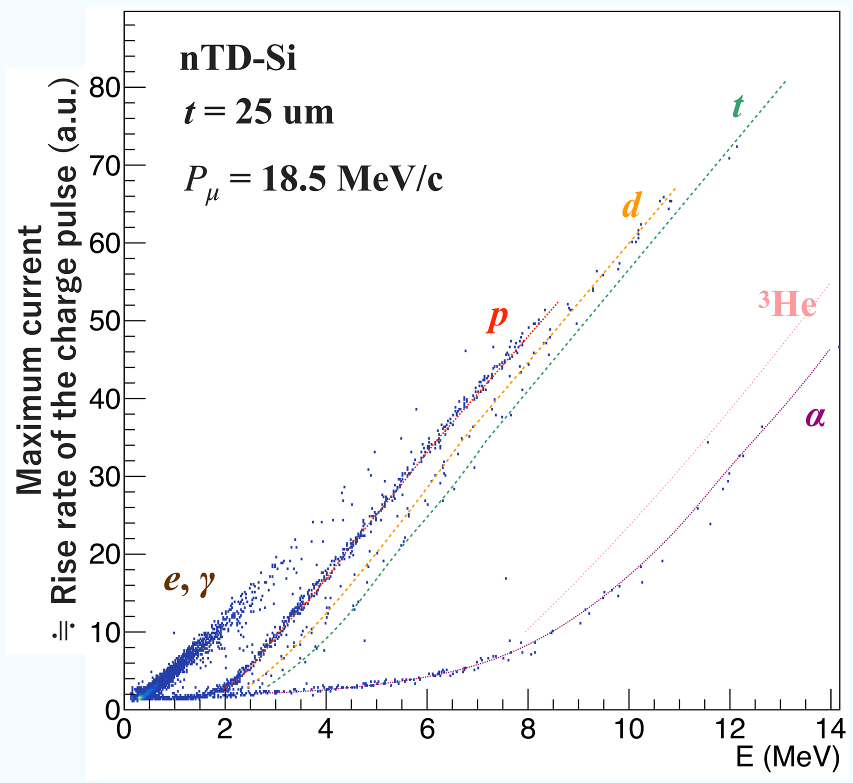




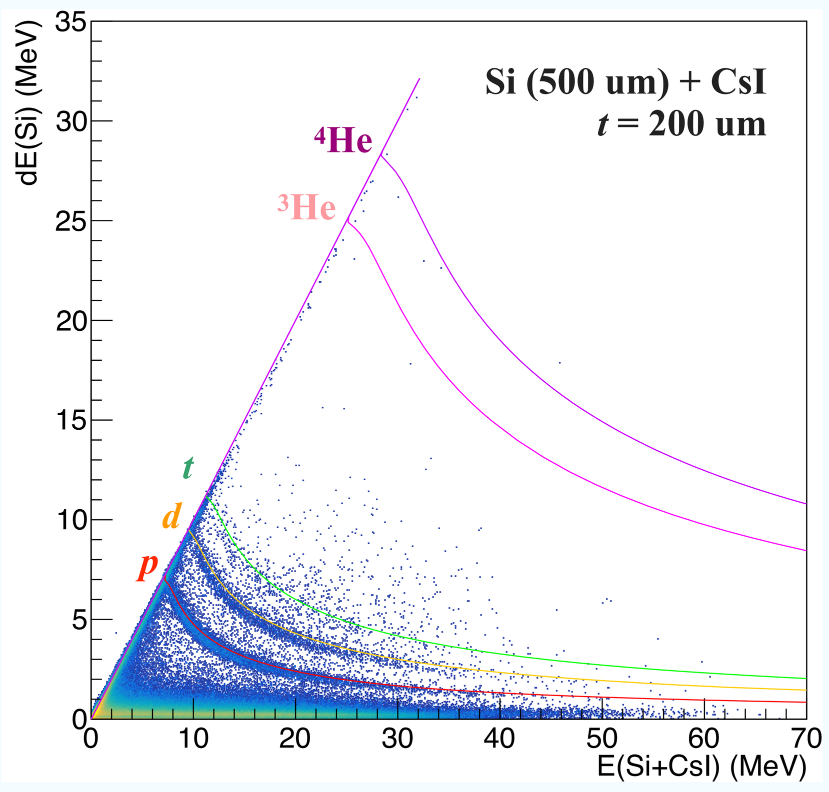
Particle identification

Particles stop in 500um Si:
Pulse shape analysis (PSA) method w/ nTD-Si

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

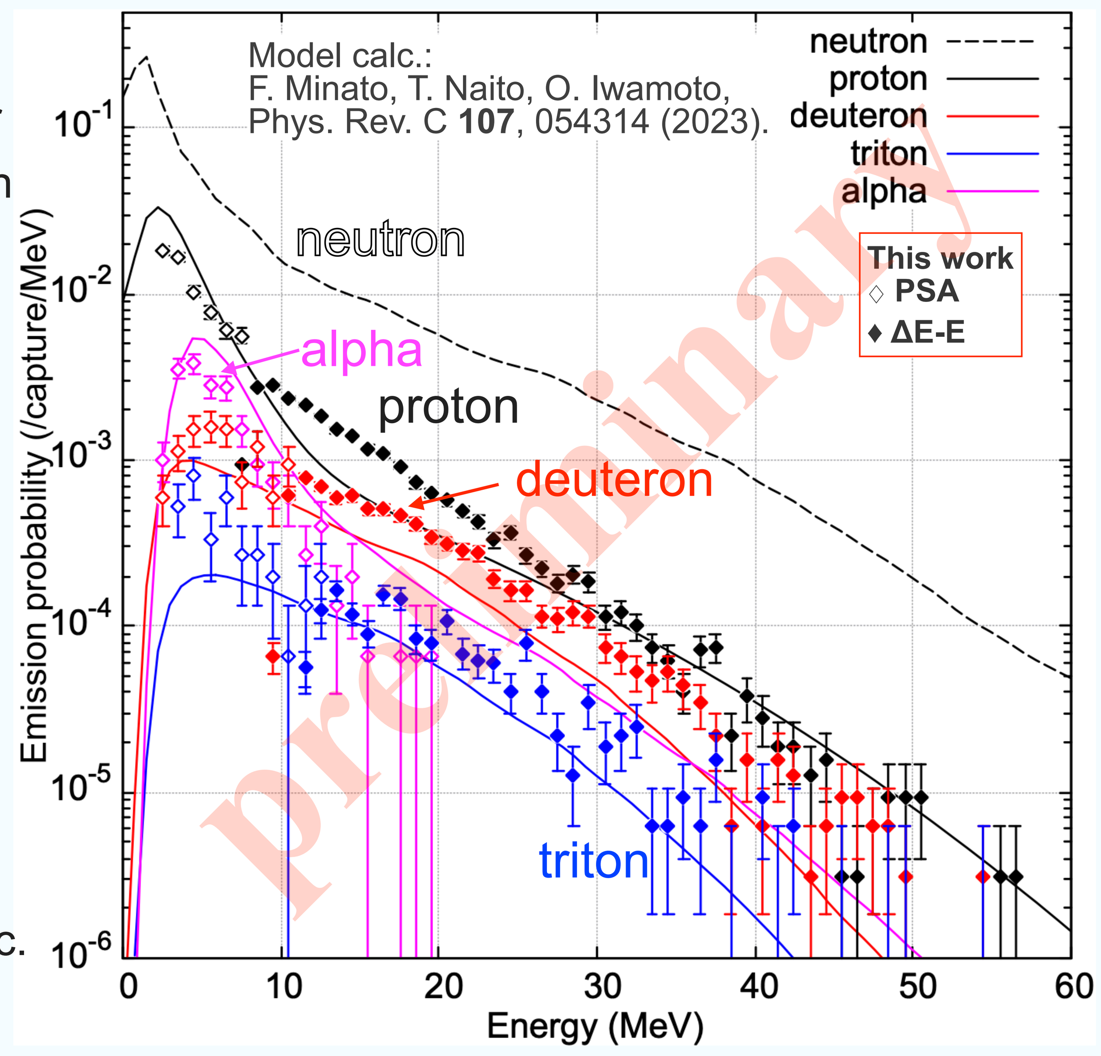


Particles penetrate 325 or 500 μm Si:
Conventional ΔE-E method
using Si (ΔE) and CsI(Tl) (E)



Measured energy spectra

- Measured energy spectra for p, d, t, and α were obtained for over a wider energy range than preceding measurements
  - Energy loss in the Si target is not considered here and the initial energy spectra in the low energy region may increase slightly
- The theoretical model calc. reproduce the overall shape.
  - The ratio of contributions from preequilibrium and compound processes may be slightly different from calc.



Unfolding analysis

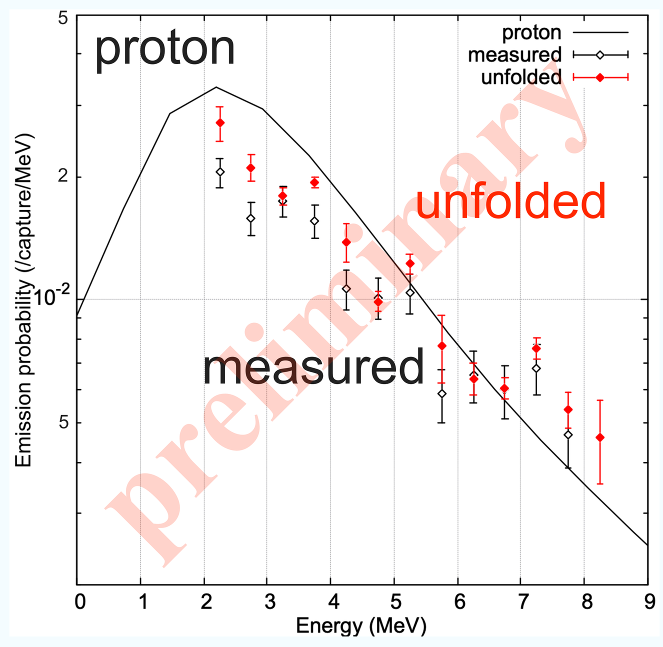
- Emitted charged particles lose their energy in the target
  - It may affect the height and shape of evaporation peak
- To compensate the energy loss in the target, unfolding analysis was carried out using an unfolding framework RooUnfold.

RooUnfold: L. Brenner et al., Int. J. Mod. Phys. A **35**, 2050145 (2020).

- Detectors' response functions were prepared with a Monte Carlo simulation using Geant4.

Geant4: J. Allison et al., Nucl. Instrum. Meth. Phys. Res. A **835**, 1 (2016).

- Analysis for d, t, α and the detailed evaluation of uncertainties are in progress …



Summary and Outlook

- Energy spectra of charged particles emitted after μNC are crucial in the evaluation of muon-induced soft error rate in semiconductor devices.
- Energy spectra of emitted particles reflect various processes in μNC, including the formation of compound nuclei.
- Energy spectra of light nuclear fragments emitted following μNC in natSi were measured in the RIKEN-RAL muon facility.

- We are planning similar measurements of μNC in heavier nuclei such as Co, Ni, and Cu for comprehensive understanding of the μNC process.
  - Data across a magic number would be helpful to understand the process.

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