FRIB-TA Topical Program
07/02/2026
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Development of the Charge-Exchange Oslo Method for Experiments with Stable and Unstable Beams

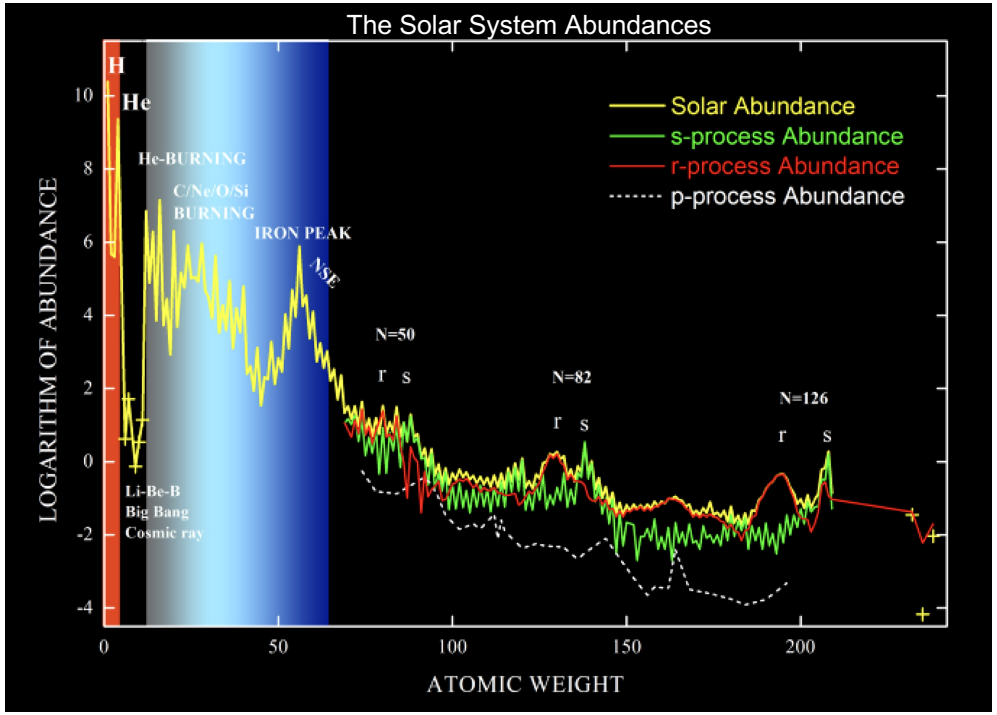
Neshad D. Pathirana

Outline

- Charge-Exchange Oslo Method
- Indirect Measurements of Neutron Capture
- Indirect Measurements of Neutrino Capture

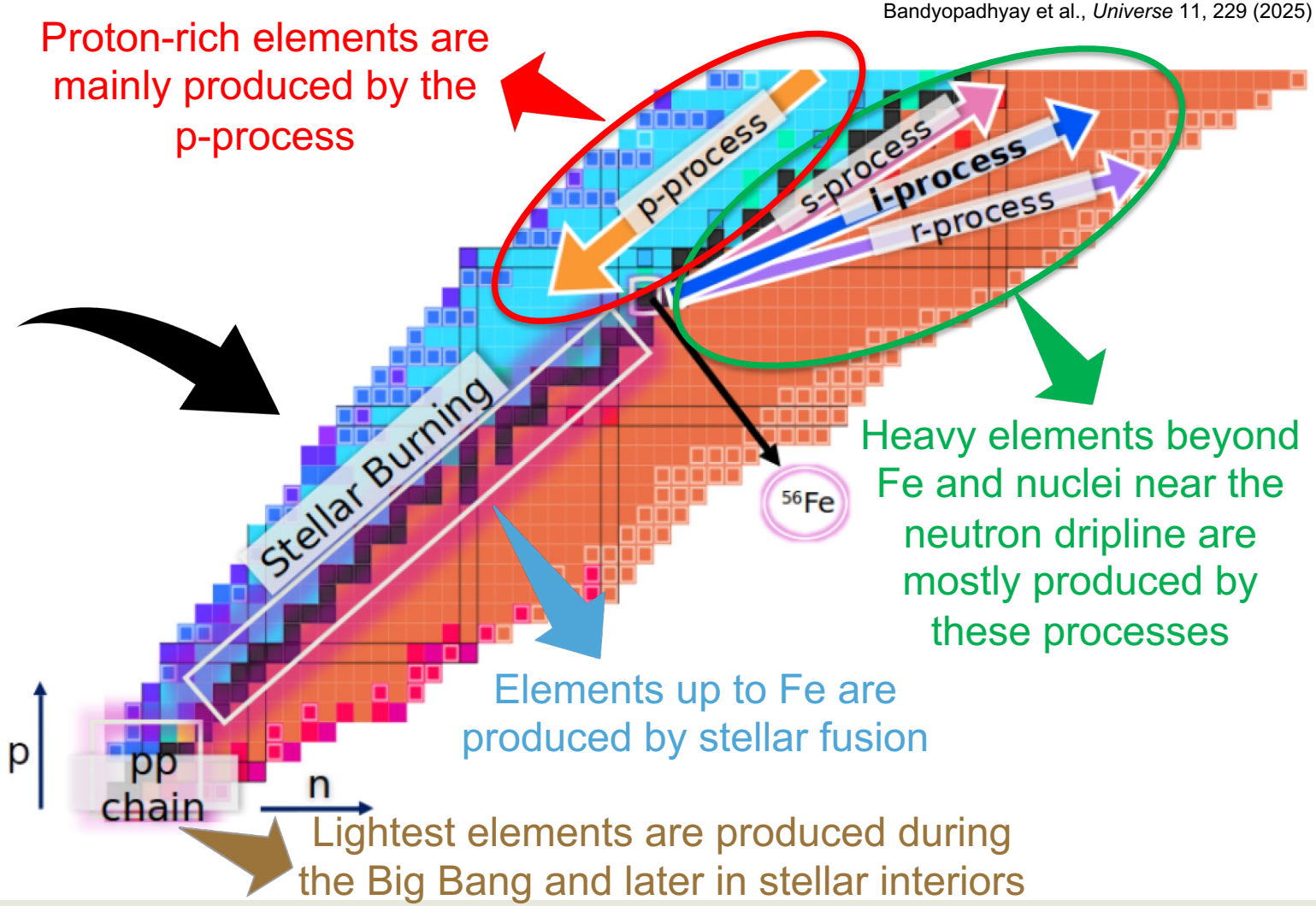
How the Elements are Made in the Universe

The distribution of Solar System abundances provides crucial insights into understanding the origin of the elements



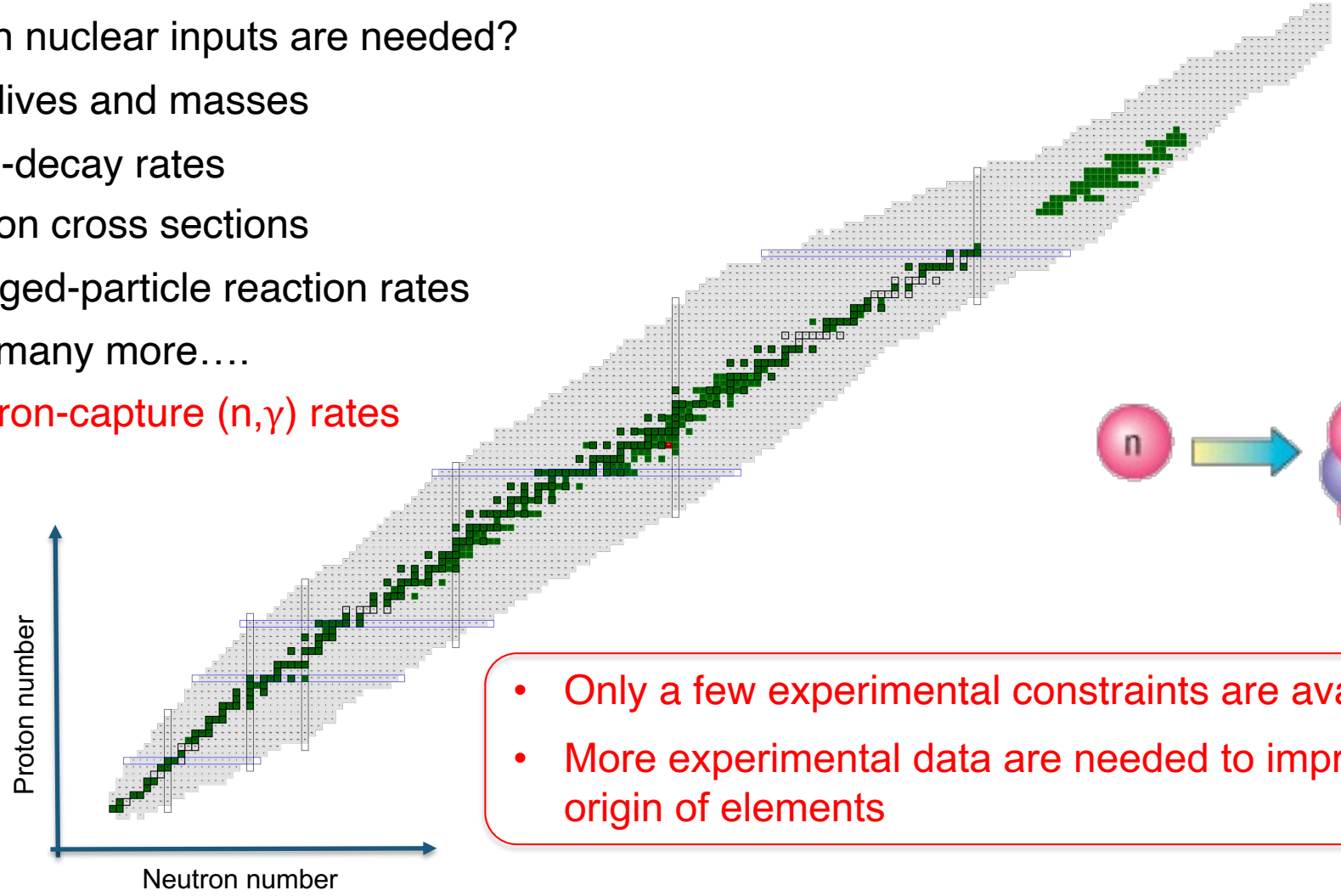
https://www2.yukawa.kyoto-u.ac.jp/~rp2019/slides/190523_10_liang.pdf

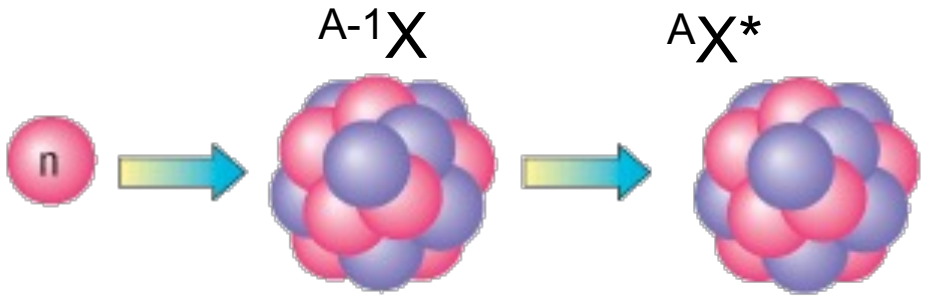
Bandyopadhyay et al., *Universe* 11, 229 (2025)



Nuclear Inputs Needed for Understanding the Origin of the Elements

- What main nuclear inputs are needed?
  - Half-lives and masses
  - EC/β-decay rates
  - Fission cross sections
  - Charged-particle reaction rates
  - And many more….
  - Neutron-capture (n,γ) rates



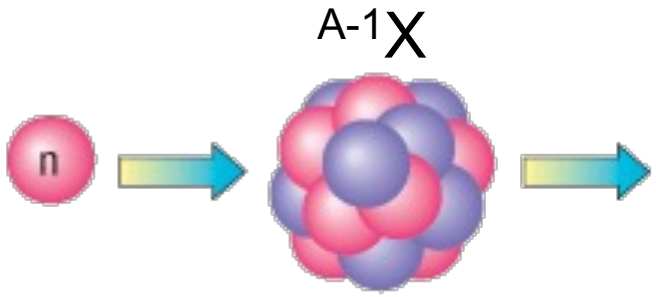


- Only a few experimental constraints are available for (n,γ) rates
- More experimental data are needed to improve our understanding of the origin of elements

How Can We Experimentally Constrain (n,γ) Reactions?

Direct measurements

Most accurate, but not feasible for nuclei away from stability



Nuclear Experiments
Beta decays
Transfer reactions
Surrogate reactions
Knockout/pickup reactions
Charge-Exchange reactions

Indirect measurements

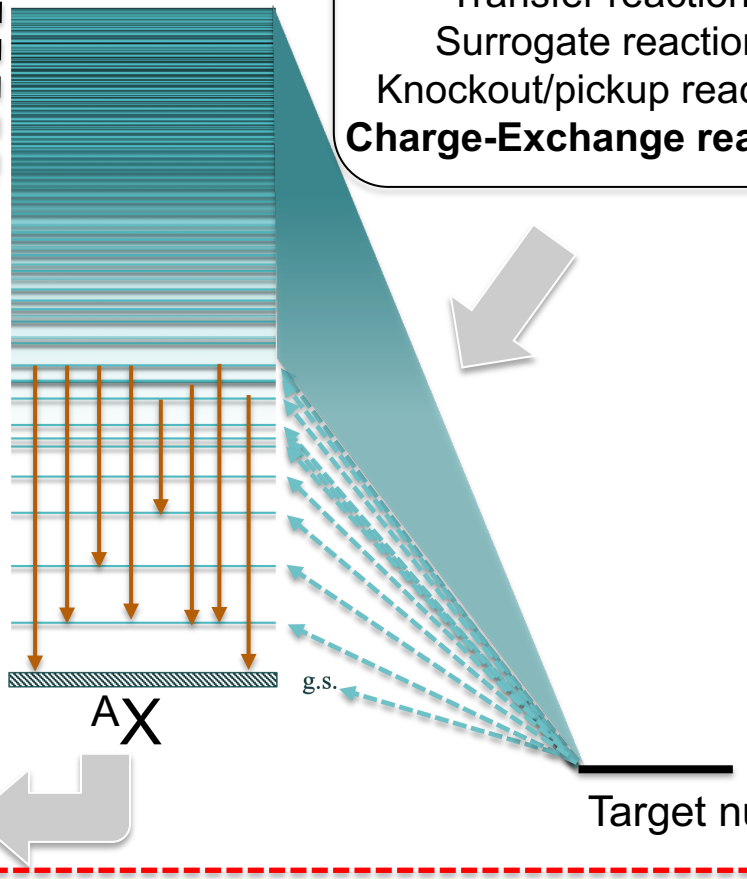
Hauser-Feshbach Calculations

Can access the same compound nucleus and can be applied for short-lived nuclei

Oslo Method[i]
β-Oslo Method[ii]
CE-Oslo Method[iii]
Surrogate Method[iv]
Inverse Oslo Method[v]
γ-ray Strength Method[vi]
Particle Evaporation Method[vii]

Optical Model Potential (OMP)

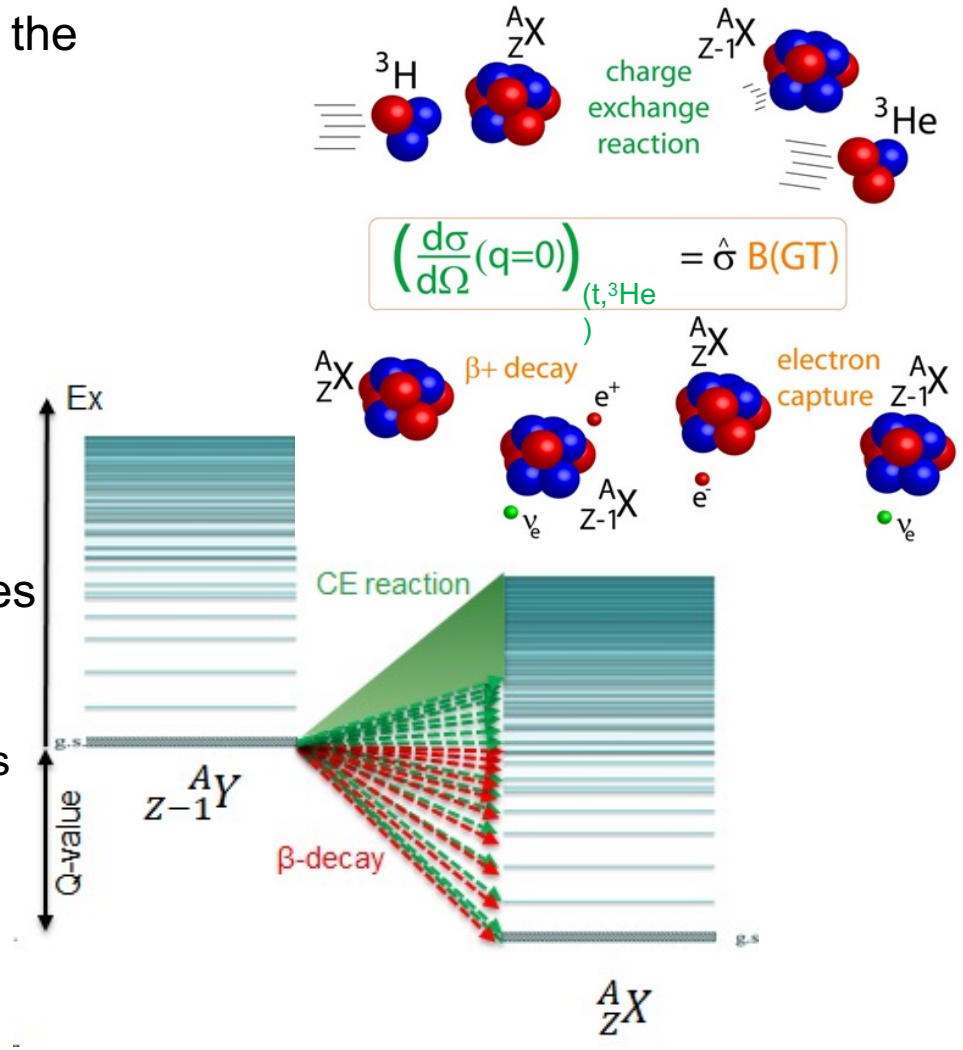
Nuclear Level Density (NLD)
γ-ray Strength Function (γSF)



i. M. Guttormsen et al., NIM A255 (1987) 518
ii. A. Spyrou et al., PRL 113, 232502 (2014)
iii. N.D. Pathirana et al., PRC 113, 015801 (2026)
iv. J. Escher et al., PRL 121, 052501 (2018)
v. V. Ingeberg et al., EPJA 56, 68 (2020)
vi. H. Utsunomiya et al., PRC 82, 064610 (2010)
vii. A. Voinov, et al., PRC 99, 054609 (2019)

Why are Charge-Exchange (CE) Reactions[i] Important?

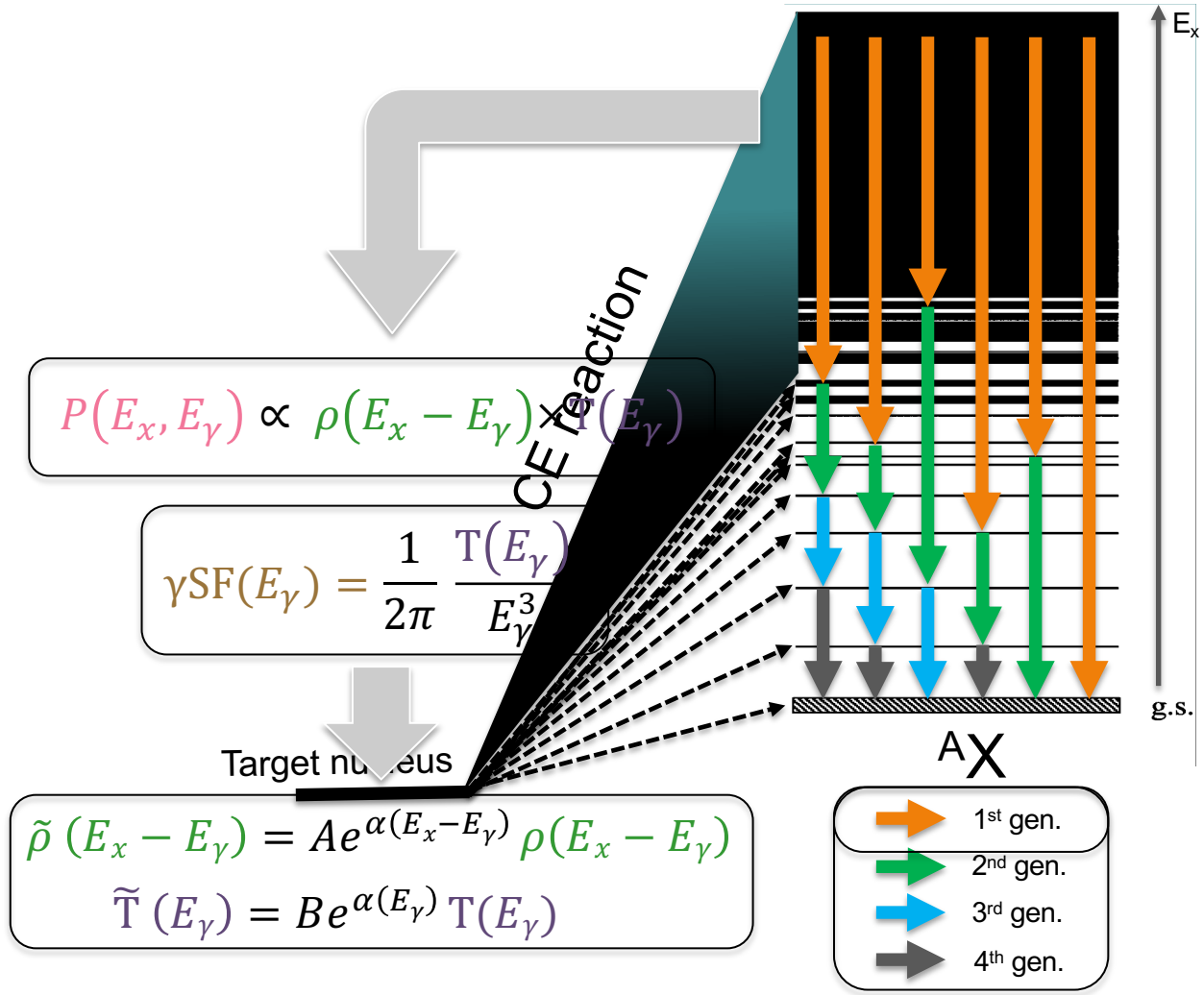
- CE reactions involve the exchange of a proton and a neutron between the target nucleus and the projectile nucleus
- Change in Isospin $\Delta T = 1$
- Populate states with the same spins and parities as in β/EC-decays, however, is not limited by the reaction Q-value window
- CE reaction data can be used to :
  1. Study the isovector spin-isospin response of nuclei
  2. Extract Gamow-Teller strength, B(GT), up to high excitation energies
     - ➢ Important for extracting electron-capture rates
     - ➢ Important for extracting charged-current neutrino-nucleus cross sections
  3. Extract nuclear level densities (NLDs) and gamma-ray strength functions (γSFs) using the Oslo-method
     - ➢ Important for extracting neutron-capture rates



i. Zegers, R.G.T., Handbook of Nuclear Physics, Springer, (2023)

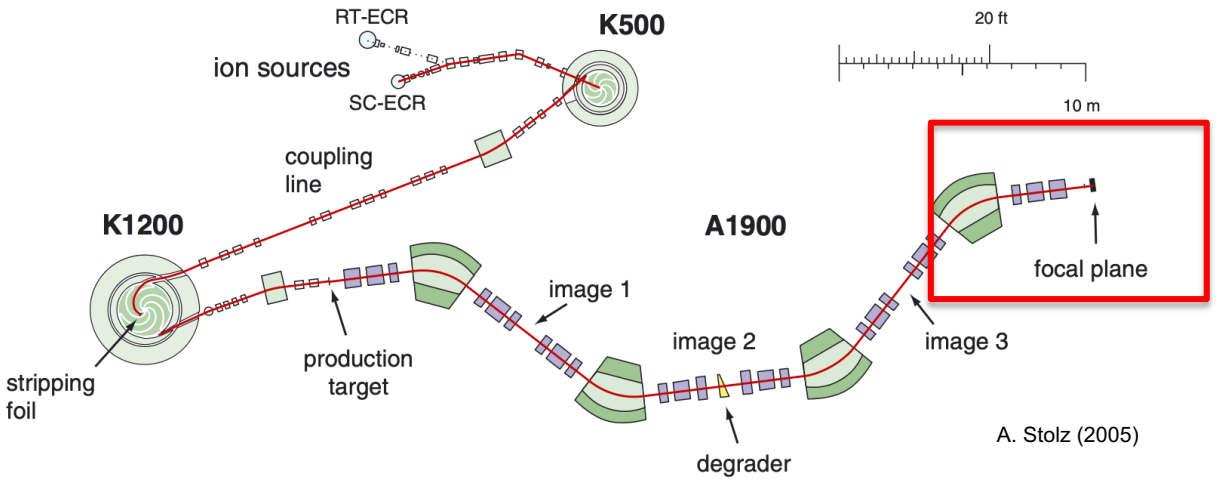
Overview of the CE-Oslo Method

- Use a CE reaction to populate the compound nucleus of interest
- Measure the excitation energies of the populated states in coincidence with the emitted γ-rays
- Unfold the γ-ray spectra at each excitation energy using the detector response function
- Extract the first generation γ-ray distribution for each excitation energy: $P(E_x, E_\gamma)$
- Extract the nuclear level density $\rho(E_x - E_\gamma)$ and the γ-ray strength function $\gamma\mathrm{SF}(E_\gamma)$ from the first generation γ-ray distribution
- Normalize the $\rho(E_x - E_\gamma)$ and $\gamma\mathrm{SF}(E_\gamma)$



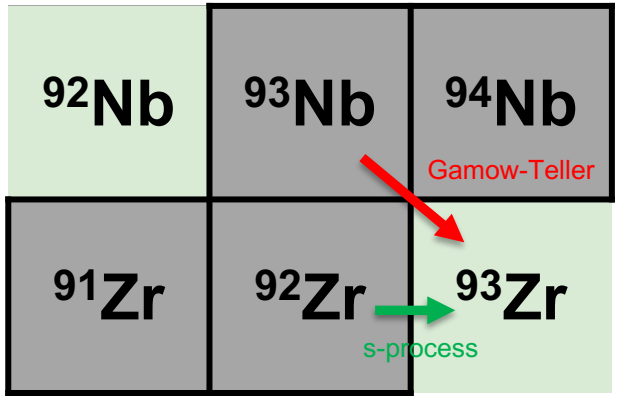
i. M. Guttormsen et al., NIM A374 (1996) 371
ii. M. Guttormsen et al., NIM A255 (1987) 518
iii. A. Schiller et al., NIM A447 (2000) 498
iv. A.C. Larsen *et al.*, Phys. Rev. **C 83**, 034315 (2011)

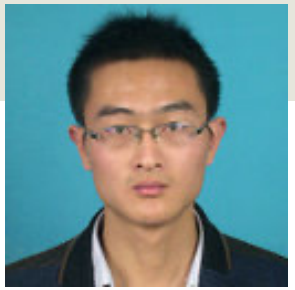
First Application of the Charge-Exchange Oslo Method: Experiment Details



A. Stolz (2005)

- The ^{93}Nb(t,^{3}He+γ)^{93}Zr CE experiment was conducted at 115 MeV/u at NSCL using the S800 spectrometer in coincidence with GRETINA[i]
- The primary purpose was to measure Gamow-Teller Transitions from ^{93}Nb to ^{93}Zr
- The CE-Oslo method was later tested using the resulting particle-γ coincidence data





B.S. Gao

^{93}Nb(t,^{3}He+γ)^{93}Zr experiment setup at FRIB

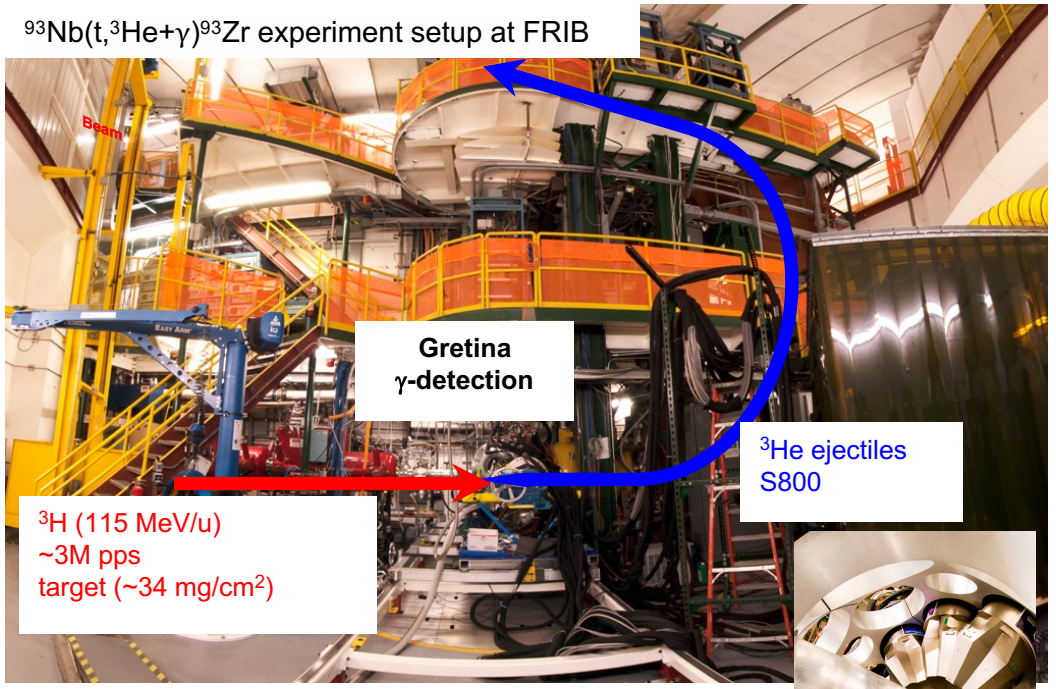


Photo from S. Noji

(t,^{3}He+γ) beam with S800 Spectrograph +GRETINA



Gamma-Ray Energy Tracking In-beam Nuclear Array

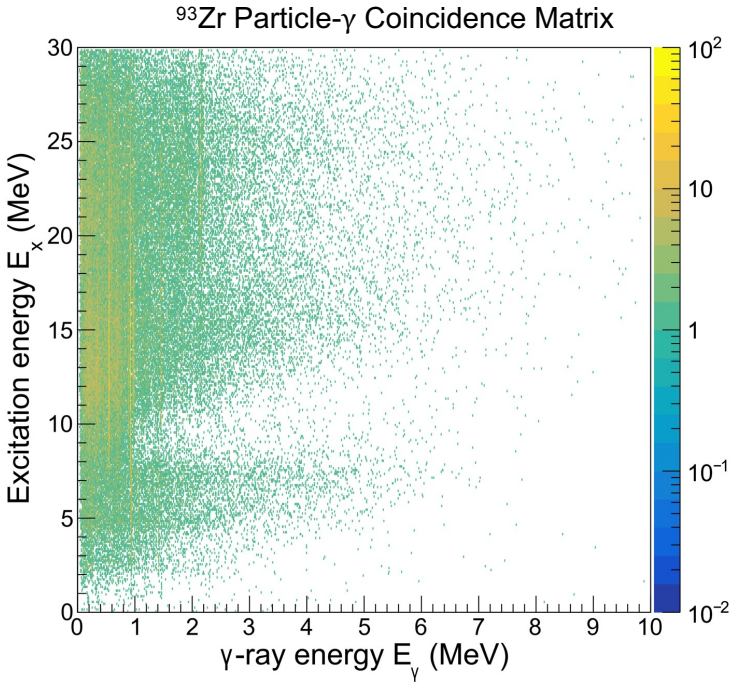
i. B.Gao et al., PhysRevC.101.014308, 2020

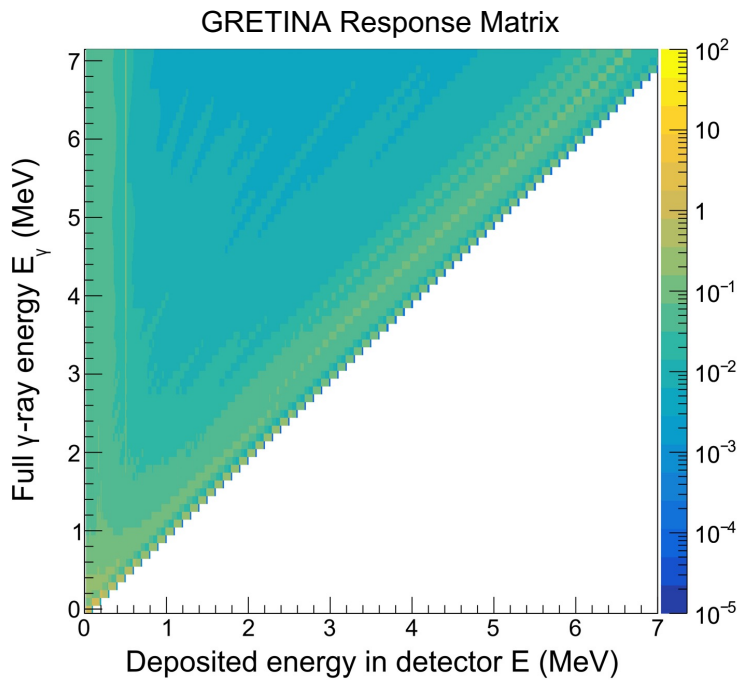
CE-Oslo Method for Extracting the 1st Generation γ-ray Distribution

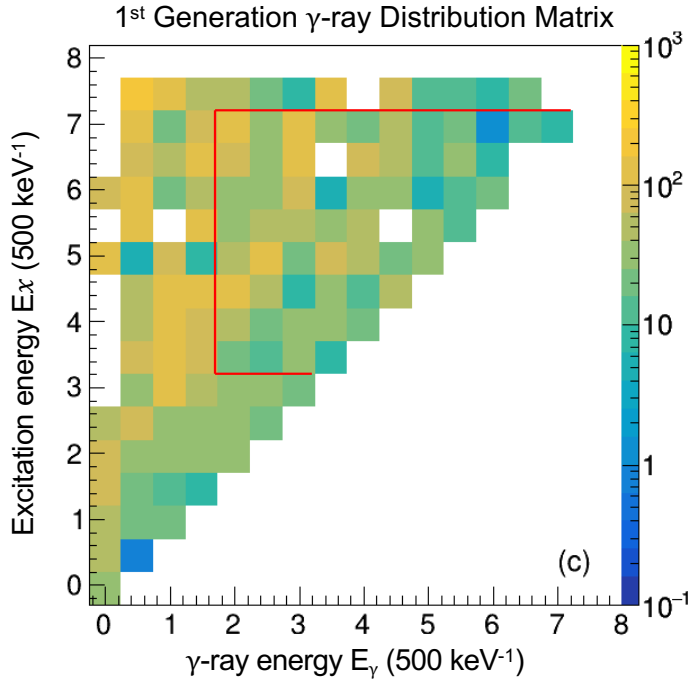
^{93}Nb(t,^{3}He+γ)^{93}Zr particle-γ coincidences data

Unfolded matrix using GRETINA response function

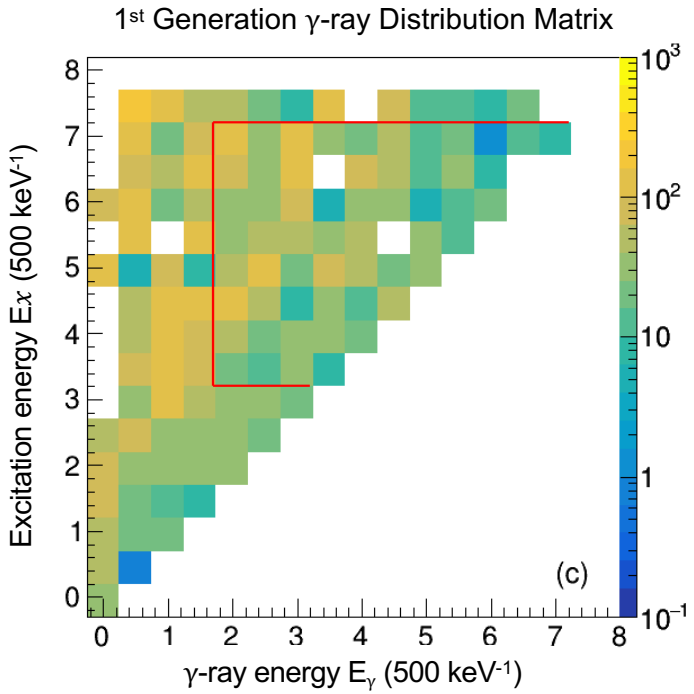
Extracted 1st generation γ-ray distribution matrix for populated ^{93}Zr

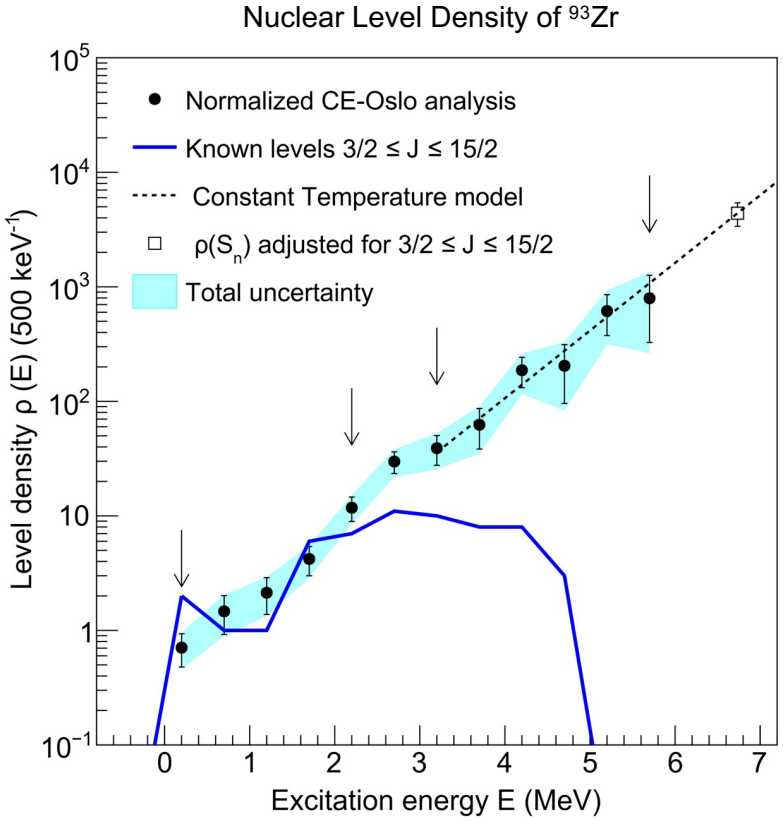


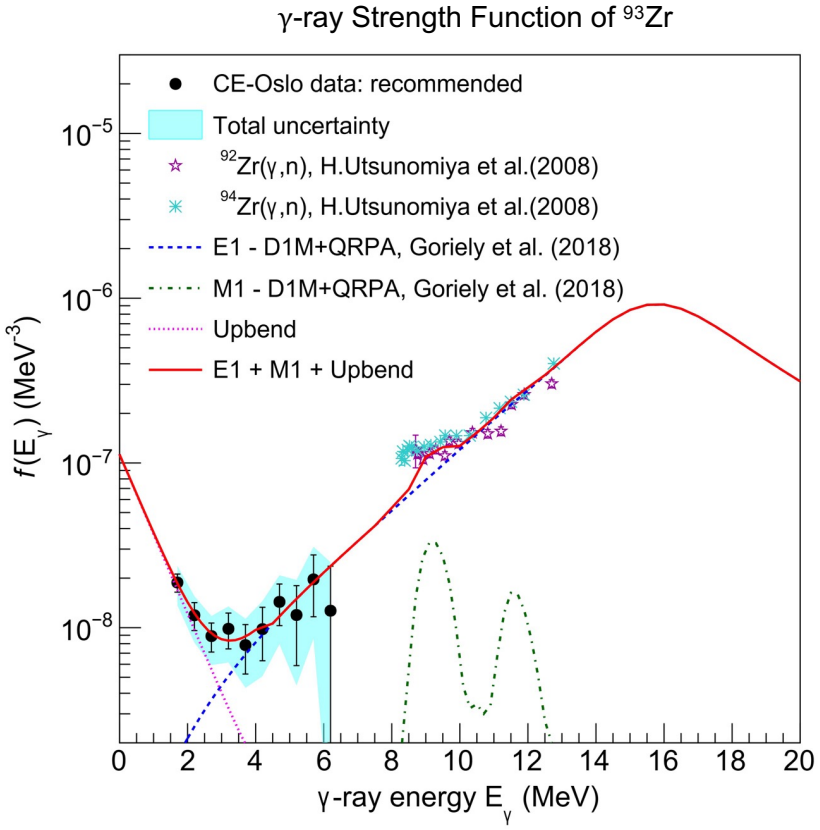




Experimentally Extracted NLD and γSF of ^{93}Zr







The 1st generation γ-ray distribution is proportional to the product of the NLD and γSF

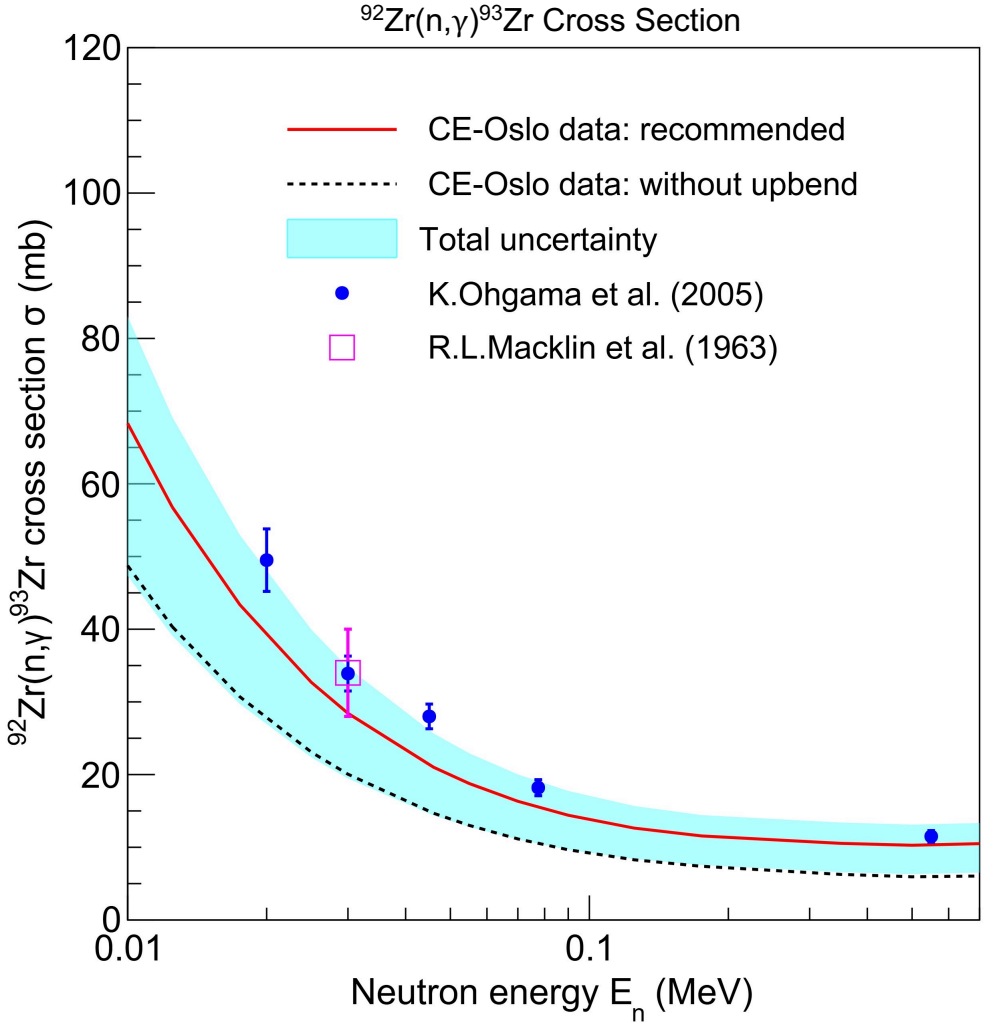
NLD: Number of levels per MeV as a function of E_x

γSF: Probability to emit any γ-ray with different multipolarity

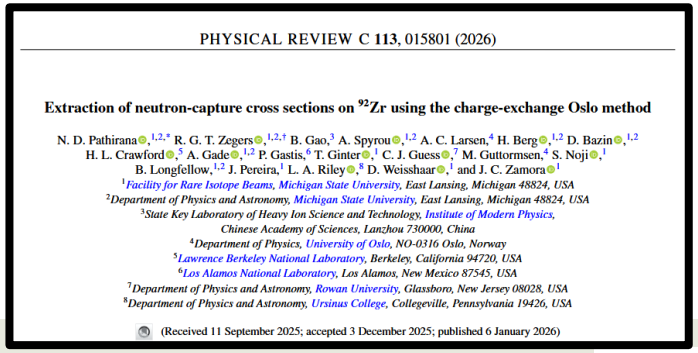
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i. N.D. Pathirana et al., Phys. Rev. C (2026) 113, 015801

Indirectly Extracted $^{92}Zr(n,\gamma)^{93}Zr$ Cross Sections



- The $^{92}Zr(n,\gamma)^{93}Zr$ cross section was constrained by propagating the extracted NLD and γSF of ^{93}Zr through Hauser-Feshbach calculations using TALYS[i]
- The extracted cross sections are in good agreement with the direct measurements within the uncertainty band
- This was the 1st time that:
  - » The NLD and γSF of ^{93}Zr were experimentally constrained
  - » The CE-Oslo method was applied to constrain an (n,γ) cross sections
  - » The Oslo method was applied to particle-γ coincidence data taken with S800 and GRETINA to constrain an (n,γ) cross section
- The results were published in Phys. Rev. C (2026) 113, 015801 as the first application of the CE-Oslo Method[ii]


PHYSICAL REVIEW C 113, 015801 (2026)

Extraction of neutron-capture cross sections on ^{92}Zr using the charge-exchange Oslo method

N. D. Pathirana,[1,2,*] R. G. T. Zegers,[1,2,†] B. Gao,[3] A. Spyrou,[1,2] A. C. Larsen,[4] H. Berg,[1,2] D. Bazin,[1,2] H. L. Crawford,[5] A. Gade,[1,2] P. Gastis,[6] T. Ginter,[1] C. J. Guess,[7] M. Guttormsen,[4] S. Noji,[1] B. Longfellow,[1,2] J. Pereira,[1] L. A. Riley,[8] D. Weisshaar,[1] and J. C. Zamora[1]

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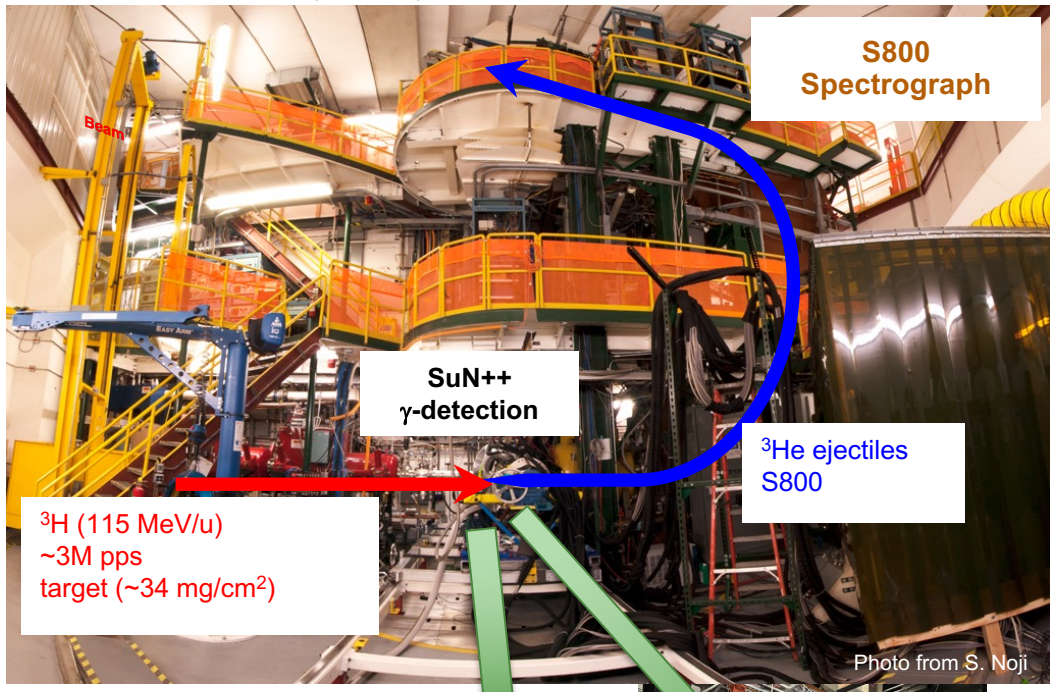
i. A. Koning et al., Eur. Phys. J. A (2023) 59:131
ii. N.D. Pathirana et al., Phys. Rev. C (2026) 113, 015801

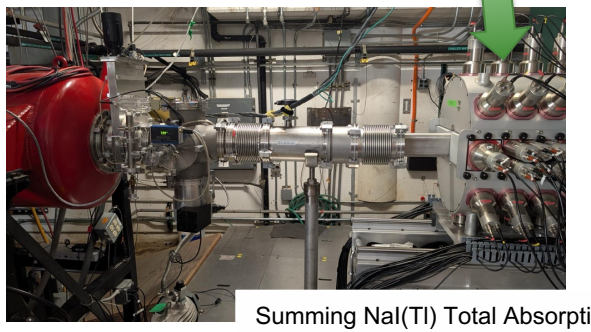
The SuN++ and S800 Were Combined to Apply the Charge-Exchange Oslo Method

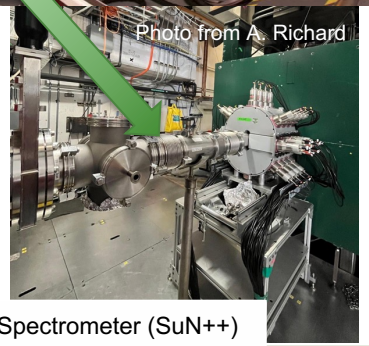


Spokesperson : Andrea Richard

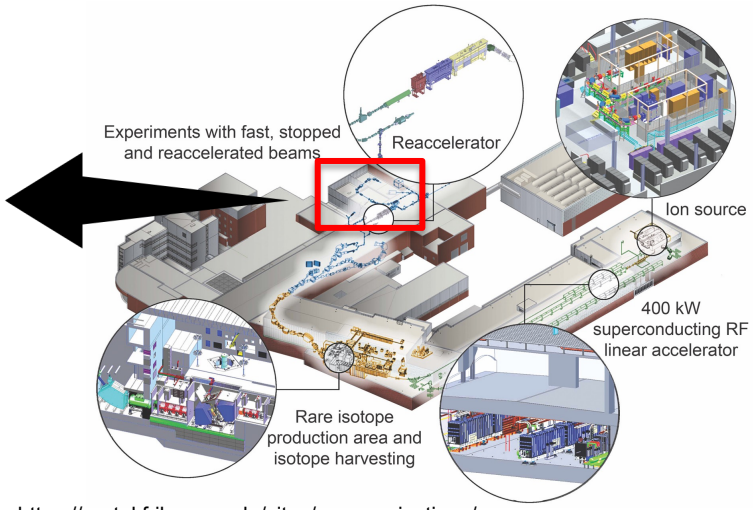
^{100}Mo(t,^{3}He+γ)^{100}Nb experiment setup at FRIB



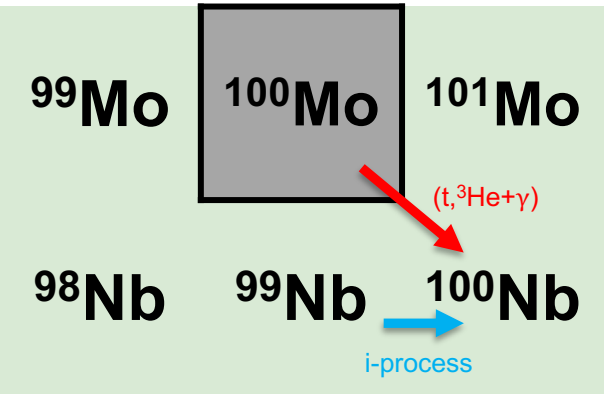




Summing NaI(Tl) Total Absorption Spectrometer (SuN++)



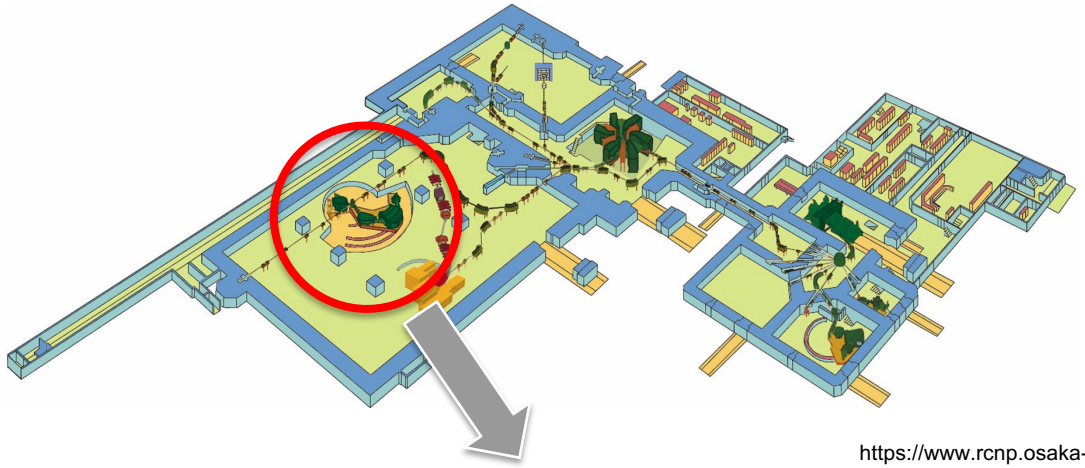
https://portal.frib.msu.edu/sites/communications/



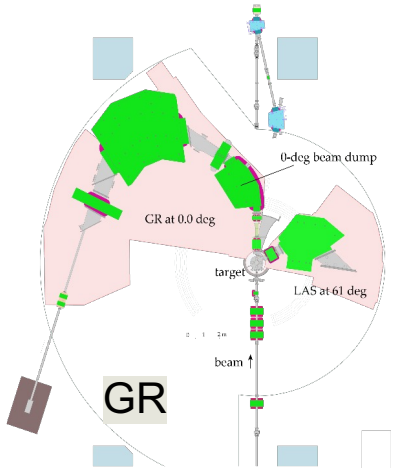
- The ^{100}Mo(t,^{3}He+γ)^{100}Nb CE experiment was conducted at 115 MeV/u at FRIB using the S800 spectrometer in coincidence with SuN++
- The purpose was to indirectly measure the ^{99}Nb(n,γ)^{100}Nb reaction for the astrophysical *i*-process
- Data Analysis is currently underway

It's also Planned to Conduct a ^{92}Zr(^{3}He,t+γ) Experiment at RCNP to apply the CE-Oslo Method

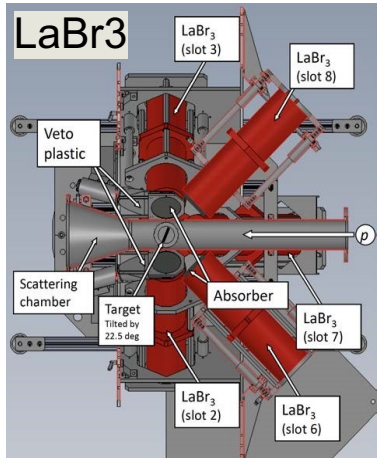
- The experiment will be run in forward kinematics using a 420 MeV ^{3}He beam, with the Grand Raiden Spectrometer in coincidence with the Scintillation Gamma-Ray Detector array
- The goal is to constrain two dominant reaction rates relevant to the nucleosynthesis of Cosmochronometer ^{92}Nb from a single experiment:
  1. ^{92}Nb(γ,n)^{91}Nb
  2. ^{92}Zr(ν_e,e^-)^{92}Nb
- Both reactions have now been constrained using two separate experiments
- It's also planned to test the CE-Oslo method using fine-structure analysis



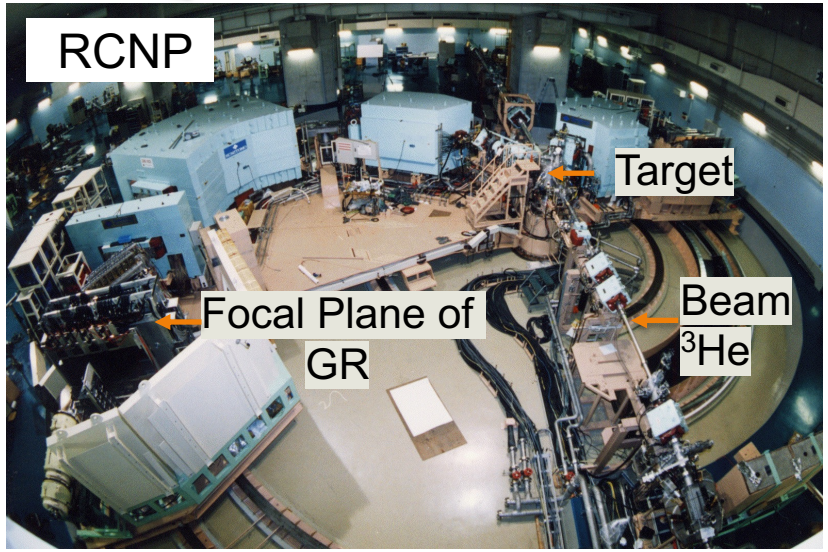
https://www.rcnp.osaka-u.ac.jp/



A. Tamii, N. Kobayashi c

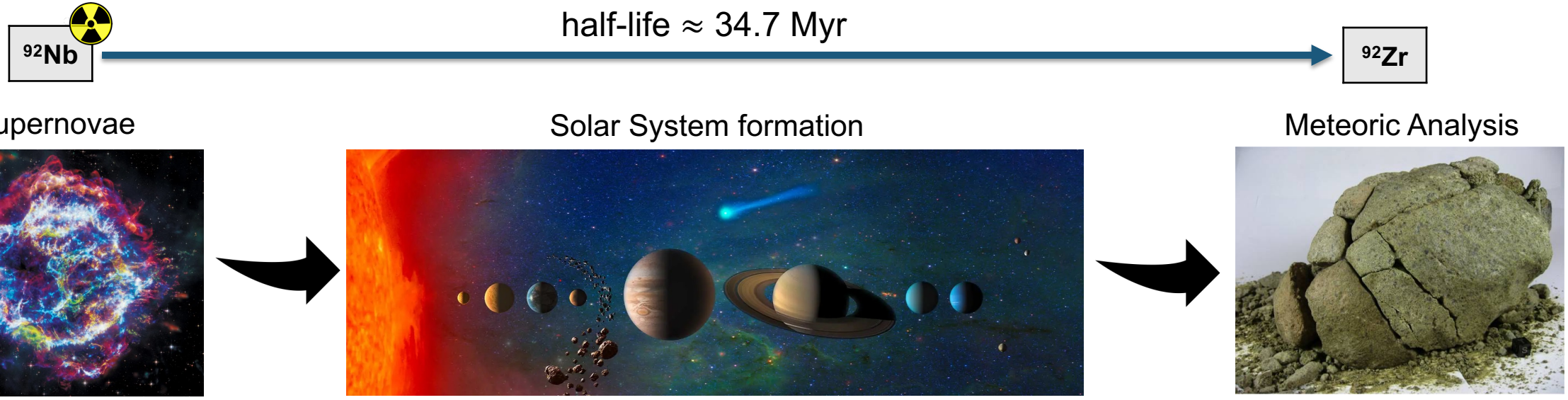


A. Tamii, N. Kobayashi c



What is ^{92}Nb?

- Short-lived radionuclides (SLRs), with half-lives of 0.1–100 Myr, are powerful chronometers of Solar System formation
- Among the 19 known SLRs, ^{92}Nb is one of the few confirmed proton-rich SLRs
- It's synthesized in supernovae environments and became extinct shortly after the formation of the Solar System
- Its former presence is inferred from excesses in its EC-decay daughter, ^{92}Zr , measured in meteorites from both the inner and outer Solar System[i,ii]

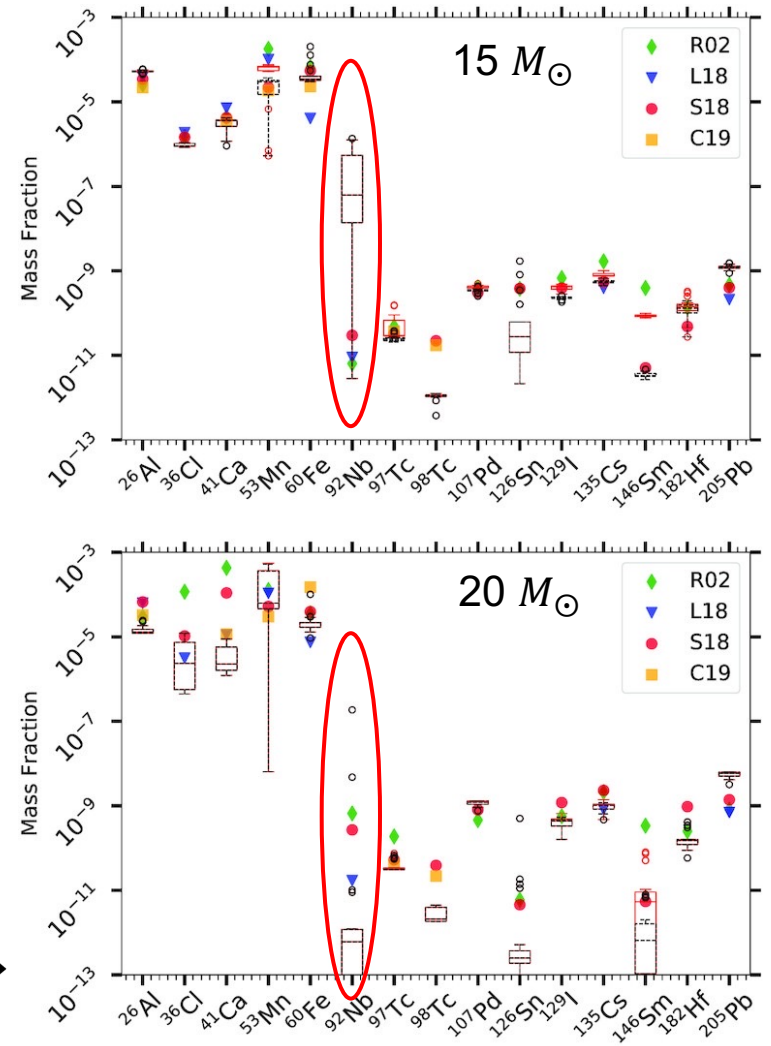


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i. Harper, C. L., Jr. 1996, ApJ, 466, 437
ii. Haba et.al, (2021) Proc. Natl. Acad. Sci. U.S.A. 118 (8)

Why is ^{92}Nb Important?

- The abundance of ^{92}Nb is usually discussed relative to ^{92}Mo because both are p nuclei
- The initial Solar System ^{92}Nb/^{92}Mo ratio is important for:
  - Probing early Solar System timescales in Galactic Chemical Evolution (GCE), and
  - Probing proton-rich nucleosynthesis
- The most recent inferred meteoric ^{92}Nb/^{92}Mo ratio for the inner Solar System is [i] $3.3 \pm 0.2 \times 10^{-5}$
- Interpreting this meteoritic ratio is currently limited by both astrophysical and nuclear-physics uncertainties in ^{92}Nb production. For example:
  - If ^{92}Nb were produced only in Type Ia supernovae, the inferred meteoric ^{92}Nb/^{92}Mo ratio would be ~50% lower to match time scales from other SLRs: Lugaro (2016)
  - Among the 15 SLRs, the production of ^{92}Nb is one the most uncertain in CCSNe stellar models: Lawson (2022)

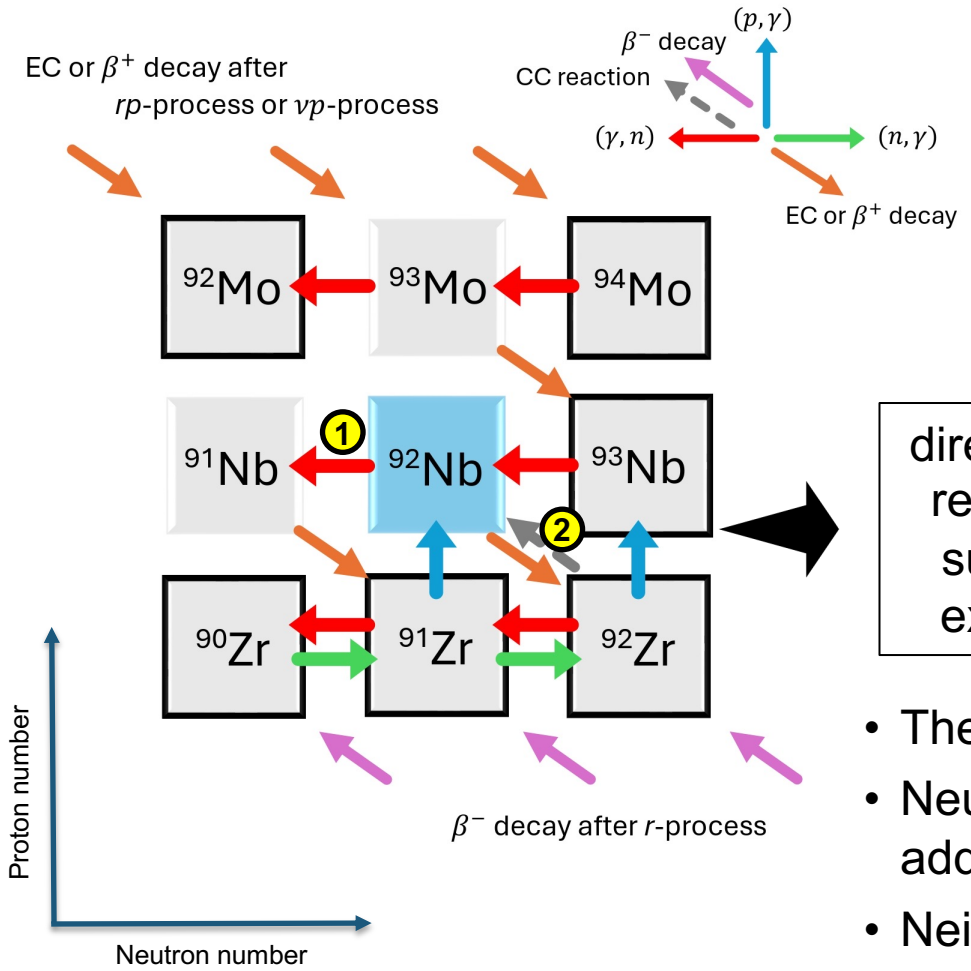


Lawson et. al, MNRAS 511, 886–902 (2022)

i. Haba et.al, (2021) Proc. Natl. Acad. Sci. U.S.A. 118 (8)

What Matters Most for ^{92}Nb Production from a Nuclear Physics Perspective?

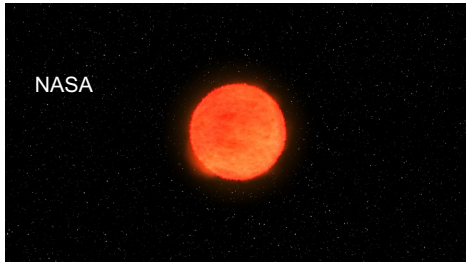
- The origin of ^{92}Nb remains uncertain because it is shielded by the stable isobars ^{92}Zr and ^{92}Mo



direct nuclear reactions in supernova explosions

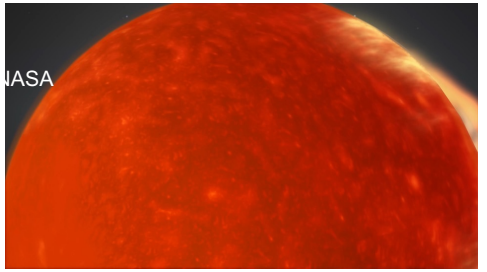
Core-Collapse Supernovae (CCSNe)

1. γ-process[i]
2. ν/νr-process[ii]
3. α-process[i]



Type Ia Supernovae (SNe Ia)

1. γ-process[iii]



- The main destruction channel is **^{92}Nb(γ,n)^{91}Nb** ① in the γ-process
- Neutrino-driven reaction **^{92}Zr(ν_e,e^-)^{92}Nb** ② in CCSNe has been proposed as an additional production pathway
- Neither reaction has any experimental constraints yet

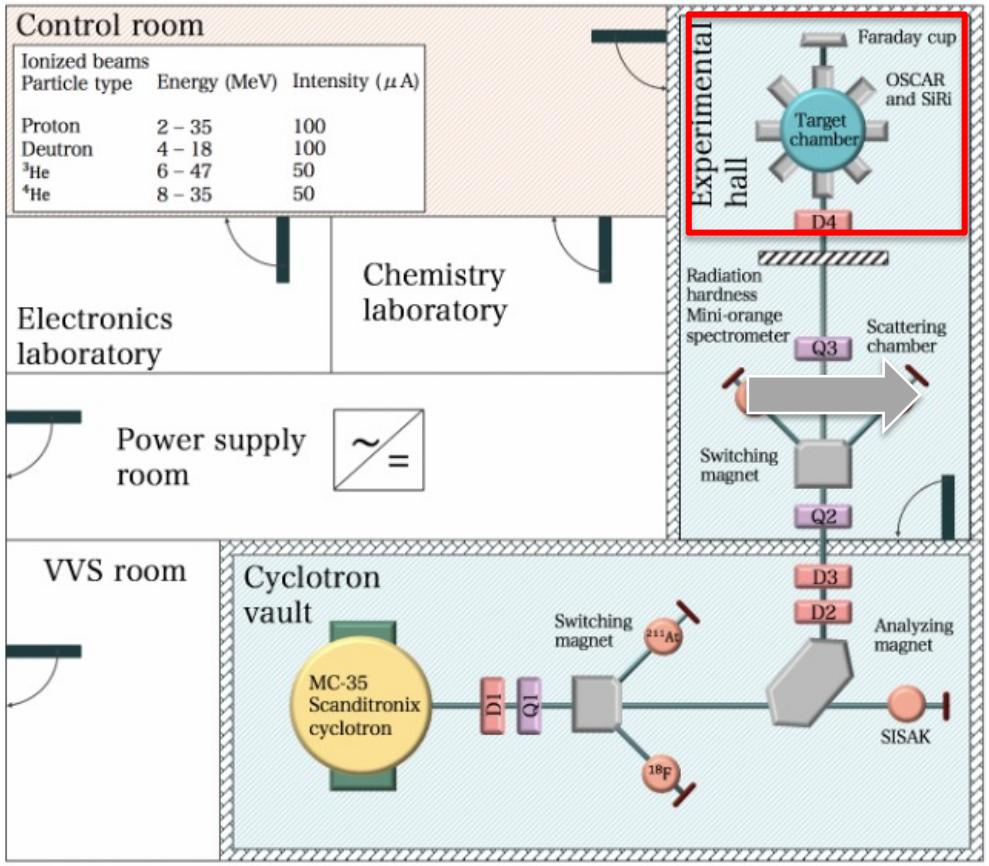
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i. Harper, C. L., Jr. 1996, ApJ, 466, 437
ii. Haba et.al, (2021) Proc. Natl. Acad. Sci. U.S.A. 118 (8)
iii. Lugaro, Proc. Natl. Acad. Sci. U.S.A. 113 (4) 907-912 (2016)
iv. T. Hayakawa et al., Ap.J.Lett. 779, L9 (2013)
v. C. Travaglio et al., Ap.J. 795: 141 (2014)

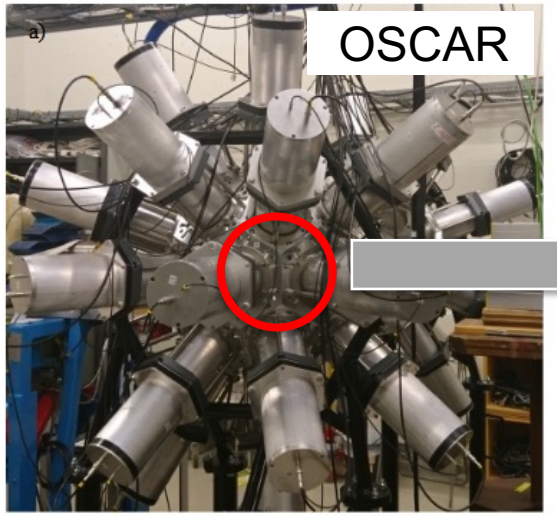
Experimental Study of ^{92}Nb Production via ^{92}Nb(γ,n)^{91}Nb Reaction

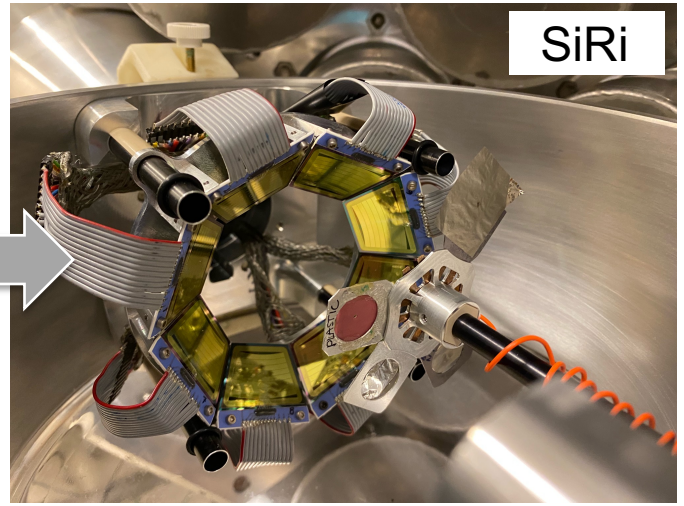


Spokesperson : Ann-Cecilie Larsen



M.Markova's M.Sc. thesis





M.Markova's M.Sc. thesis

Captured by A.C. Larsen

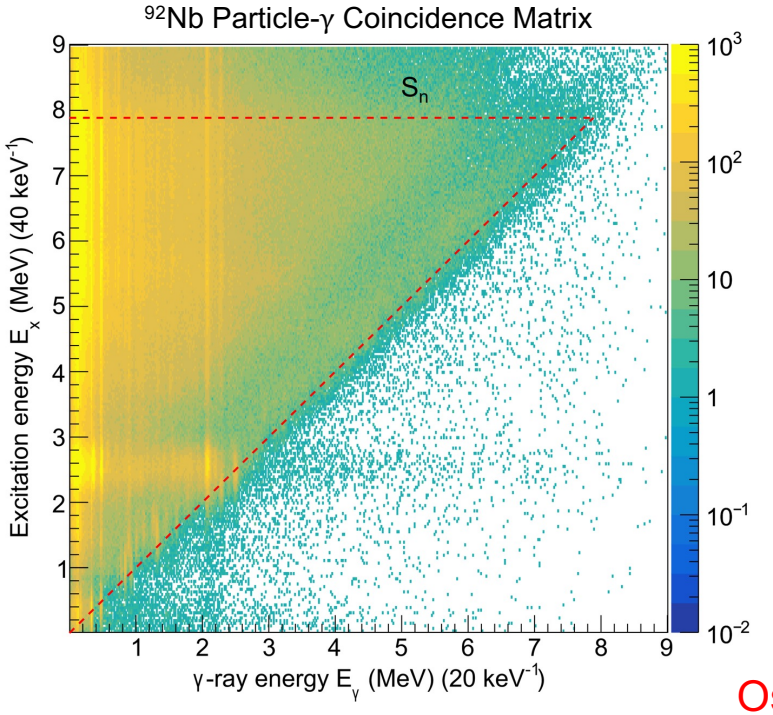
- The ^{90}Zr(α,d+γ)^{92}Nb experiment was performed in forward kinematics using a 30 MeV ^{4}He-beam at Oslo Cyclotron Laboratory
- Particle-γ coincidence data for ^{92}Nb were measured using the SiRi[i] particle telescope in coincidence with the Oslo SCintillator ARray (OSCAR[ii]) and used in the Oslo method to extract the NLD and γSF of ^{92}Nb and thereby ^{91}Nb(n,γ)^{92}Nb rate

i. M. Guttormsen *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect. A* **648**, 168 (2011)
ii. F. Zeiser *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect. A* **985**, 164678 (2021)

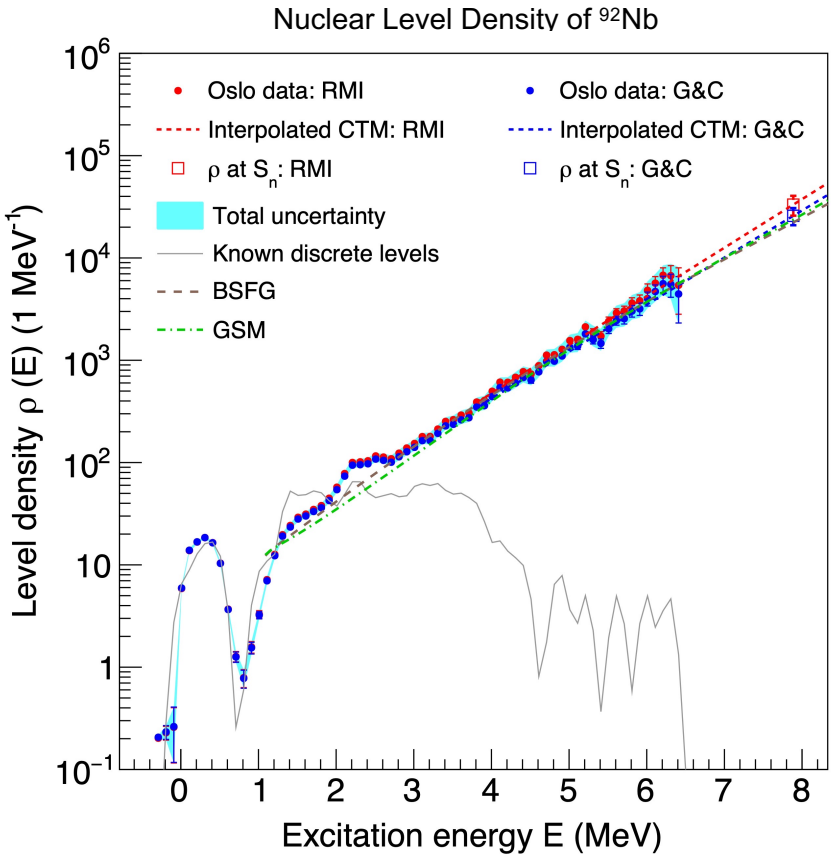
Experimentally Extracted NLD and γSF of ^{92}Nb

N.D. Pathirana et al., (submitted)

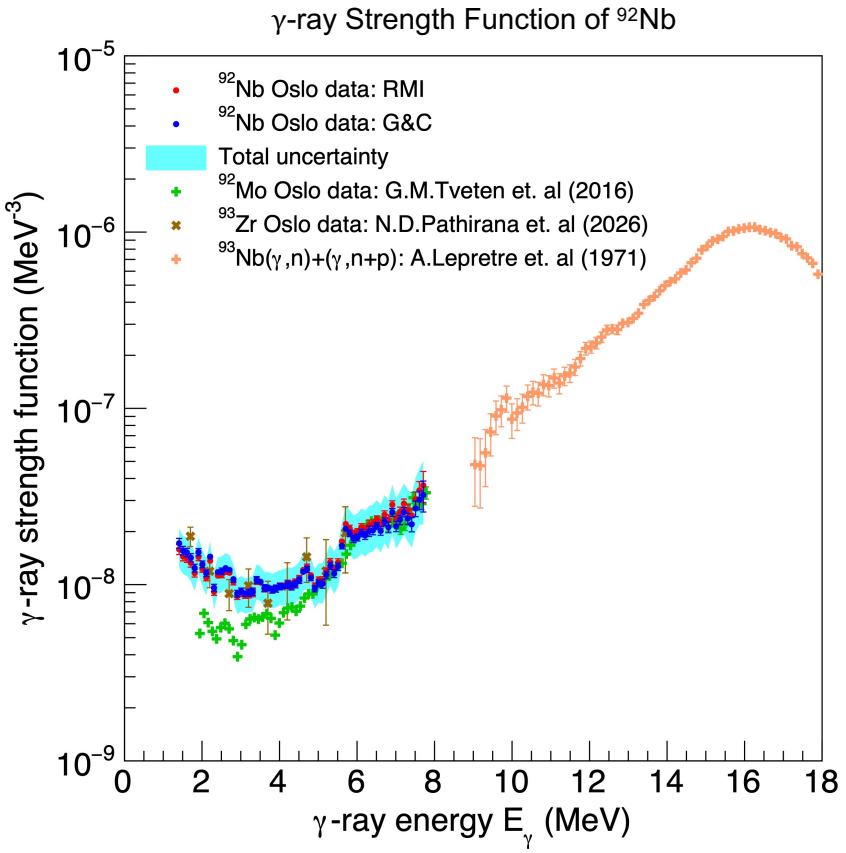
Measured excitation energies in ^{92}Nb, combined with coincident γ-rays detected at each excitation energy



Oslo Method



NLD: Number of levels per MeV as a function of E_x



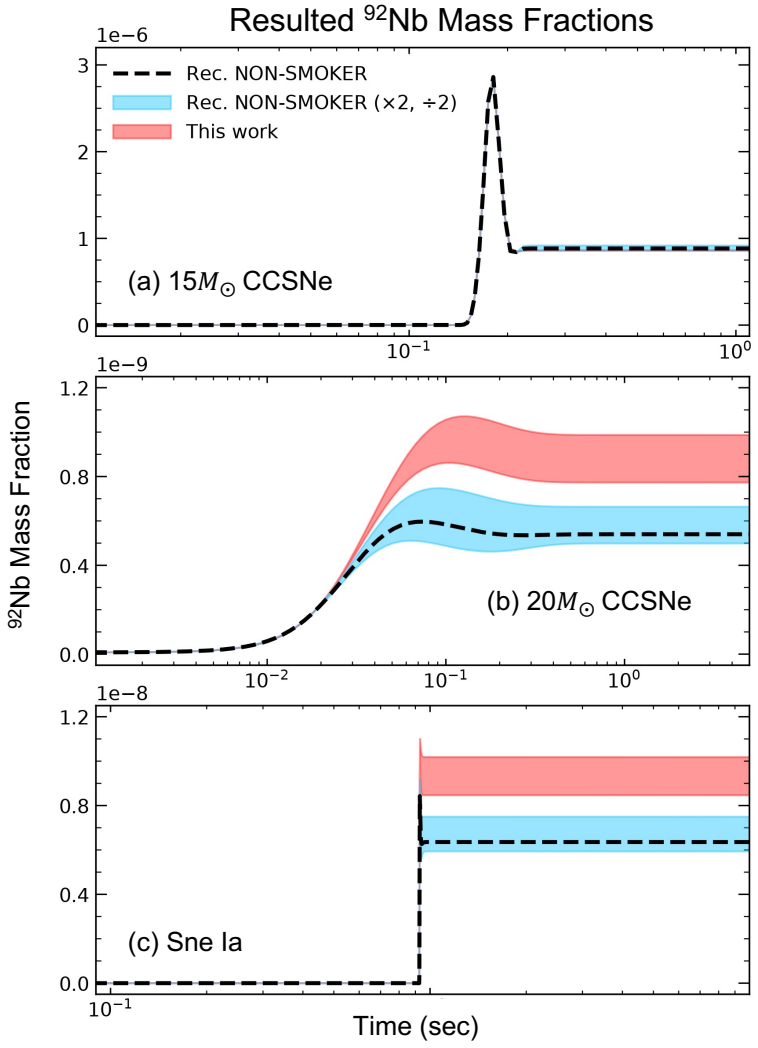
γSF: Probability to emit any γ-ray with different multipolarity

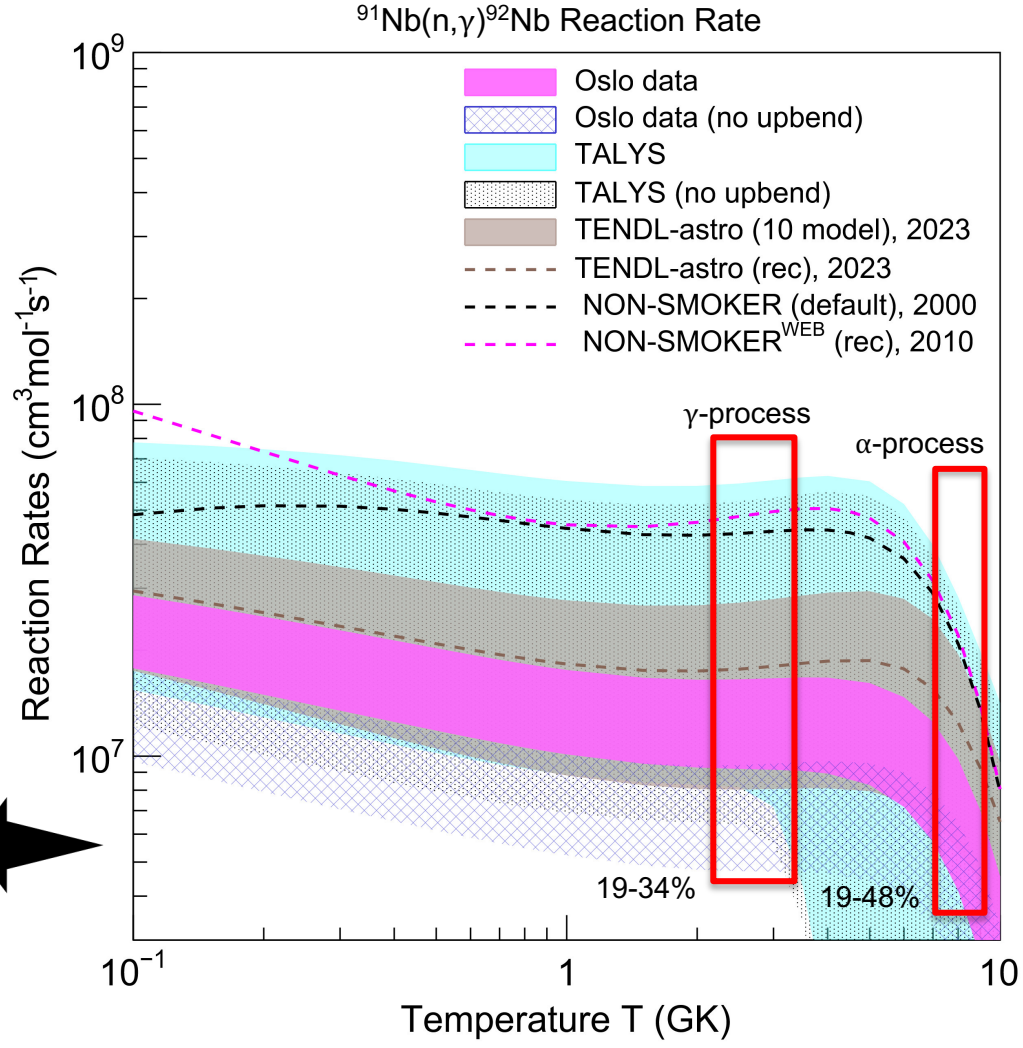
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Constrained ^{91}Nb(n,γ)^{92}Nb Reaction Rate and Impact on CCSNe and SNe Ia Simulations

N.D. Pathirana et al., (submitted)

- The experimentally constrained rate is significantly lower than the widely used recommended NON-SMOKER[ii] rate
- The astrophysical impact of the improved rate was evaluated for both CCSNe and SNe Ia scenarios
- The improved rate enhances the ^{92}Nb abundance by 50-90% relative to recommended rate and shifts γ-process predictions in the direction needed to ease the long-standing ESS ^{92}Nb/^{92}Mo discrepancy





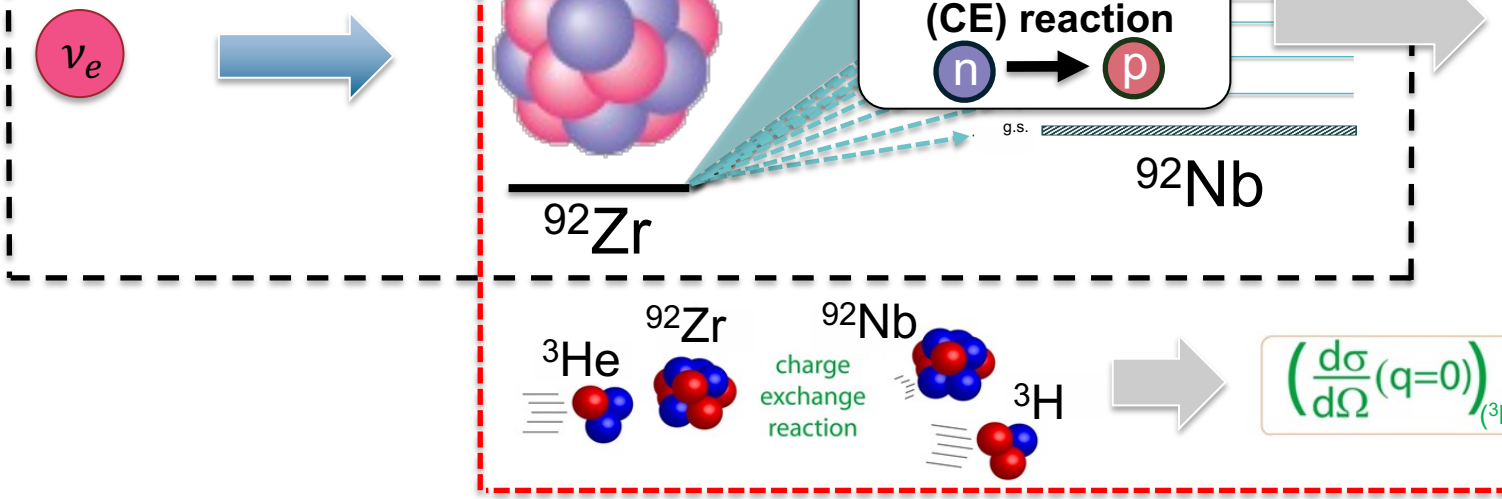
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640 South Shaw Lane • East Lansing, MI 48824, USA
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i. A. Koning et al., Eur. Phys. J. A (2023) 59:131
ii. R.H. Cyburt et al., (2010), ApJS, 189, 240
iii. F. Herwig et al., PoS NIC X 053 (2009) 023.
iv. Ritter et al., MNRAS 480 (2018) 538–571
v. C. Travaglio et al., Ap.J. 795: 141 (2014)

Experimental Study of ^{92}Nb Production via $^{92}Zr(\nu_e,e^-)^{92}Nb$ Reaction: How Can We Constrain $^{92}Zr(\nu_e,e^-)^{92}Nb$ Reaction Rate?

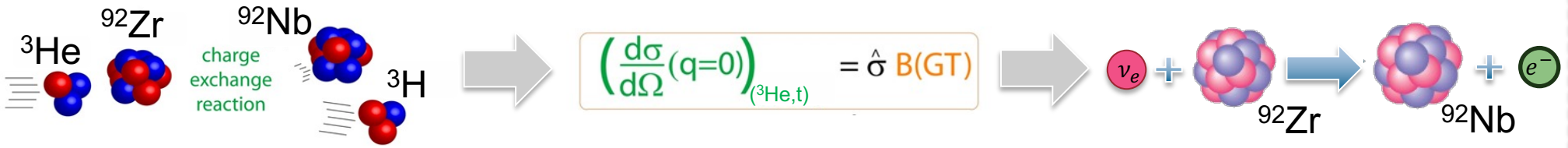
Direct measurements

- Not really feasible to measure directly



Indirect measurements

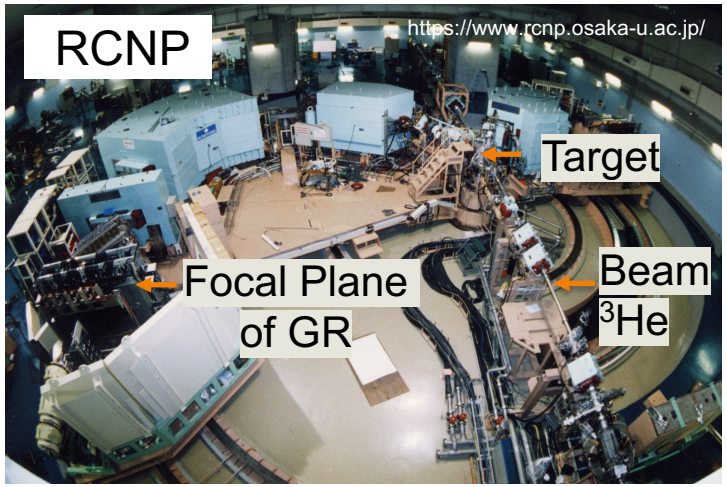
- The dominant contribution is the charged-current (CC) neutrino interactions
- At astrophysical energies, the CC cross section is dominated by Gamow-Teller B(GT) and Fermi B(F) transitions from the ground state of ^{92}Zr
- The CE experiments at ~ 100 MeV/u provide a way to extract these transition strengths through Multipole Decomposition Analysis (MDA)
- The CE differential cross section at zero momentum transfer (q~0) is proportional to B(GT) and B(F)



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The first experimental extraction of CC ^{92}Zr(ν_e,e^-)^{92}Nb cross sections is currently in progress

^{92}Zr(^{3}He,t)^{92}Nb experiment setup at RCNP



- The ^{92}Zr(^{3}He,t) CE experiment was performed in forward kinematics using a 420 MeV ^{3}He-beam at RCNP
  - The Gamow-Teller strength distribution was extracted using Multipole Decomposition Analysis (MDA) applied to the experimental data at forward-peaking angles
- The extraction of CC ^{92}Zr(ν_e,e^-)^{92}Nb cross sections is currently in progress in collaboration with a theory group at the University of Zagreb

Nils Paar



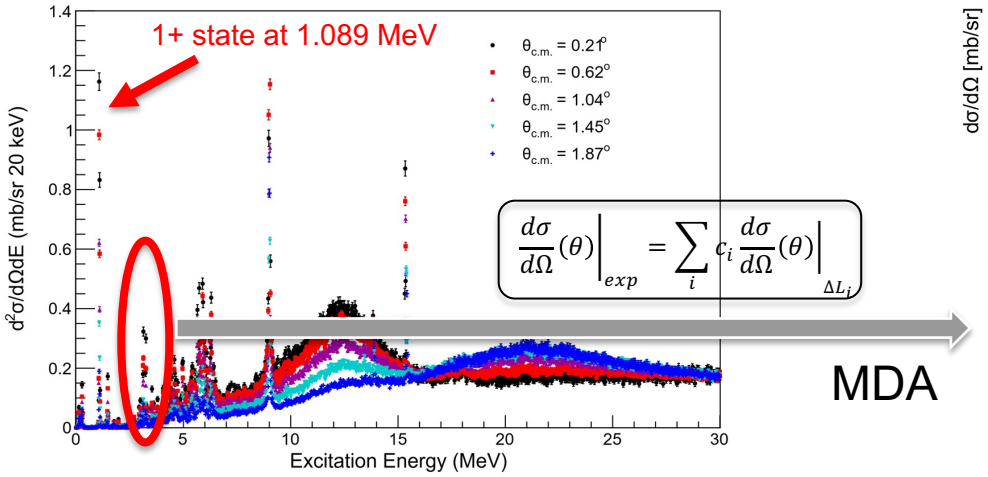
Ante Ravlić



Rade smolović

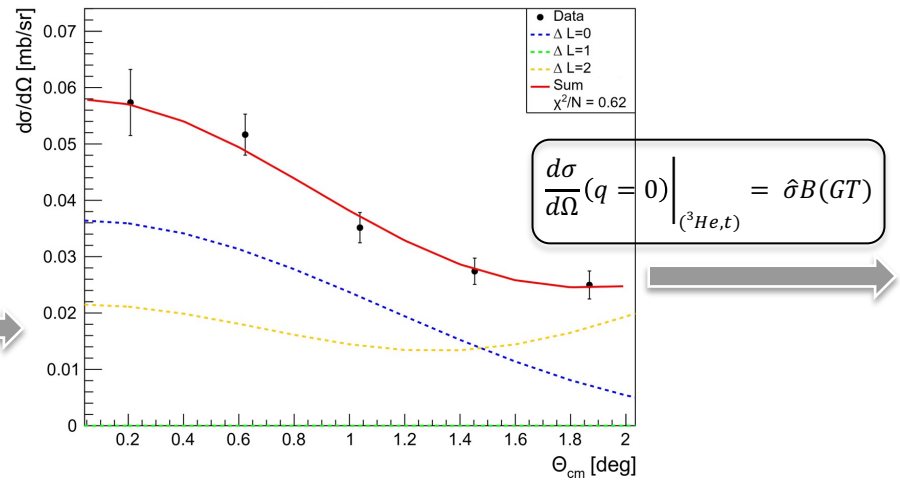


Excitation energy spectrum for angles 0-2 deg

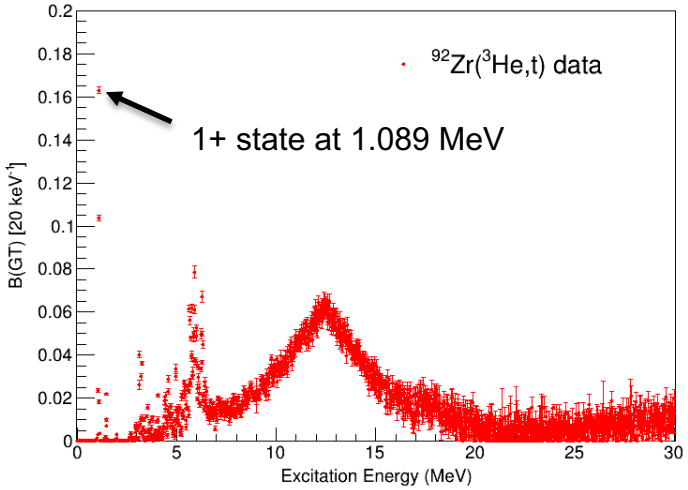


MDA

Angular distribution from the MDA for 3.29 < Ex < 3.31 MeV

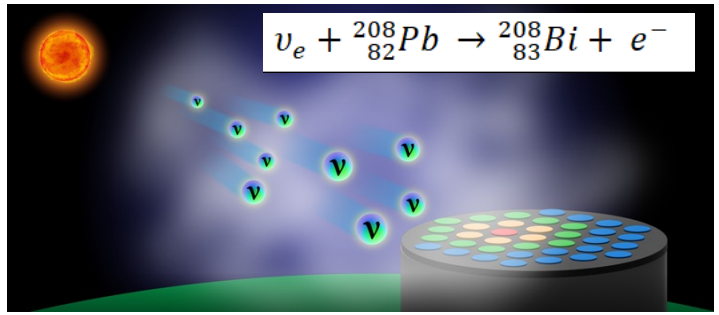


Gamow-Teller distribution



i. T. Hayakawa et al., Ap.J.Lett. 779, L9 (2013)

One More Example: Experimental Study of Charged-Current Neutrino Reaction on ^{208}Pb



- The CC ^{208}Pb$(\nu_e,e^-)^{208}$Bi cross sections is important for neutrino detector applications
  - Gamow-Teller strength distribution was extracted using the experimental data obtained from ^{92}Zr(^{3}He,t) experiment performed at RCNP
- The CC ^{208}Pb$(\nu_e,e^-)^{208}$Bi cross sections are being calculated and currently under finalizations
- Also working on ^{40}Ar and ^{136}Xe

Nils Paar



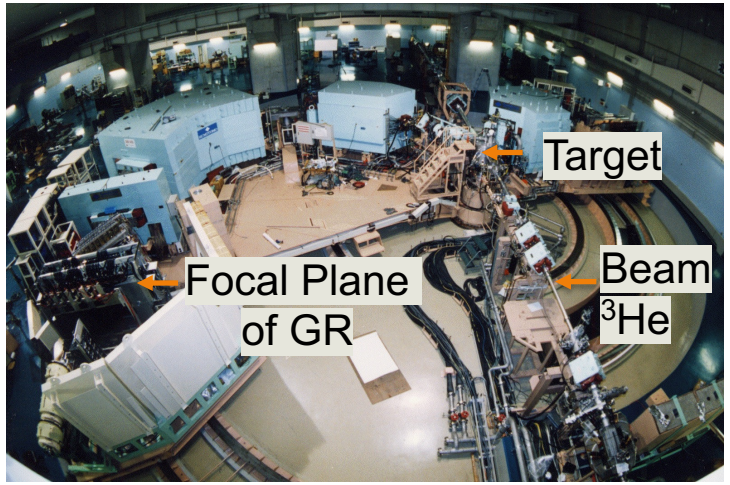
Ante Ravlić



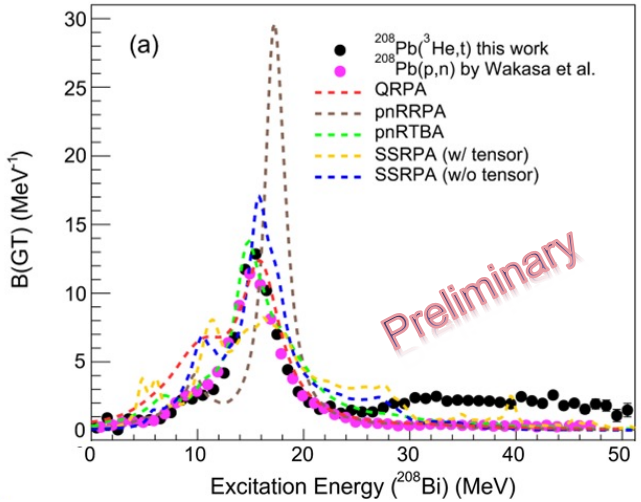
Rade smolović



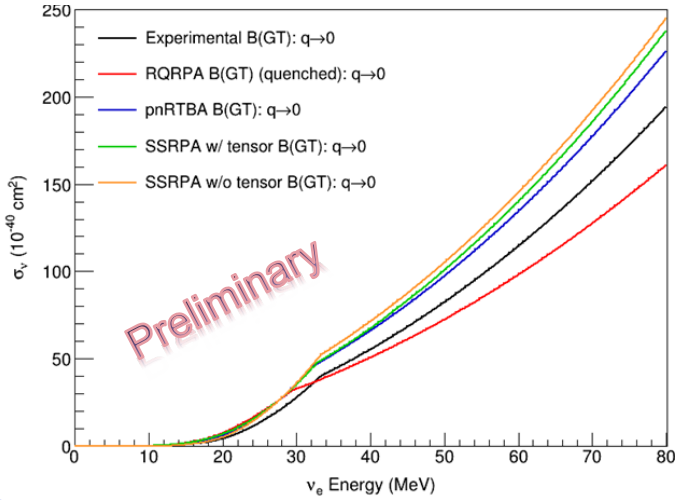
^{92}Zr(^{3}He,t)^{92}Nb experiment setup at RCNP



B(GT) distribution



CC ^{208}Pb$(\nu_e,e^-)^{208}$Bi cross sections

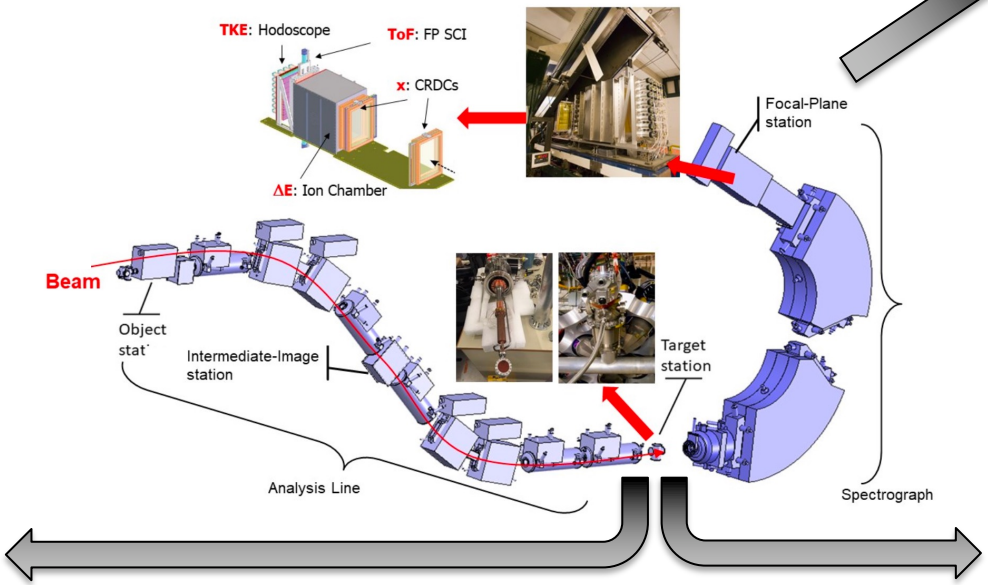


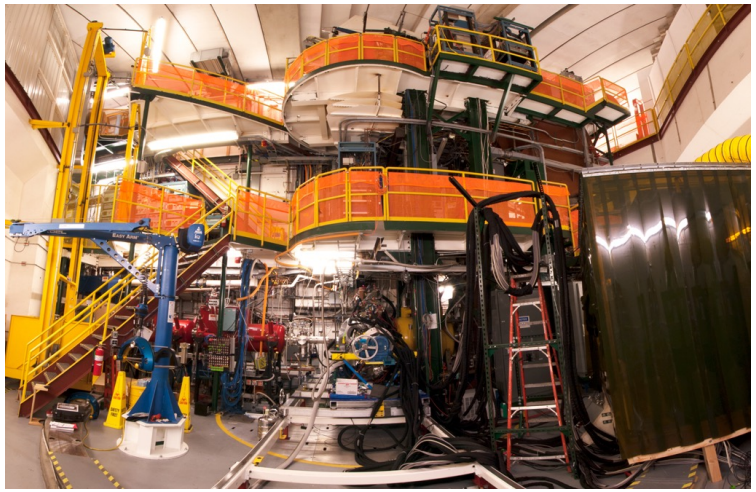
i. T. Hayakawa et al., Ap.J.Lett. 779, L9 (2013)
ii. Z. Xiong et al., Phys. Rev. Lett. 132, 152701 (2024)

CE-Oslo Method in Inverse Kinematics!!!



$^{A}X(p,n+\gamma)$

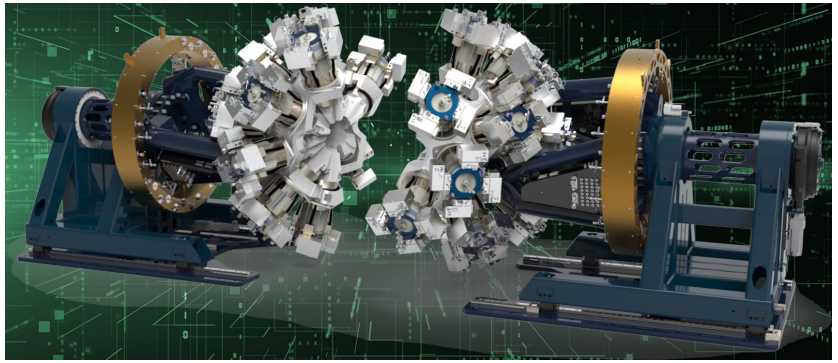




S800 Spectrometer



LENDA: Low Energy Neutron Detector Array



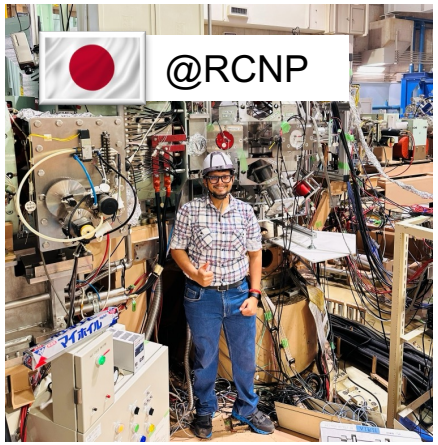
GRETA: Gamma-Ray Energy Tracking Array

MICHIGAN STATE UNIVERSITY

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H. Berg
A. Spyrou

C. Maher
S. Noji
V. Jones
J. Zamora
R.G.T. Zegers

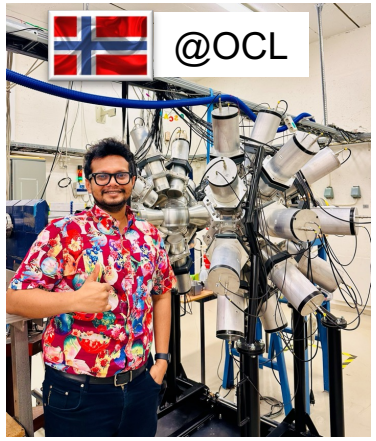


RCNP
大阪大学 核物理研究センター

H. Fujita
Y. Fujita
A. Tamii

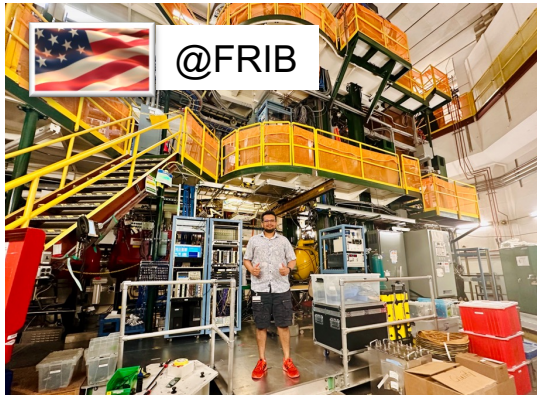
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UNIVERSITAS OSLOENSIS MDCCCXI
UiO : University of Oslo

M. Guttormsen
V.W. Ingeberg
A.C. Larsen
M. Markova
S. Siem

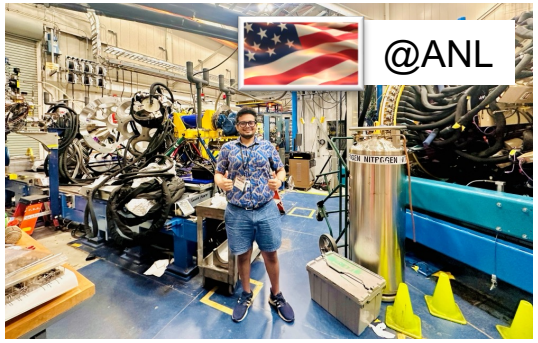


University of Zagreb

N. Paar
A. Ravlic
R. Smolović



Thank You!



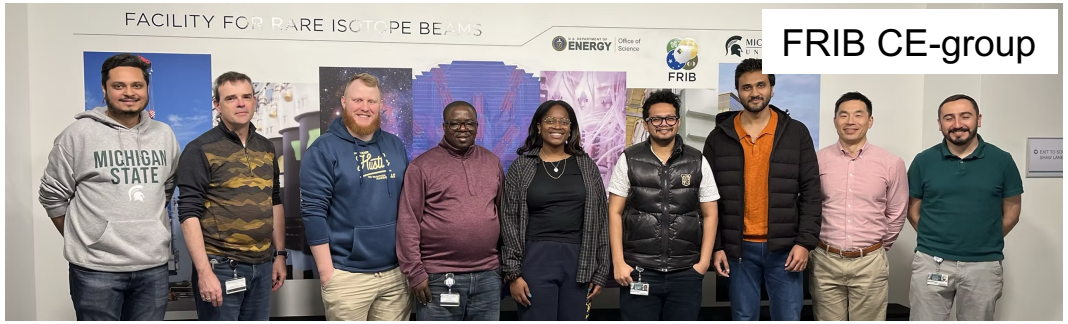
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A. Tsantiri

TECHNISCHE UNIVERSITÄT DARMSTADT

P. von Neumann-Cosel





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Travel support