NuSym 2023
XIth International Symposium on Nuclear Symmetry Energy
GSI Darmstadt, Germany

Constraining the nuclear equation of state using Coulomb excitation of neutron-rich Sn isotopes

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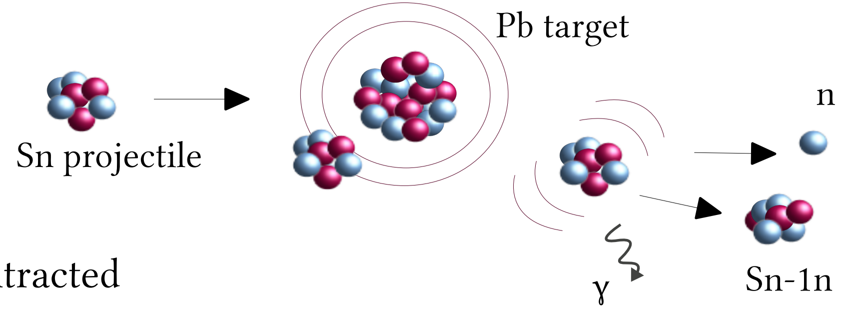
Coulomb excitation of neutron-rich nuclei in EOS study



- Fast projectile at relativistic energies excited in a Lorentz-contracted Coulomb field of a high Z-target

- Probing the electric dipole response (E1) of nuclei

  GDR – oscillation of protons against neutrons

  PDR – oscillation of neutron skin against isospin symmetric core

- Isospin sensitivity – access to the symmetry energy of nuclear EOS $\longrightarrow$ slope parameter, L

- Electromagnetic probes – large cross sections due to the long range of the interaction, smaller uncertainties than for hadronic probes

- α_D – dipole polarizability

- **σ_C – new observable** [A.Horvat, PhD thesis, TUDa, 2019]

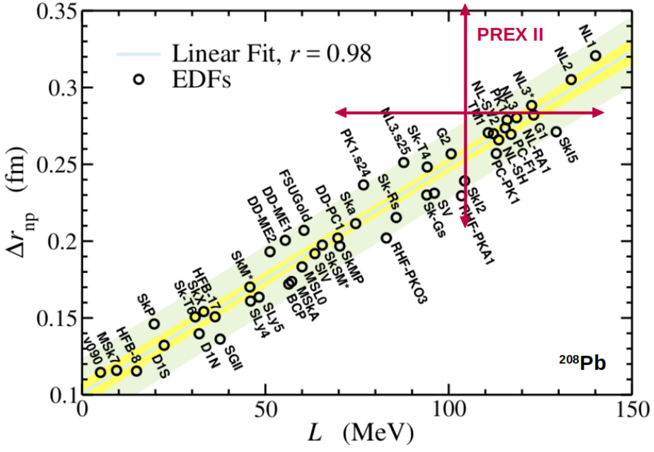
Dipole polarizability α_D

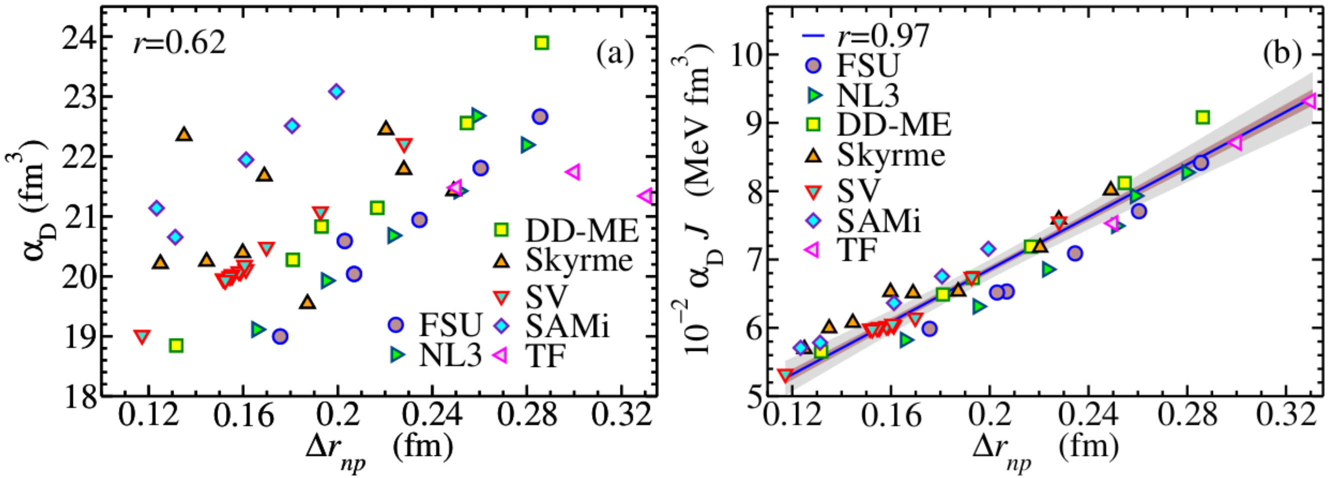
- Inverse-energy weighted sum rule (weighted electric dipole response function)

$$\alpha_D = \frac{8\pi}{9} \int \frac{B(E1)}{\epsilon} d\epsilon$$

- Sensitivity to L – correlation with Δr_{np}
- α_D (Δr_{np}) correlation coefficient : 0.62
- $\alpha_D J$ (Δr_{np}) correlation coefficient : 0.97

[X. Roca-Maza, N.Paar, Prog.Part.Nucl.Phys. (2018) 101:96–176.]
[Roca-Maza et al., Phys.Rev.C (2013) 88:024316]



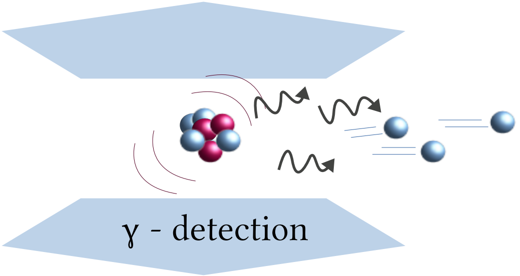


Dipole polarizability α_D - measurements

- Full dipole response function of the nucleus needs to be measured
- Proton inelastic scattering at relativistic velocities at very forward angles – for stable nuclei (^{40}Ca, ^{48}Ca, $^{112-124}$Sn, ^{208}Pb)
- Relativistic Coulomb excitation of projectile nucleus in inverse kinematics – for neutron-rich unstable nuclei (^{68}Ni)
- Going away from the stability valley:

→ inverse kinematics, relativistic energies – forward focusing of decay products

→ accurate excitation energy reconstruction becomes more challenging



^{40}Ca [R. Fearick et al., Phys. Rev. Res. 5 (2023) L022044 (2023)]

^{48}Ca [J. Birkhan et al., Phys. Rev. Lett. 118 (2017) 252501]

$^{112-124}$Sn [S. Bassauer et al., Phys. Lett. B 810 (2020) 135804]

^{208}Pb [A. Tamii et al., Phys. Rev. Lett. 107 (2011) 062505]

^{68}Ni [D.M.Rossi et al., Phys. Rev. Lett. 111 (2013) 242503]

New observable – total Coulomb excitation cross section, σ_C

- Correlation of σ_C with α_D at relativistic energies ⟶ sensitivity of σ_C to L
- Where does correlation come from? Virtual photon method calculation:

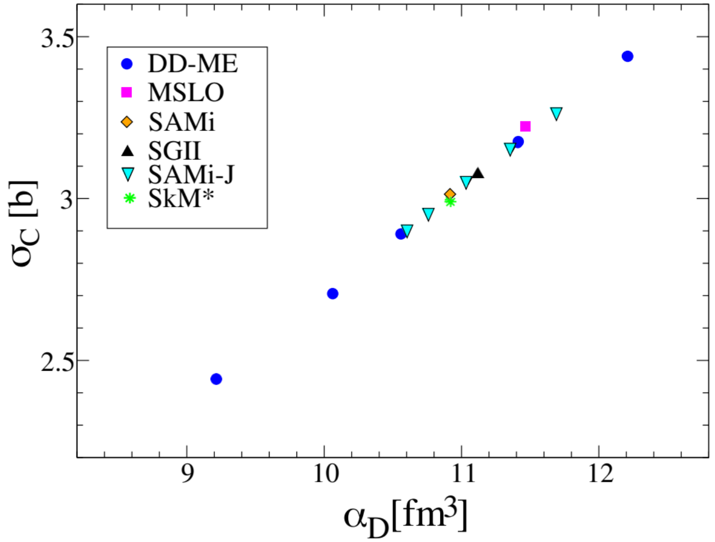
$$\sigma_C^{\pi\lambda} = \int N^{\pi\lambda}(\epsilon) \frac{d\epsilon}{\epsilon} \sigma_\gamma^{\pi\lambda}(\epsilon)$$

$$N_{\pi\lambda}(\epsilon) = Z^2 \alpha \frac{\lambda[(2\lambda+1)!!]^2}{(2\pi)^3(\lambda+1)} \sum_m g_m(\xi) \left| G_{\pi\lambda m}(c/v)^2 \right|$$

$$\sigma_\gamma^{\pi\lambda} = e^2 \frac{(2\pi)^3(\lambda+1)}{\lambda[(2\lambda+1)!!]^2} \sum_f \rho_f(\epsilon) \left(\frac{\epsilon}{\hbar c}\right)^{2\lambda-1} B_{i\to f}^{\pi\lambda}(\epsilon)$$

$$\alpha_D = \frac{\hbar c}{2\pi^2} \int \frac{\sigma_\gamma^{E1}}{\epsilon^2} d\epsilon = \frac{8\pi}{9} \int \frac{B(E1)}{\epsilon} d\epsilon$$

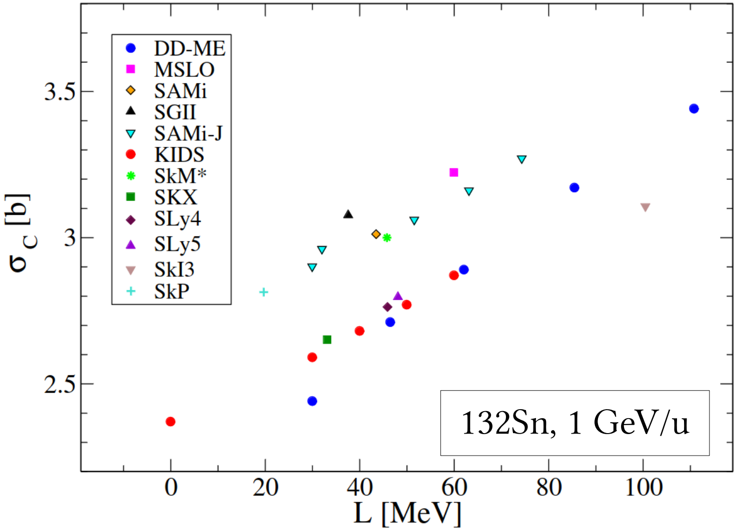
- $\pi\lambda$ = E1 – at relativistic energies N_{E1} follows ≈1/ε functional dependence - as α_D

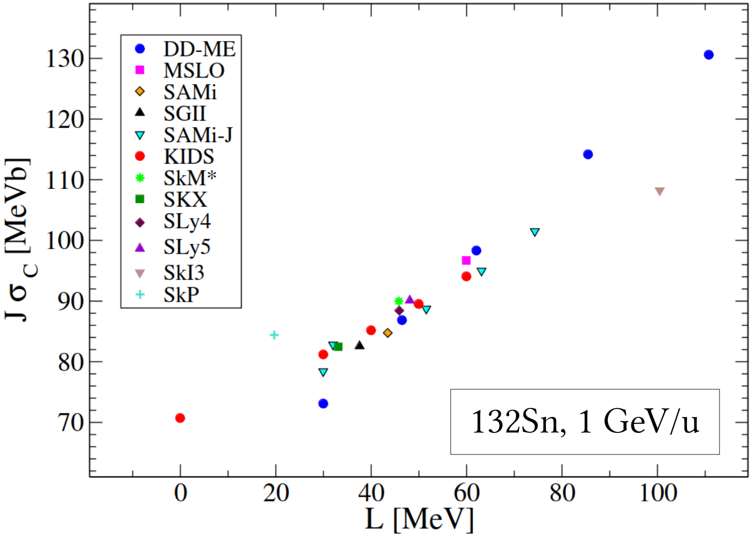


^{132}Sn at 1 GeV/u
[A.Horvat, PhD thesis, TUDa, 2019]

Correlation of σ_C to L

- (Q)RPA calculations using different relativistic and nonrelativistic EDFs – B(E1) values
- σ_C calculation via virtual-photon method [C.Bertulani, G.Baur, Phys.Rep., 163 (1988) 229]
- σ_C is easier to measure – doesn't require reconstruction of full excitation energy spectrum

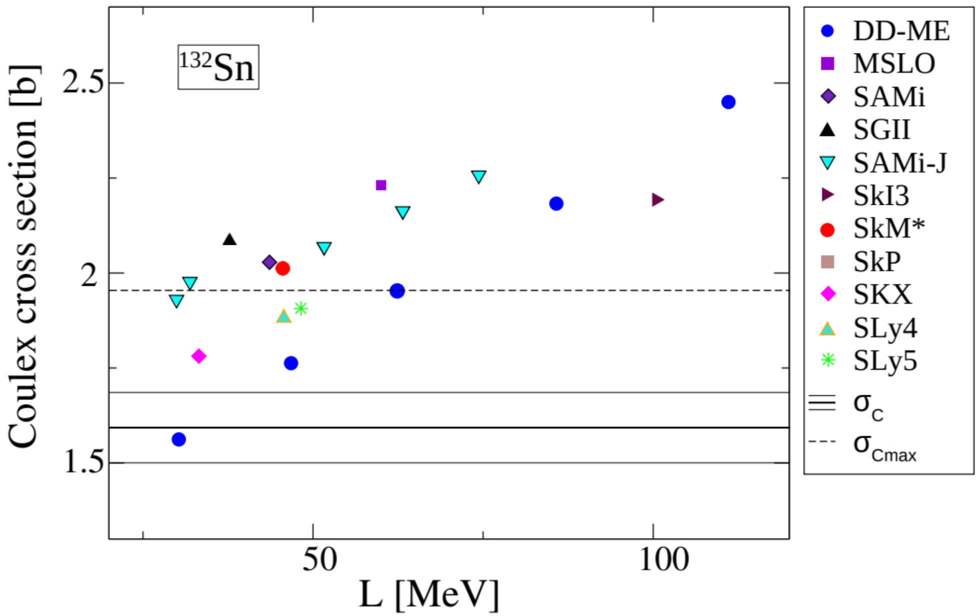




[A. Horvat, private communication]

First experiment exploring σ_C at GSI - S412

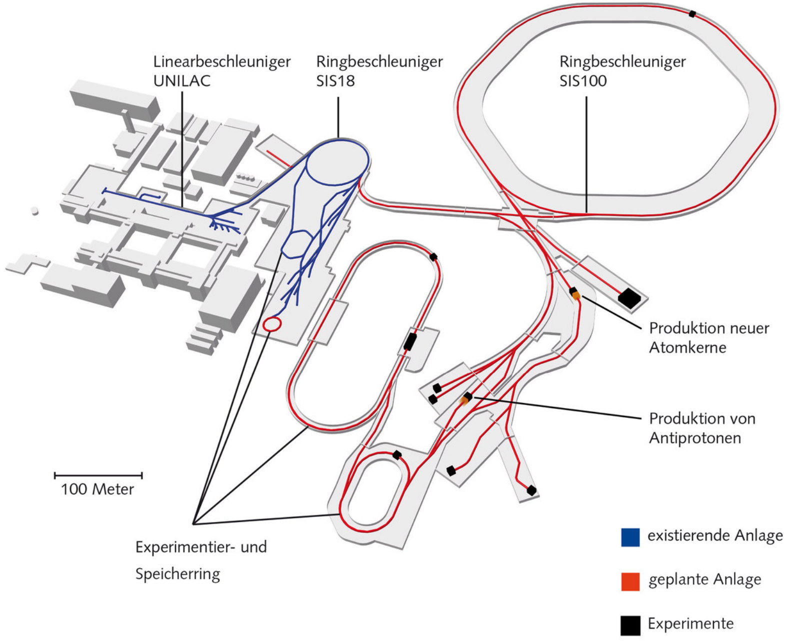
- R³B@GSI, Darmstadt 2012
- R³B-LAND setup
- Evolution of dipole response in $^{124-132}$Sn by measuring σ_C (in field of ^{208}Pb target)
- Beam energies ≈ 510-580 MeV/u
- Estimation of contribution below 1n threshold from [P. Schrock., PhD thesis, TUDa, 2015.]
- Softer L values preferred
- **Publication in preparation!**



[A.Horvat, PhD thesis, TUDa, 2019]

Follow-up experiment - S515

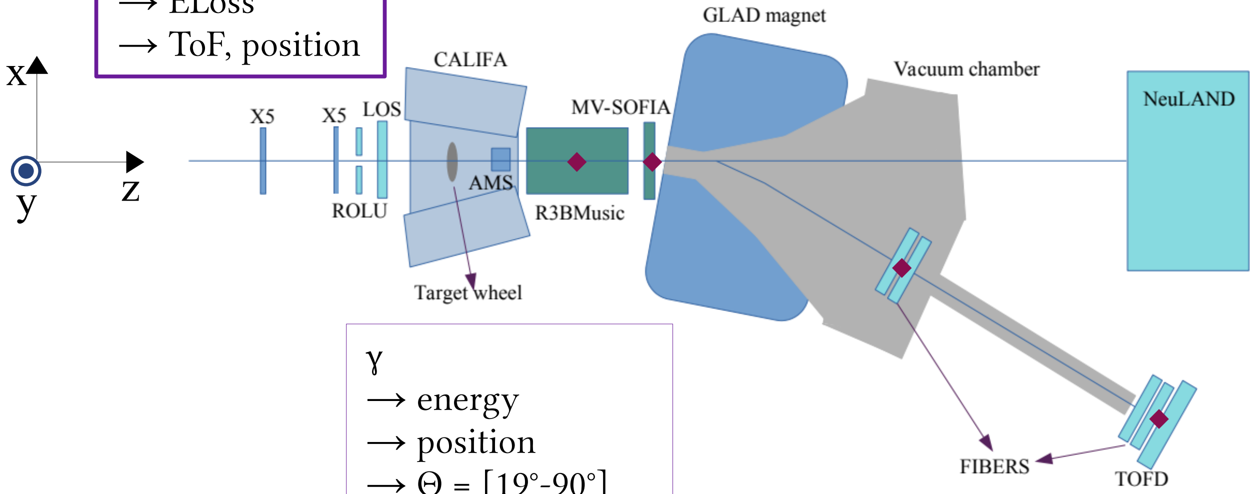
- Further investigation of Sn isotopes; mass range 124-134
- R^3B@GSI, FairPhase0 campaign, 2021
- σ_C measurement (predicted accuracy 5%)
- Accurate measurement of $\sigma_{\Delta N}$ (+/- 10 MeV constraint on L)
- UNILAC, SIS18 – primary beam ^{136}Xe, ^{238}U
- FRS – secondary cocktail beam: $^{124\text{-}134}Sn$ (fragmentation and fission process using "Bρ-ΔE-Bρ" method) on Be and Pb production targets
- Beam energies ≈ 680-900 MeV/u
- Secondary beam intensity ≈ $3{\cdot}10^4$ pps
- R^3B-NeuLAND setup



S515 experiment

Beam received from FRS.

Incoming beam
⟶ ELoss
⟶ ToF, position

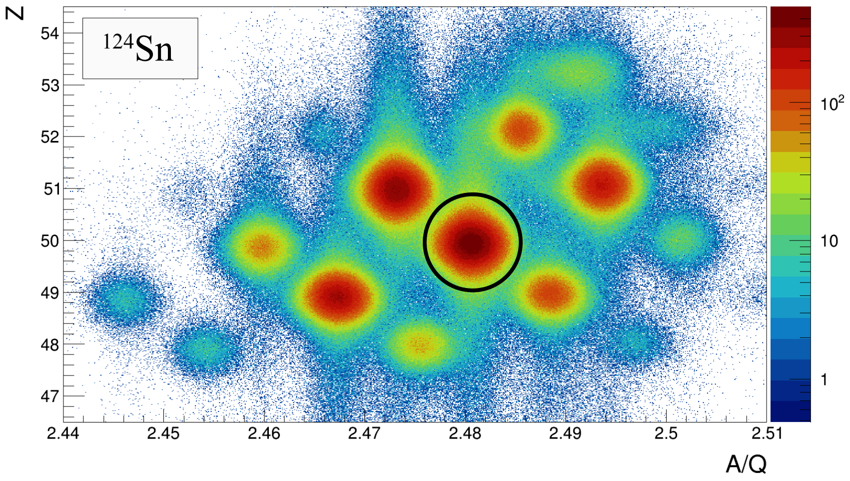


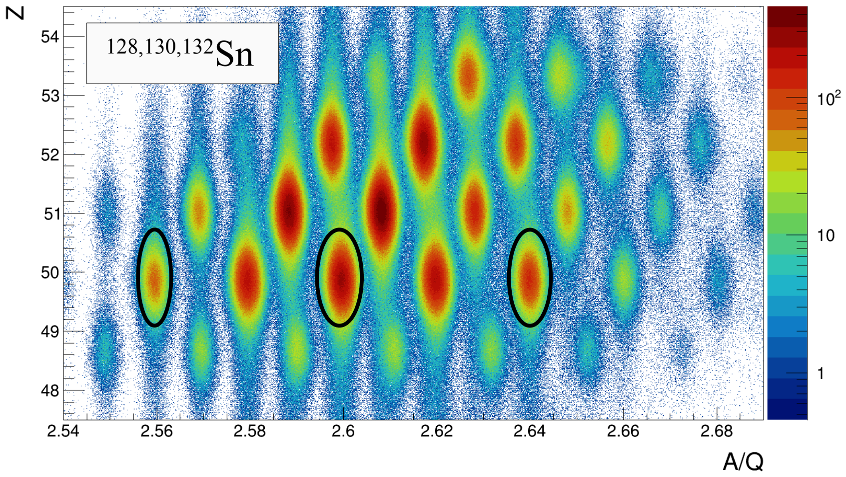
γ
⟶ energy
⟶ position
⟶ Θ = [19°-90°]

Neutrons
⟶ ToF (w.r.t. LOS start det.)
⟶ position
⟶ ELoss

Fragments ◆
⟶ Eloss (charge)
⟶ position

- Detection of incoming beam and reaction products
- Beam energies ≈ 680-900 MeV/u
- Targets: ^{208}Pb (980 mg/cm2) , ^{12}C (1 g/cm^2, 2 g/cm^2)
- σ_C measurement above 1n separation threshold





Incoming beam identification

- Bρ – position measured in the second focal plane S2 of FRS

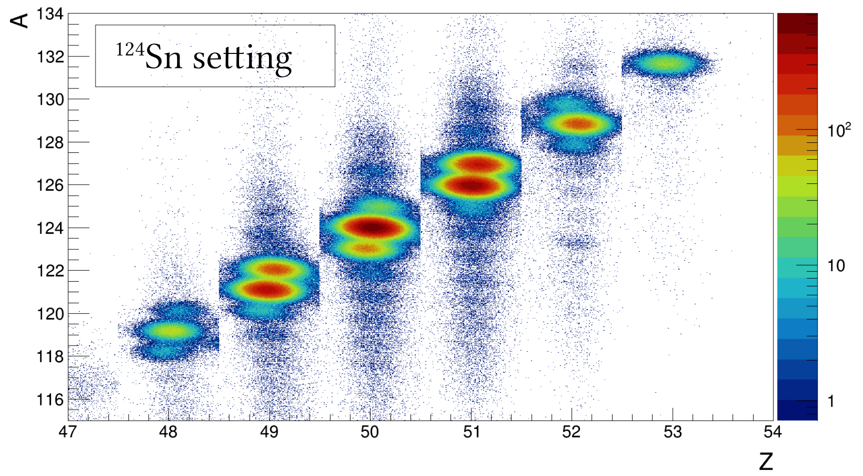
$$B\rho = B\rho_0 \left(1 - \frac{\Delta x_{S2}}{D_{S2}}\right)$$

- ToF – measured between S2 and LOS ⟶ β

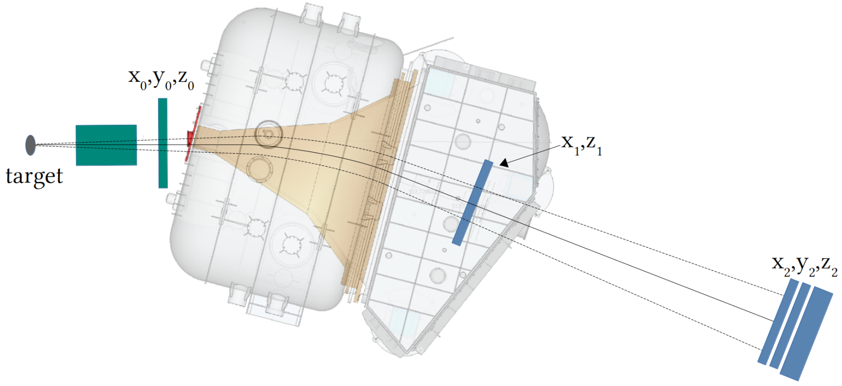
$$\frac{A}{Q} = \frac{B\rho}{3.107\beta\gamma}$$

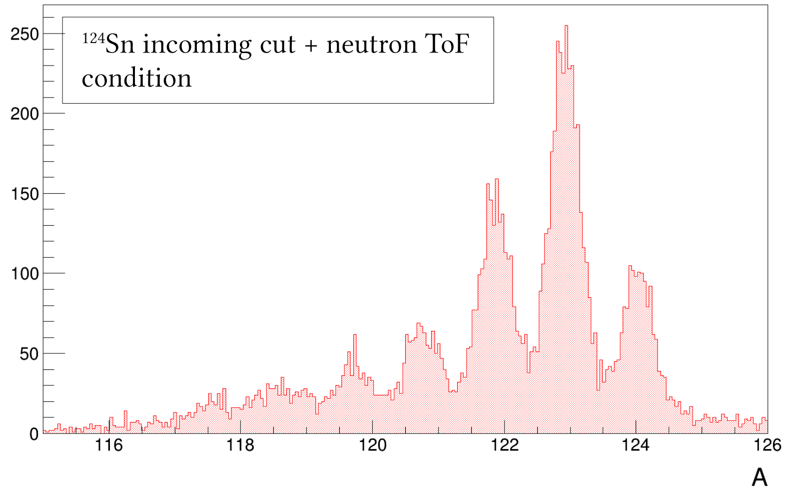
- ELoss – measured with X5 sillicon det. ⟶ Z
- β-correction for charge
- Charge resolution $\sigma_Z/Z \approx 0.7$ %
- A/Q resolution $\sigma_{A/Q}/A/Q \approx 0.07\%$

Outgoing fragment identification



- Z-measurement (ionization chamber R3BMusic)
- Z resolution $\sigma_Z/Z \approx 0.28$ %
- Mass – tracking of fragments after reaction on target through GLAD magnet

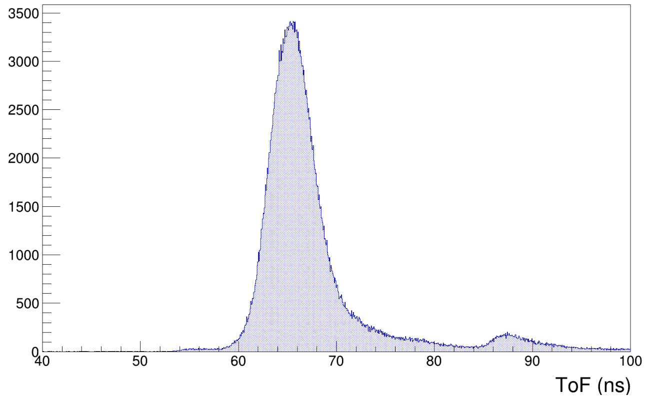


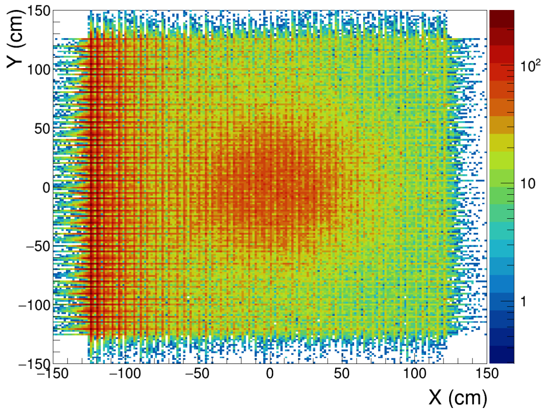


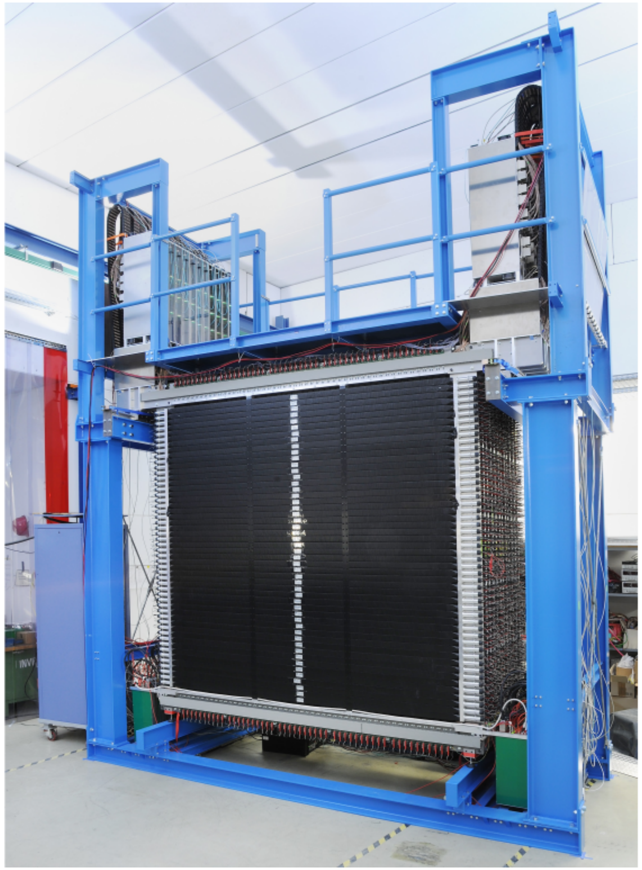
- "multi-dimensional fit" method (V. Panin)
- A resolution $\sigma_A/A \approx 0.2\%$

Neutron detection

- NeuLAND detector – ToF, ELoss, position measurement
- Modular design – organic scintillator bars arranged in double planes
- 12 double planes present at the time of the experiment
- Current ToF resolution reached σ ≈ 230 ps
- 1n efficiency ≈ 80%



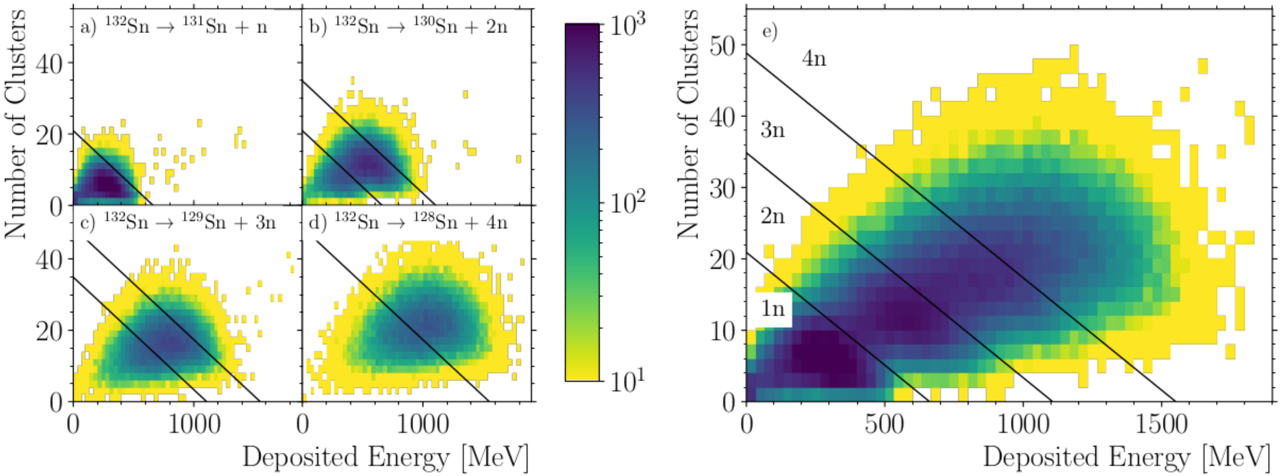




Double plane:
1st plane ⟶ 50 horizontaly oriented bars
2nd plane ⟶ 50 vertically oriented bars

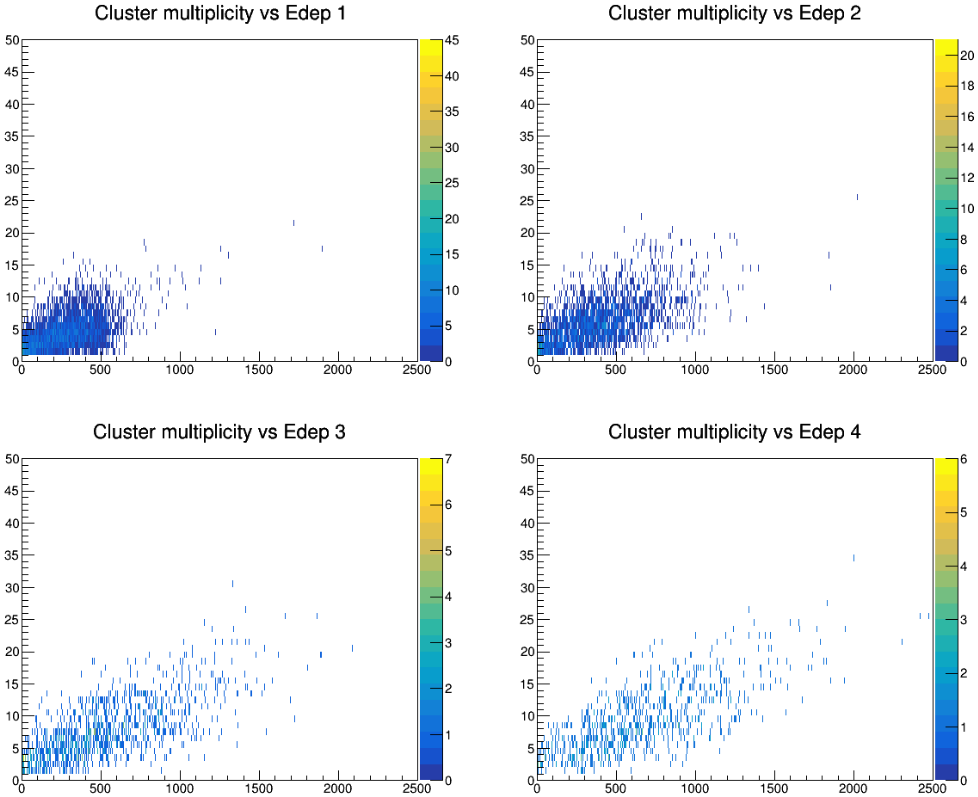
Neutron detection

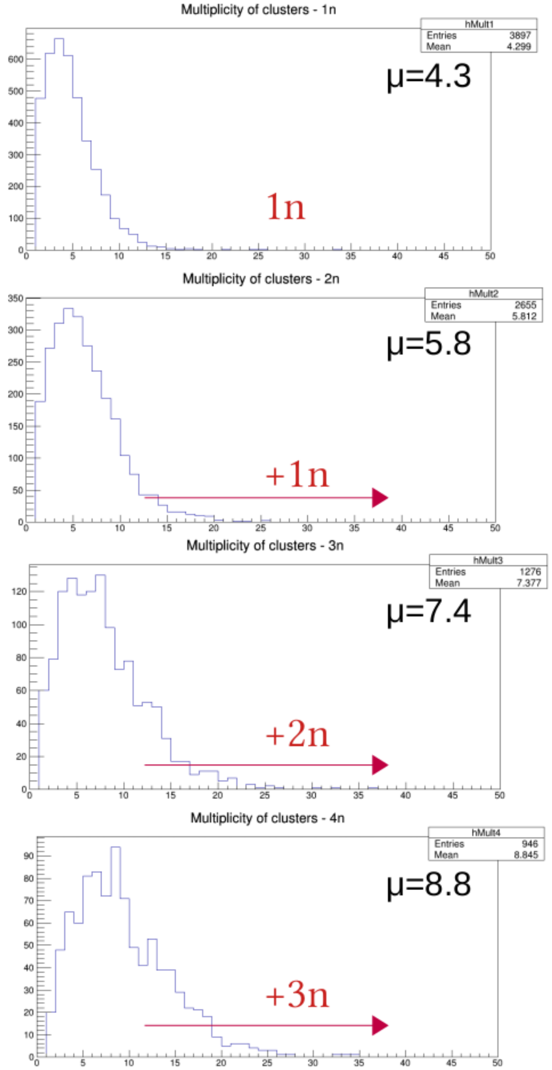
- multi-neutron recognition
- IDEA: clustering detected hits, sorting them and attributing to neutrons
- few algorithms developed for NeuLAND detector
- main algorithm: calorimetric method (Number of clusters vs Total energy deposition)
  – BUT works best for full detector (30 DP)



600 MeV neutrons, 30DP, multiplicity up to 4
[K.Boretzky et al., Nucl. Instrum. Methods Phys. Res. A 1014 (2021) 165701]

- For 12 DP large overlap in the 2D plot for 1/2/3/4 neutrons
- Shift in average number of clusters and ELoss visible for increasing neutron number
- Work in progress





Coulomb excitation cross section

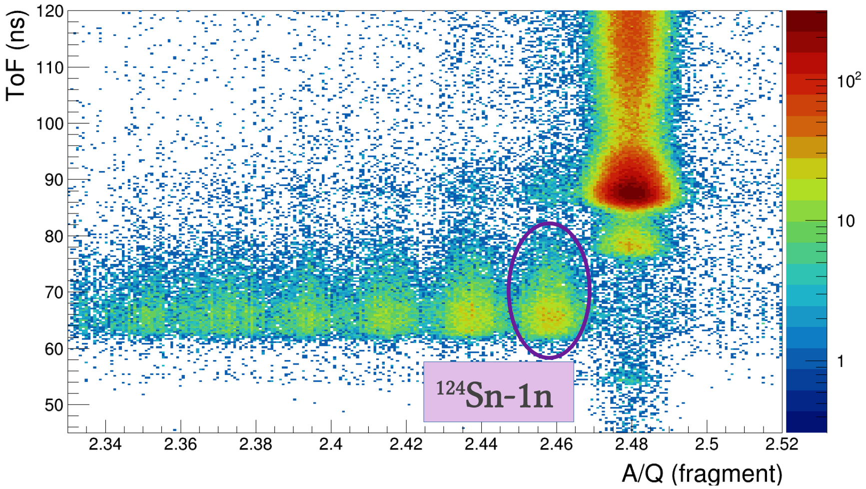
- correlation of neutron ToF with fragments – allows for the evaluation of 1n cross section
- Efficiency and acceptance from GEANT4 simulations
- background contribution subtracted with the "empty target" run
- nuclear contribution subtracted with the carbon target run – scaled up for the lead target (currently using semi-empirical model)

$$\sigma_C = \frac{M(Pb)}{d(Pb)N_A}[p(Pb)-p(empty)] - \alpha(Pb,C)\frac{M(C)}{d(C)N_A}[p(C)-p(empty)]$$

M(x) – molar mass of the nucleus x | p(x) – reaction probability

d(x) – target thickness (nucleus x) | α (Pb, C) – scaling factor

$$\alpha(Pb,C) = \frac{1+aA(Pb)^{1/3}}{1+aA(C)^{1/3}} \quad , \quad a=0.14+-0.01$$



Preliminary 1n-decay channel results

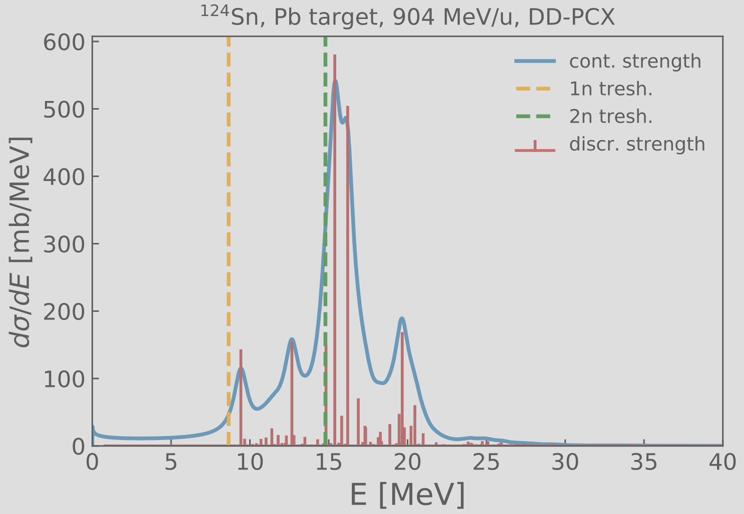
Table 1. Coulomb excitation cross sections for ^{124}Sn at 904 AMeV. In the theoretical results only E1 excitations were taken into account.

EDF	σ [mb] – virtual photon –	σ [mb] – coupled channel –
DD-PCX	2302	2324
Sly4	2499	2601

@514 AMeV

PRELIMINARY!

Decay ch.	1n	2n	3n	4n
σ [mb] (S412)	1088 ± 75	374 ± 95	-	-
σ [mb] (S515)	1280 ± 56	*	*	*



- Mean field calculations of nuclear ground state densities
- (Q)RPA calculations of electromagnetic response (B(E1), B(E2) values) using non-relativistic and relativistic energy density functionals
- cross sections calculated via virtual-photon method and Coulomb coupled-channel method

* All theoretical calculations are performed by C. Bertulani and A.Ravlić.

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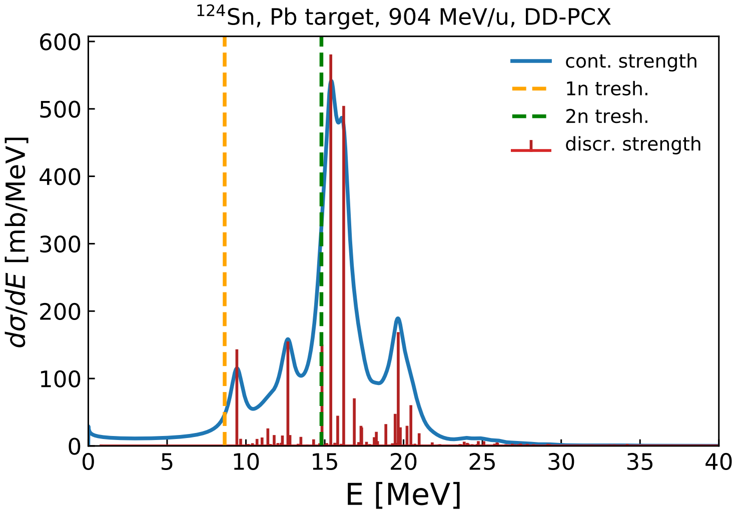

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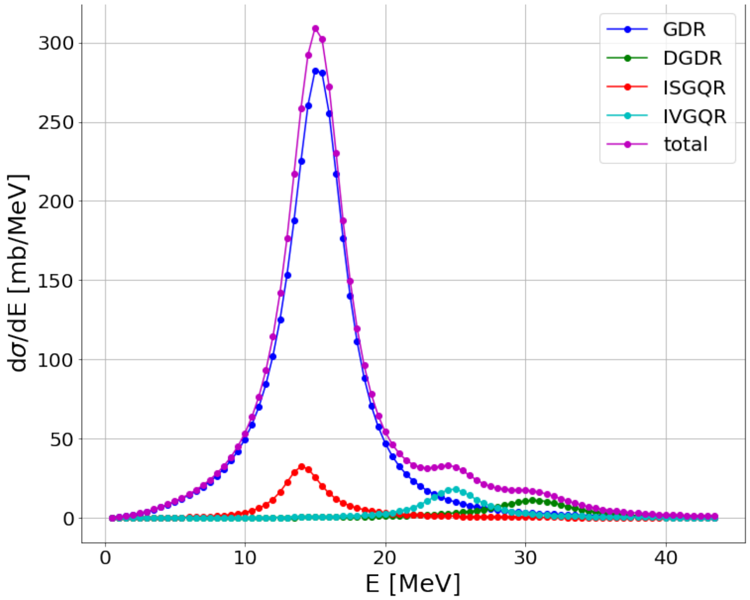
Additional contributions to cross sections

- Quadrupole contribution (ISGQR, IVGQR)
- Double GDR contribution
- Contribution from nuclear processes – further refinement of subtraction from σ_C



- ^{124}Sn, Pb target, 904 AMeV, DD-PCX
- coupled channel calculation
- quadrupole contribution calculated from global experiment systematics of GQR:

E1 : 88 % σ_C
ISGQR : 5 % σ_C
IVGQR : 3.5 % σ_C
DGDR : 3.5 % σ_C

Challenges

- Neutron rich nuclei are interesting because of larger isospin asymmetry
- <u>Challenges:</u>
- multi-neutron recognition
- measurements below neutron separation threshold for neutron rich nuclei

  → good coverage of forward angles with gamma detector

  → hasn't been done so far: accounting for gammas coming from target excitations

Thank you for your attention!
&
Special thanks to my collaborators:

E. Kudaibergenova[2], M. Feijoo-Fontán[3], I. Gašparić[1], A. Horvat[1],
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