The quenching of nucleon knockout in nuclei far from stability and the role of nucleon correlations

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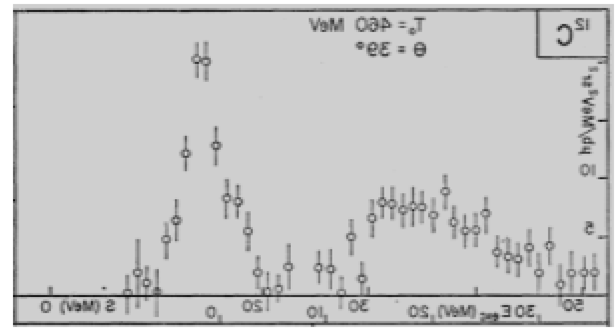
Nucleon knockout reactions

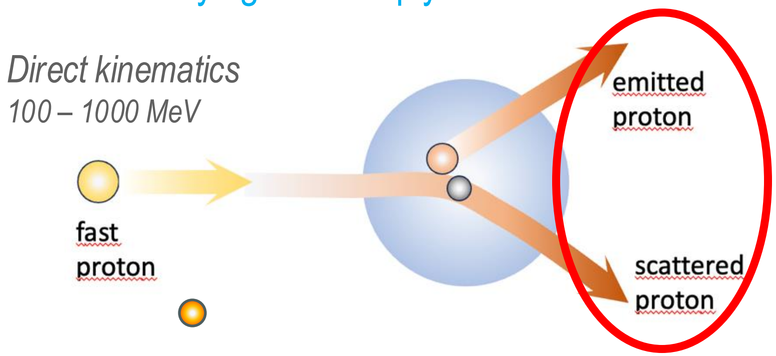
Single nucleon knockout.

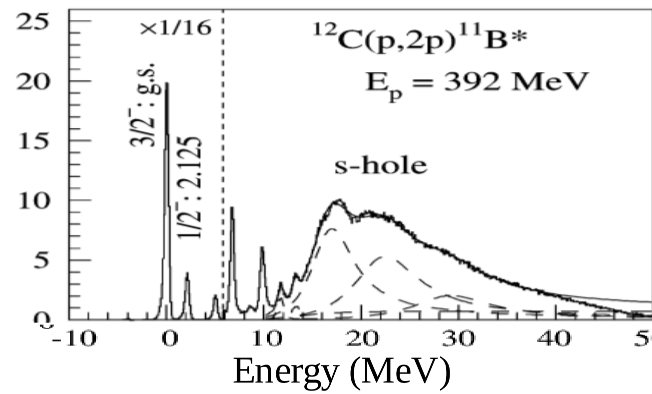
Quasi-free knockout of nucleons, (N,2N) or (e^-,e^-N), a spectroscopic tool proposed in the 1950s to get access to single-particle configuration mixing through spectroscopic factors and single particle energies obtained from measured cross sections of individual final states.

Final states are characterized from the missing energy determined by the measurement of the momenta of the two outgoing nucleons. This technique gives access to low-lying and deeply bound states.



G. Jaqob and Th. Maris, RMP 38, 1 (1966)

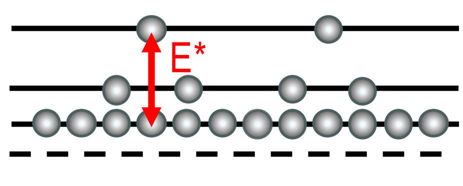




M. Yosoi et al., PLB 551, 255 (2003)

Mean field approach:
- Non-interacting nucleons.
- Shell structure (magic numbers).

Particle-hole excitations.



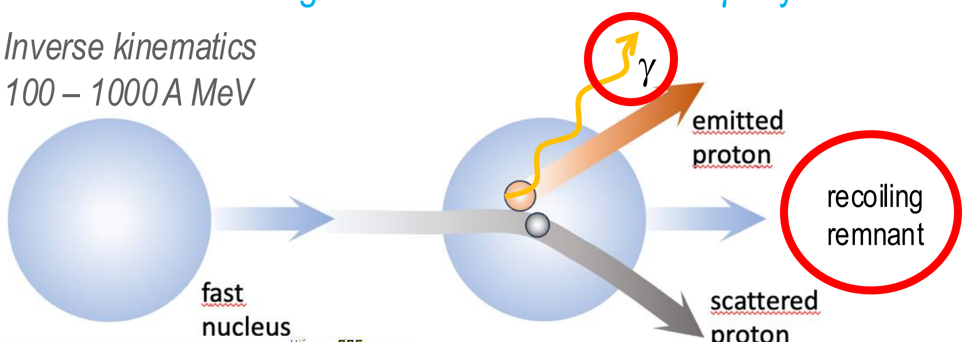
Nucleon knockout reactions

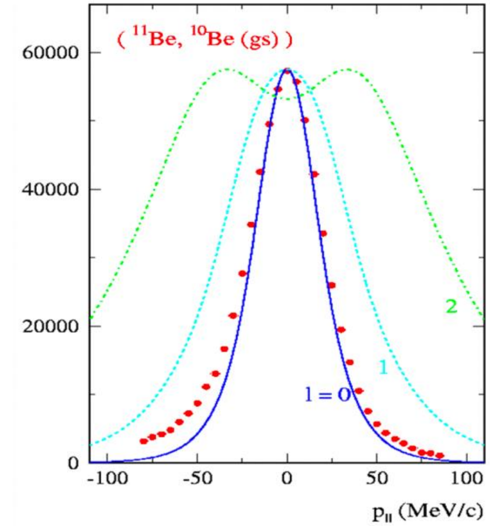
Single nucleon knockout.

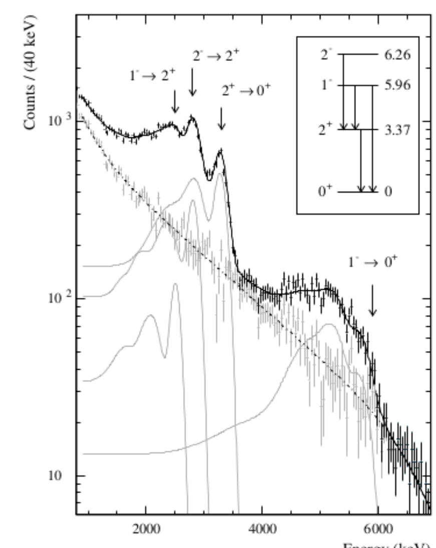
Single nucleon knockout combined with γ-ray spectroscopy, a complementary technique proposed in the late1990s to be used in inverse kinematics with short-lived nuclei.

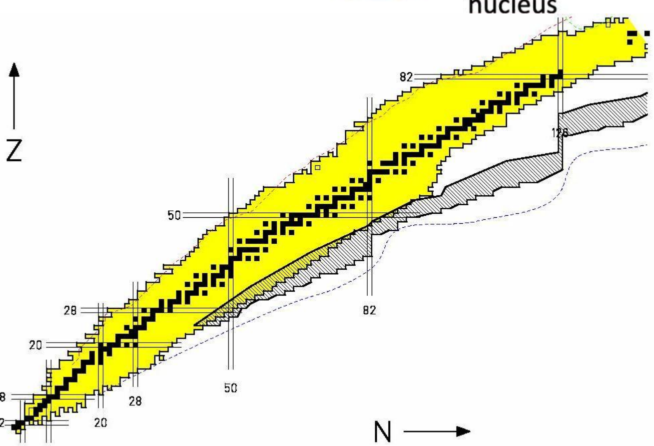
Low-lying hole states can be investigated from the coincident measurement of the momentum of the recoiling remnant and the emitted γ-rays.

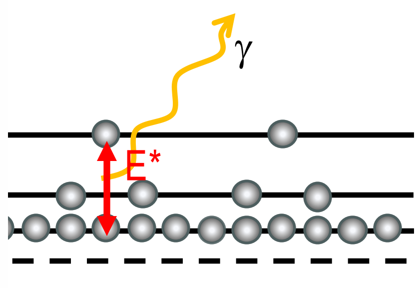
Inverse kinematics
100 – 1000 A MeV











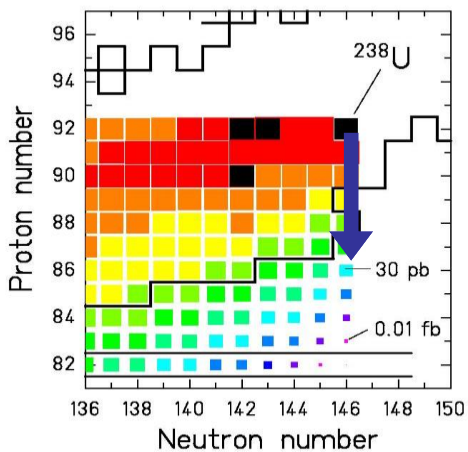
T. Aumann et al., PRL 84, 35 (2000)

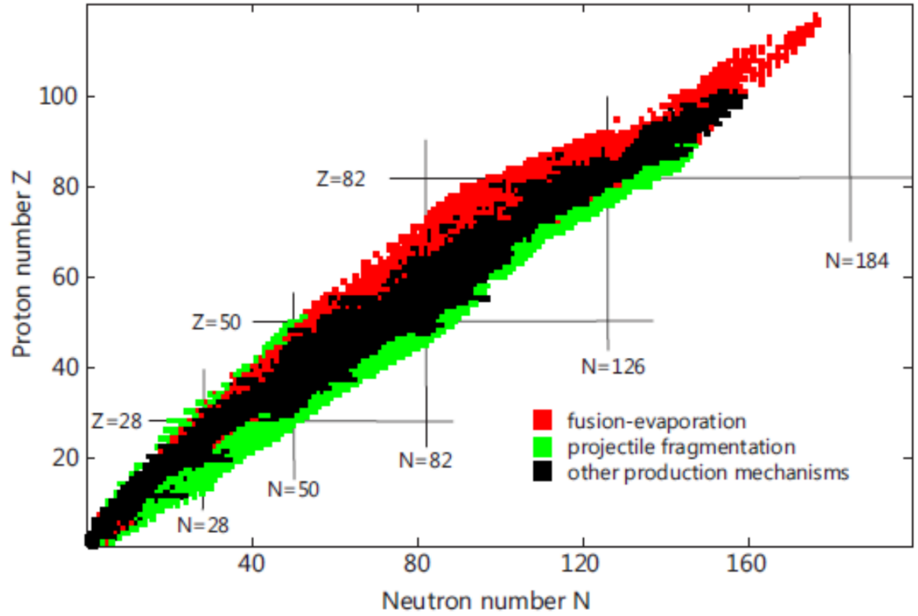
Nucleon knockout reactions

Multi-nucleon knockout (fragmentation).

Multi-nucleon knockout is an optimum process for the production of nuclei far from stability using both, Isol and In-flight technologies.

Wide range in mass and neutron excess of the final fragments.



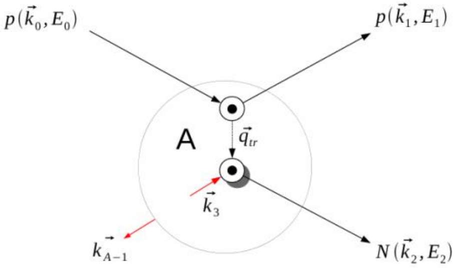


Nucleon knockout reactions

Model description of nucleon knockout reactions at high energies.

The Glauber model provides a relatively simple description of these reactions, based on the quantum mechanical multiple-scattering theory, using two main approximations:

- The impulse approximation, which reduces the problem to a series of individual nucleon-nucleon scatterings.
- The eikonal approximation, which provides a simple form for the scattering amplitudes.



Quasi-free scattering: no re-scattering, 2-body kinematics.

Nucleon knockout: re-scattering.

Nucleon removal: nucleon emission from unbound states.

Implications of the impulse approximation:

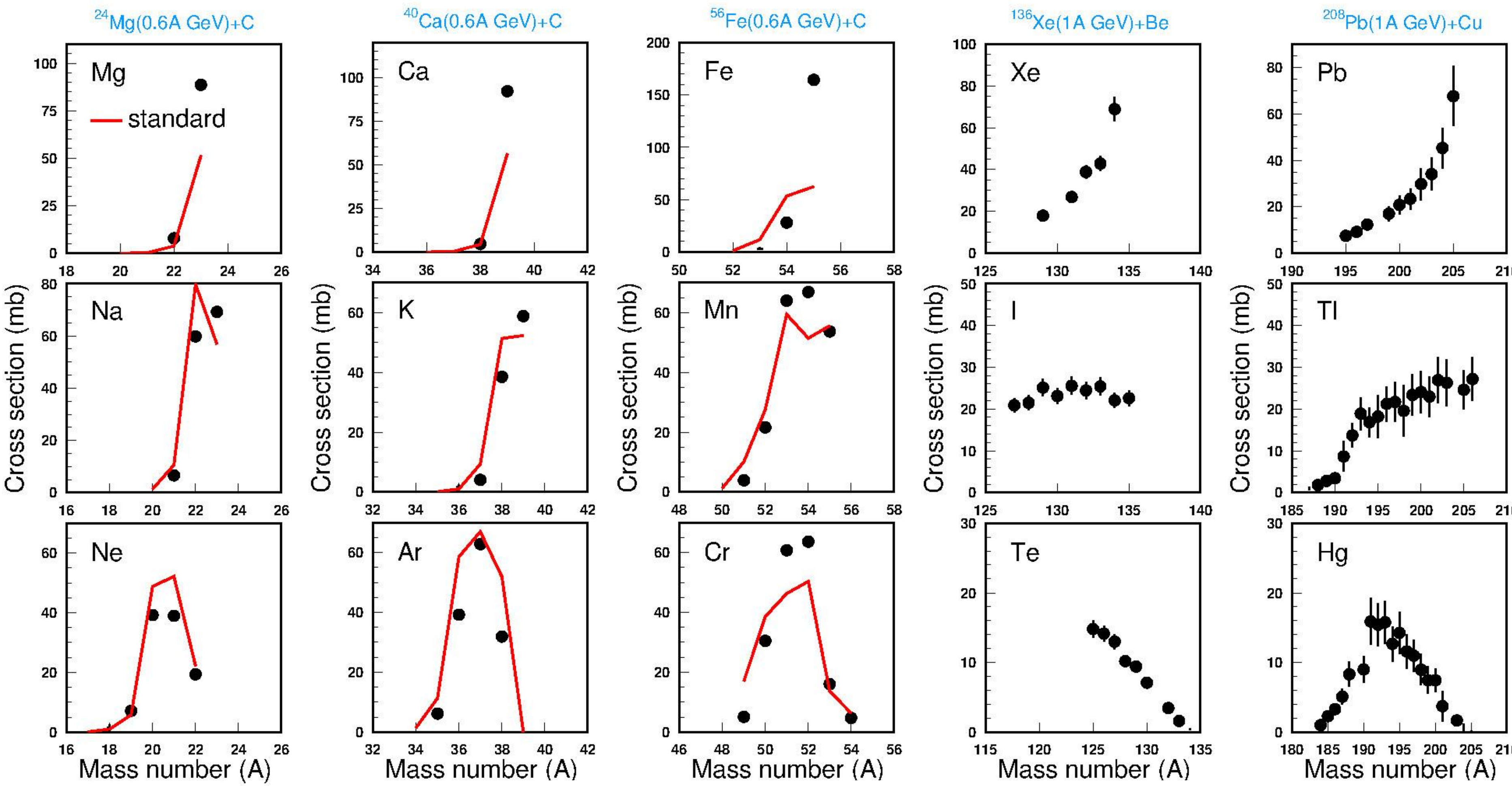
- The wave function describing the interaction with one nucleon is not affected by the presence of other nucleons.
  → No correlations between nucleons.
- The collision occurs over such a short time that binding energies can be neglected and the scattering centers can be considered to be at rest.
  → Reactions at energies well above the Fermi energy.

The Glauber model does not describe the final state of the A-1 remnant (core):

- Particle-hole excitations (shell model single-particle states).
- Excitations by initial- and final-state interactions (collective excitations, re-scattering).

Nucleon knockout from stable nuclei

Quenching of proton-removal channels



Fragmentation of light-stable nuclei is reasonably well described with a Glauber model including core excitations.

Nucleon knockout from stable nuclei

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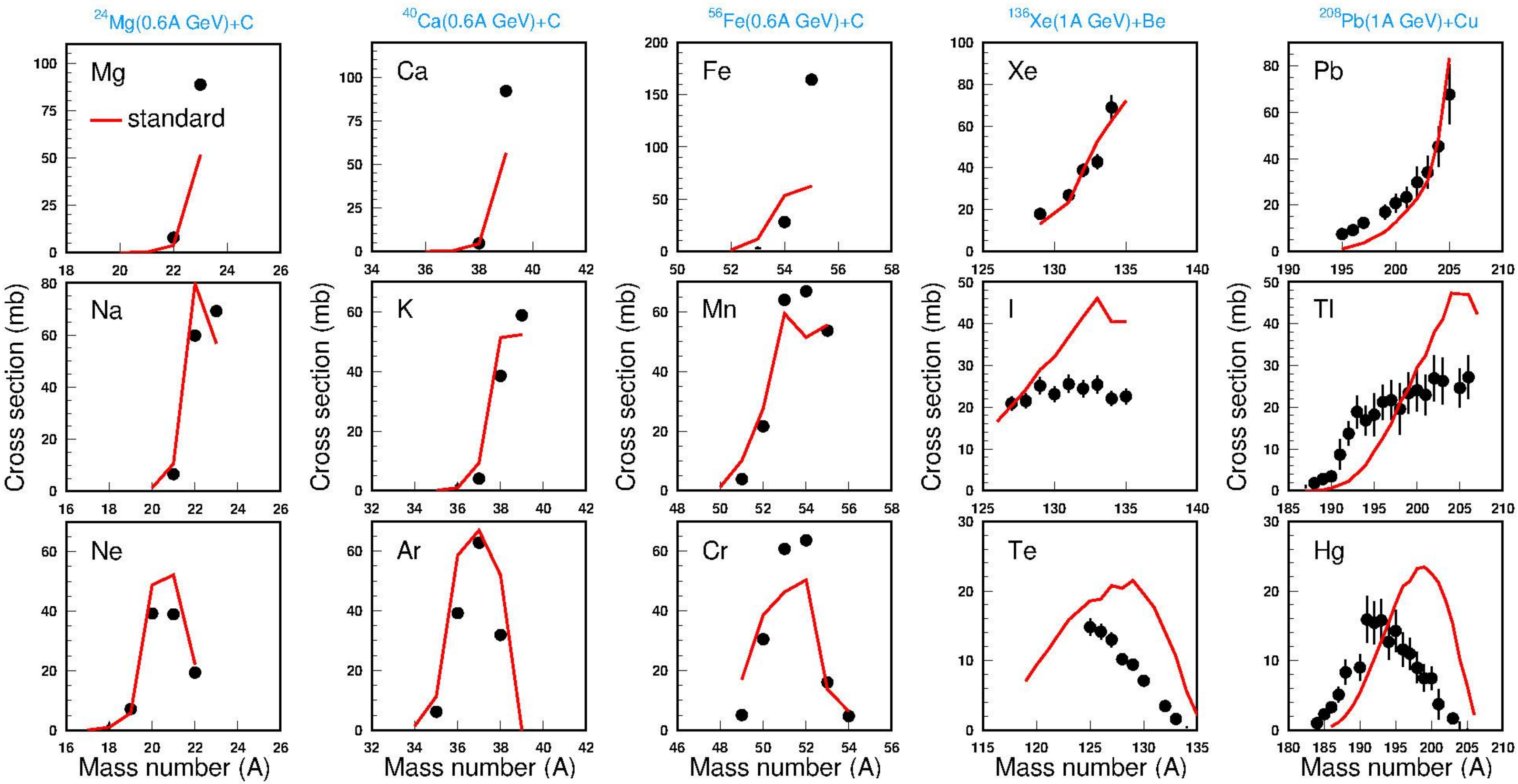
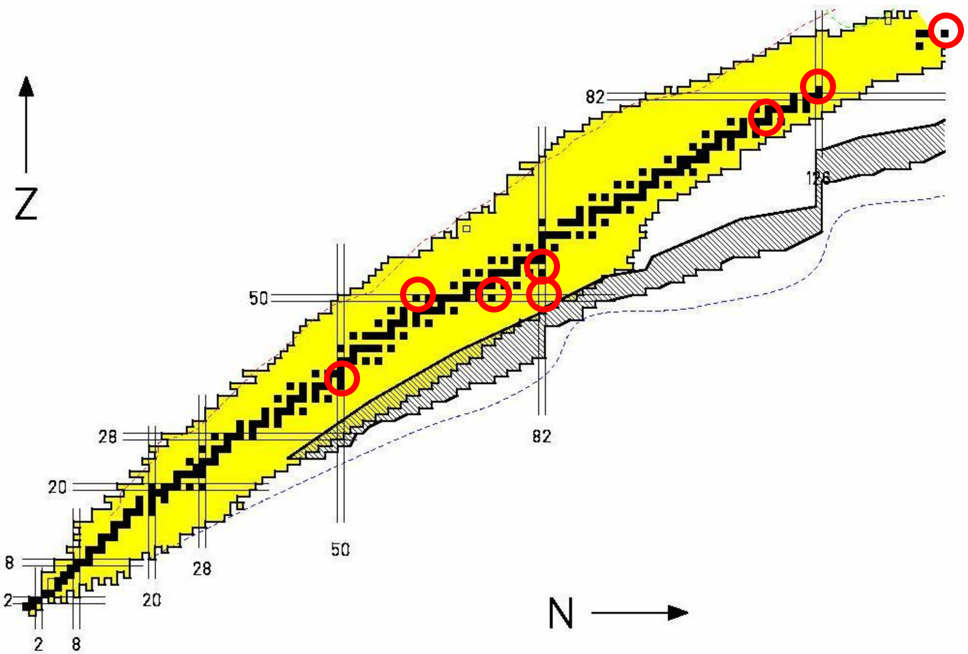
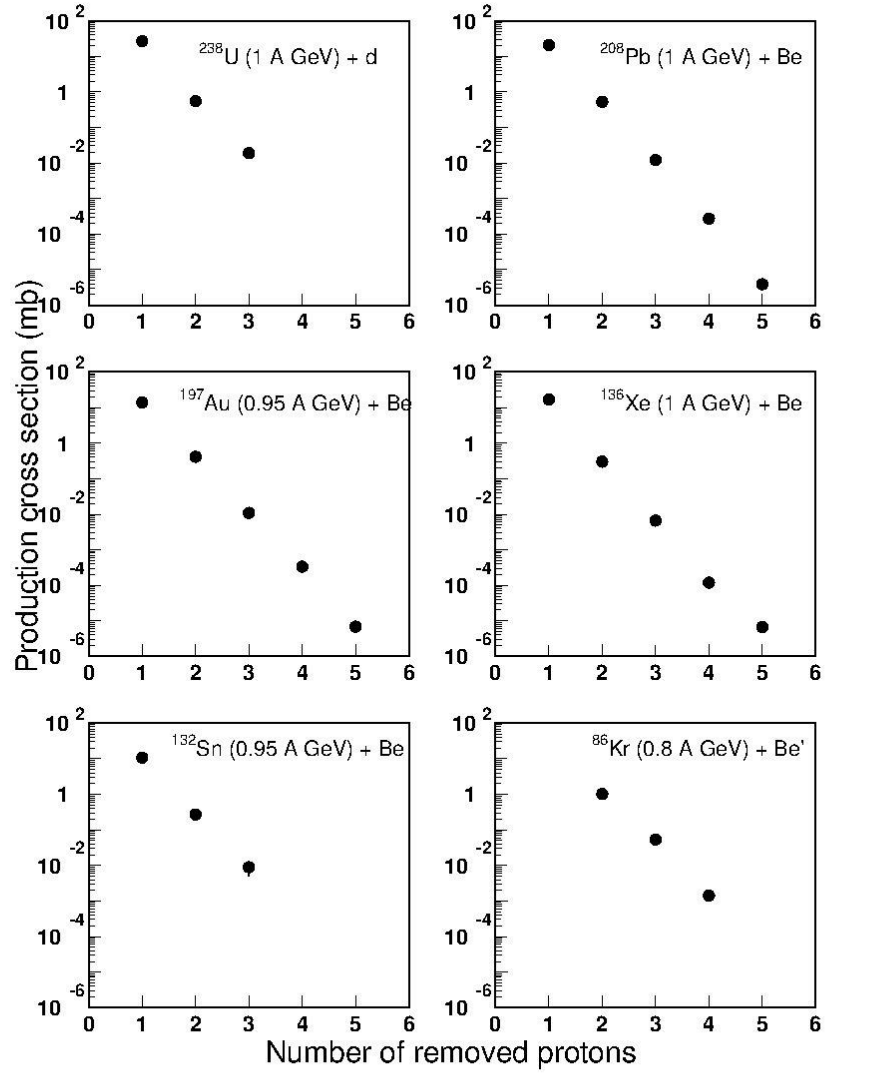


The same calculations overestimate the nuclei produced by removal of protons from medium-mass and heavy nuclei.

Nucleon knockout from stable nuclei

Quenching of proton-removal channels





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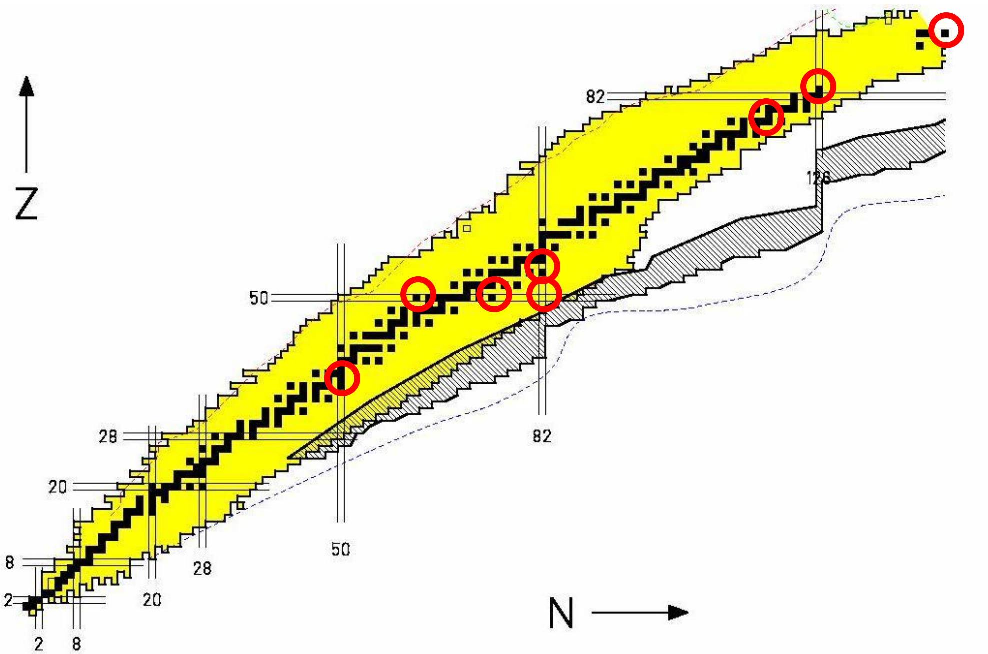
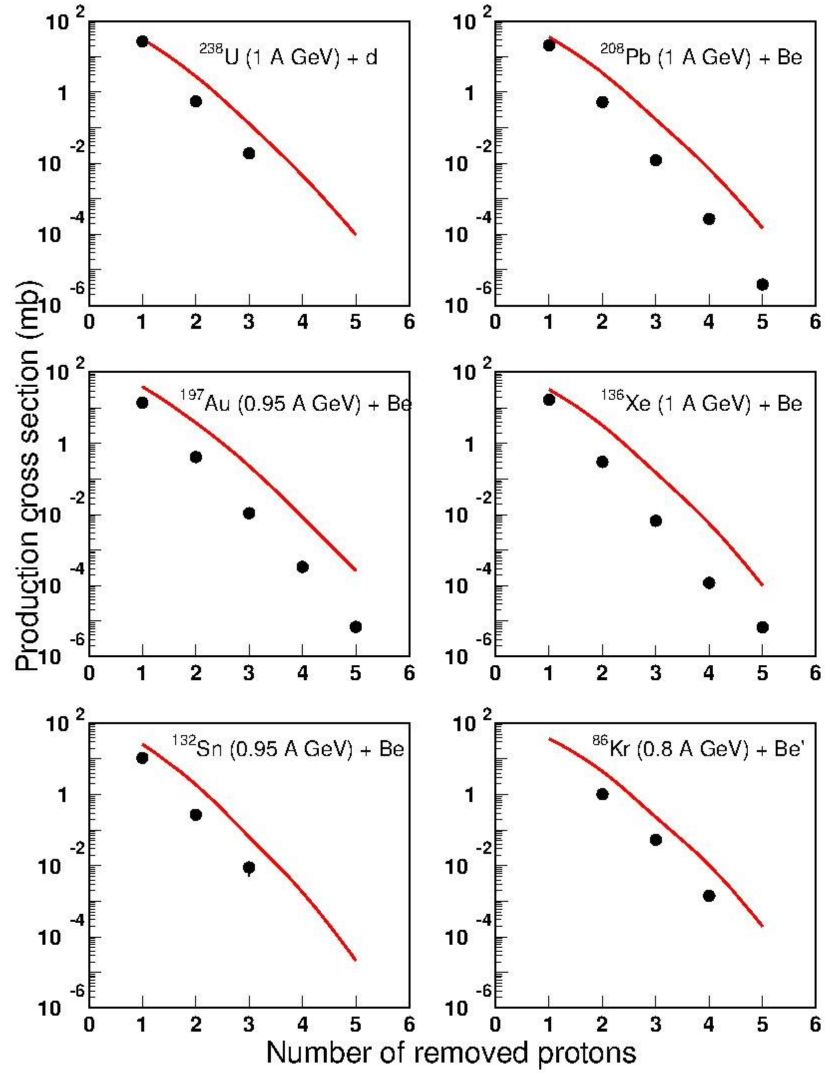


The quenching of the proton-removal channels seems to be a general effect in stable medium-mass and heavy nuclei.

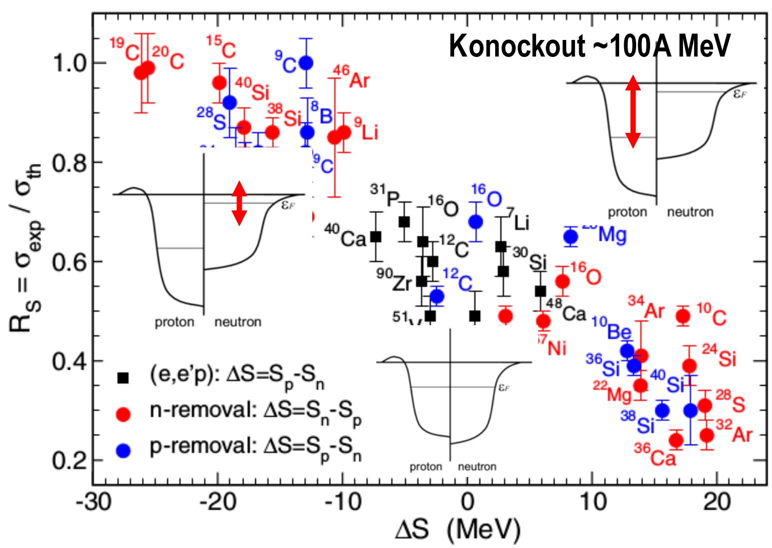
Stable medium-mass and heavy stable nuclei are neutron-rich.



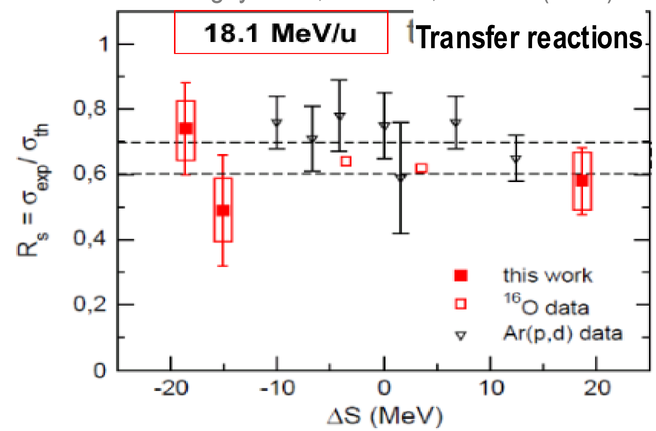
Nucleon knockout from unstable nuclei

The puzzling quenching of deeply bound nuclei.

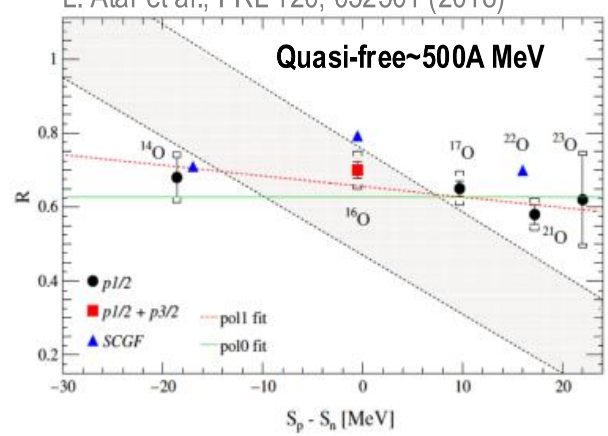
J. A. Tostevin and A. Gade, PRC 90, 057602 (2014)



F. Flavigny et al., PRL 110, 122503 (2013)



L. Atar et al., PRL 120, 052501 (2018)



- Increase of the quenching in single-nucleon knockout with the nucleon binding.
- Other reaction mechanisms also indicate a quenching but not a correlation with the nucleon binding.

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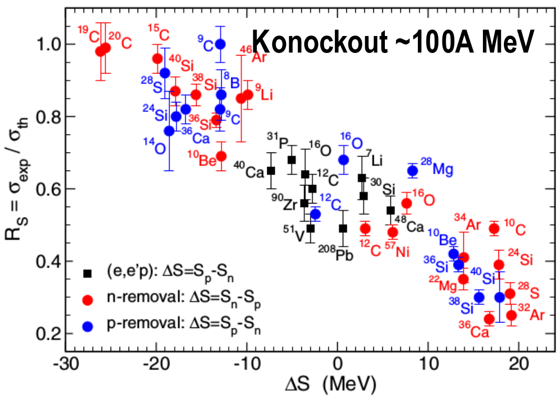
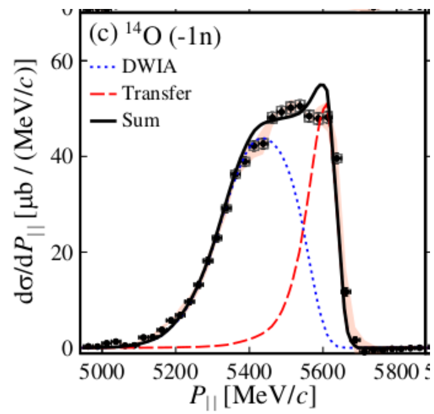


Competing reaction mechanisms.



T. Pohl et al, PRL 130, 172501 (2023)

Core excitations.

- Particle-hole excitations.

M. Gómez-Ramos et al, PLB 847, 138284 (2023)

C. Bertulani, PLB 846, 138250 (2023)

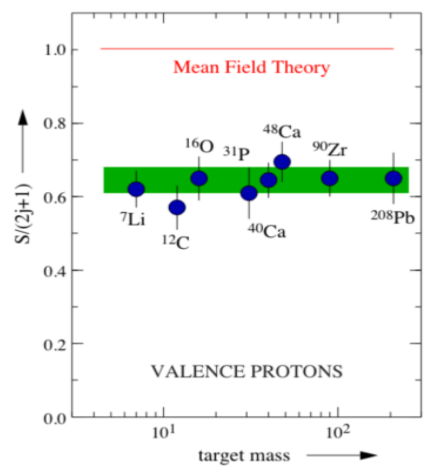
- Final state interactions or knockout from deeply-bound states.

T. Aumann et al, PPNP 118, 103847 (2021)

Uncertainties in the nucleon-nucleus effective interactions.

C. Hebborn et al, PRL 131, 212503 (2023)

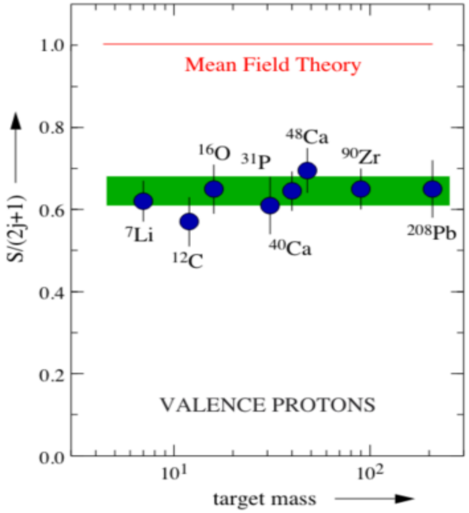
Nucleon-nucleon correlations.



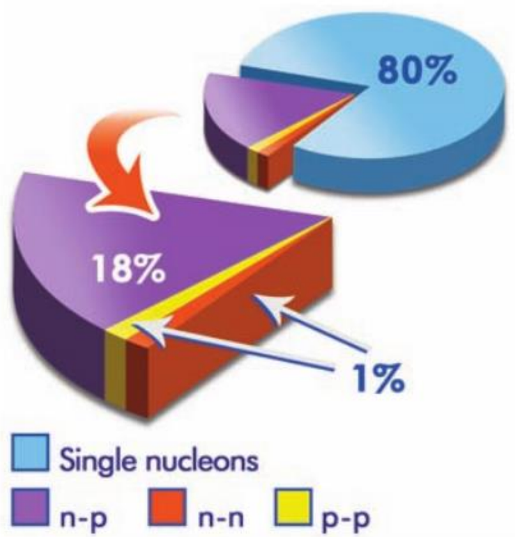
Nucleon knockout and NN correlations

Quenching of deeply-bound nucleons

L. Lapikas et al, NPA 553, 297 (1993)



CLAS collaboration, Science 320, 1476 (2008)

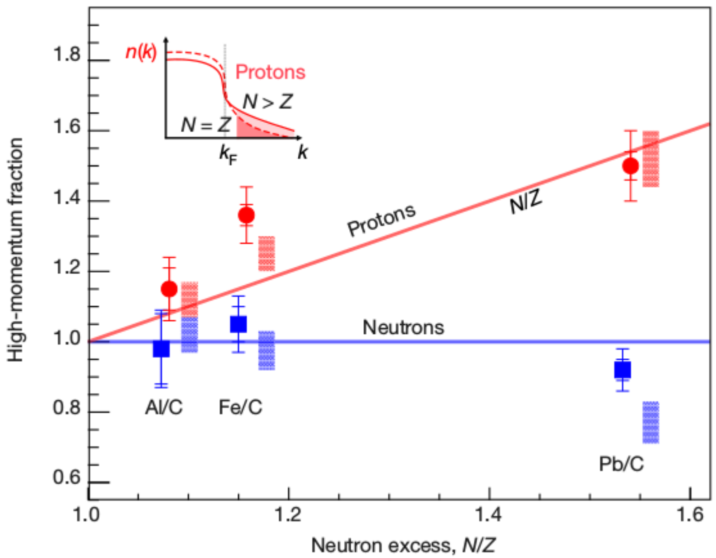


- Quenching of spectroscopic factors in (e,e'p) and (p,2p) reactions partially attributed to short-range correlations.

Nucleon knockout and NN correlations

Quenching of proton-removal channels

CLAS collaboration, Nature 560, 617 (2018)



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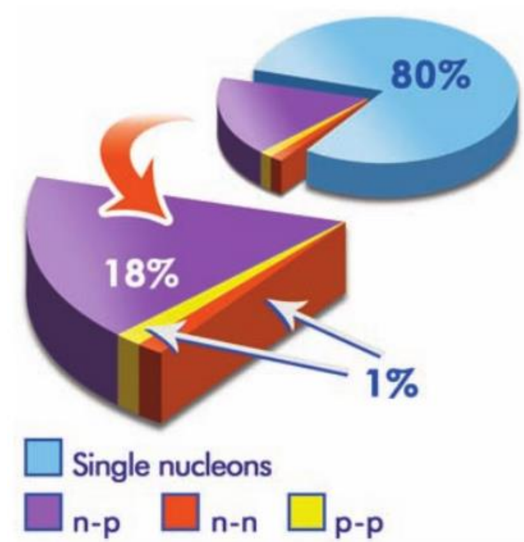

- Quenching of spectroscopic factors in (e,e'p) and (p,2p) reactions partially attributed to short-range correlations.
- Evidences for a dominance of p-n SRC pairs: the number of SRC protons increases with the neutron excess.

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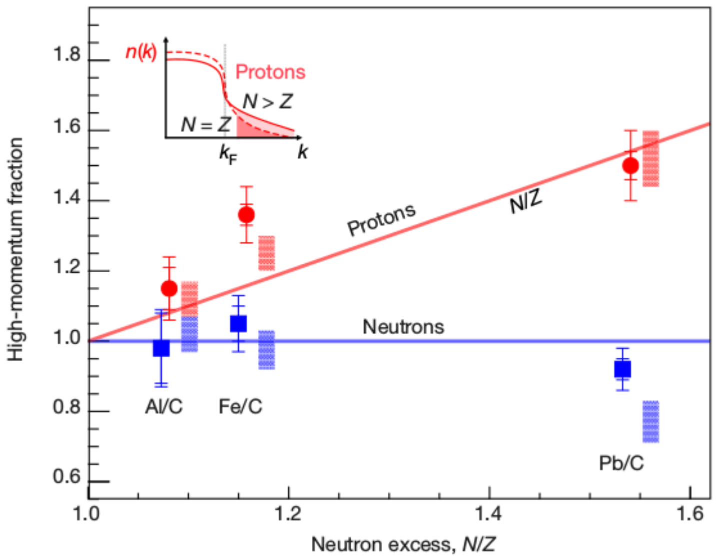
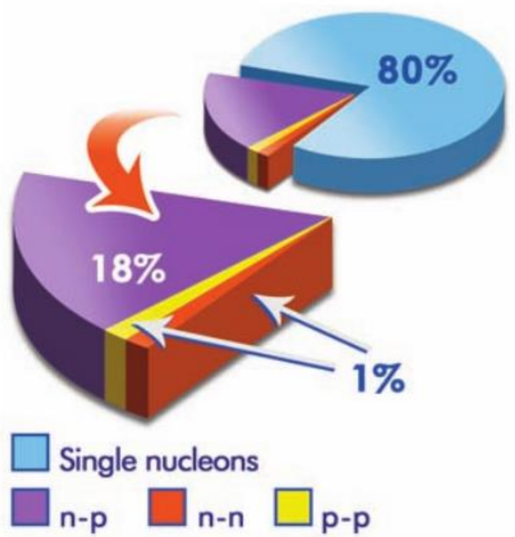


CLAS collaboration, Science 320, 1476 (2008)



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Because of the large relative momentum between SRC pairs the knockout of one of the nucleons produces the emission of the partner.

Nucleon knockout and NN correlations

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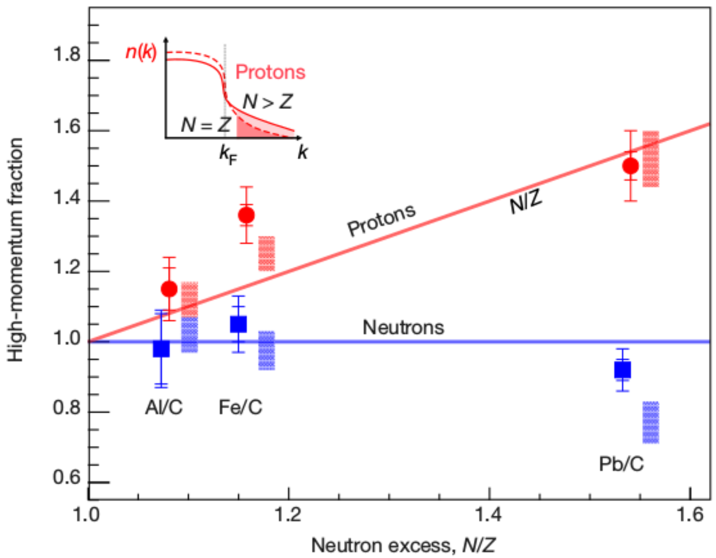

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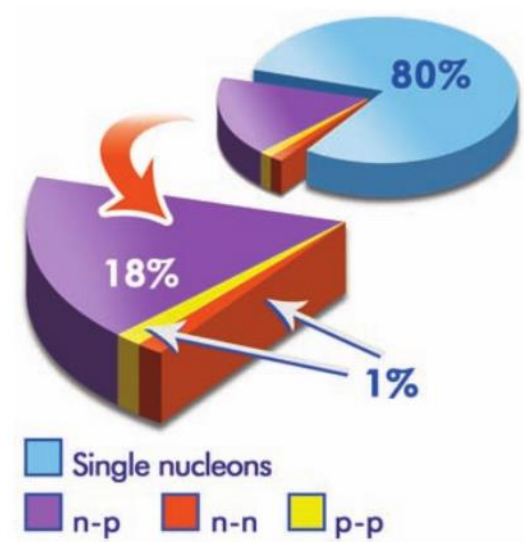

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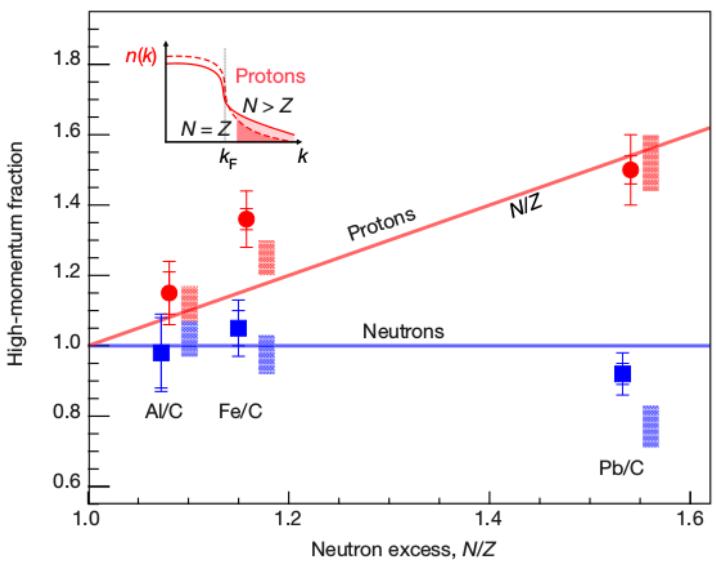
→ Knockout of non correlated protons: (A,Z)→(A-1,Z-1)

Nucleon knockout and NN correlations

Quenching of proton-removal channels

CLAS collaboration, Nature 560, 617 (2018)



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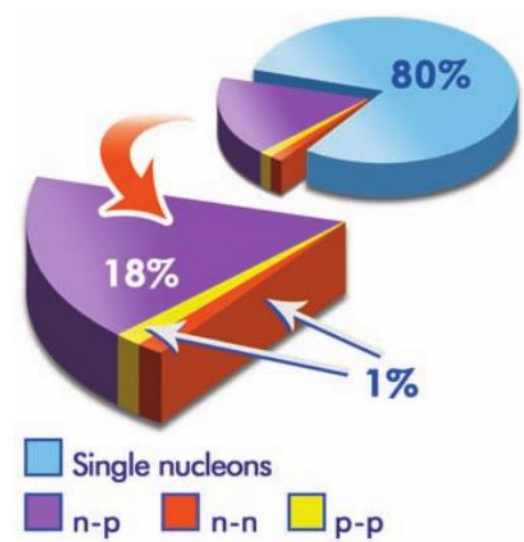


- Quenching of spectroscopic factors in (e,e'p) and (p,2p) reactions partially attributed to short-range correlations.
- Evidences for a dominance of p-n SRC pairs: the number of SRC protons increases with the neutron excess.

Because of the large relative momentum between SRC pairs the knockout of one of the nucleons produces the emission of the partner.

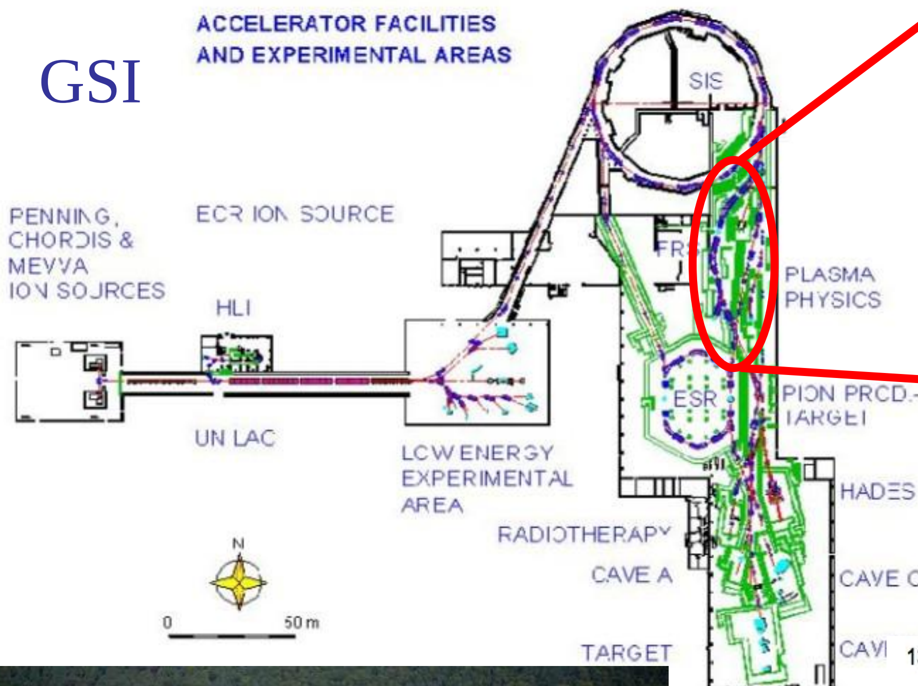
→ Knockout of non correlated protons: (A,Z)→(A-1,Z-1)

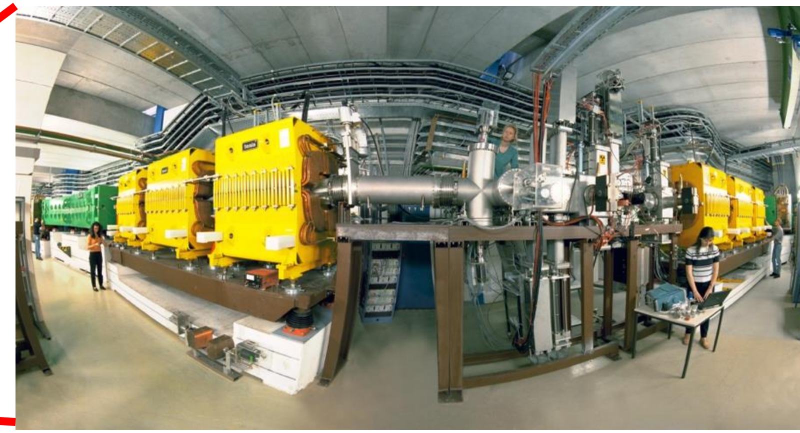
→ Knockout of correlated protons: (A,Z)→(A-2,Z-1) reducing the neutron-excess of the remnant.

Systematic investigation of nucleon removal

Knockout over a wide range of tin isotopes

GSI

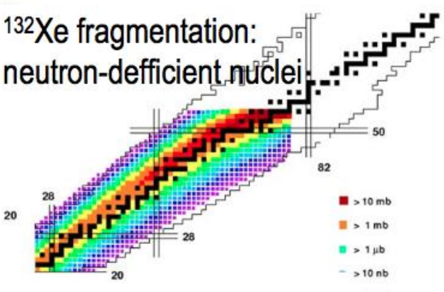




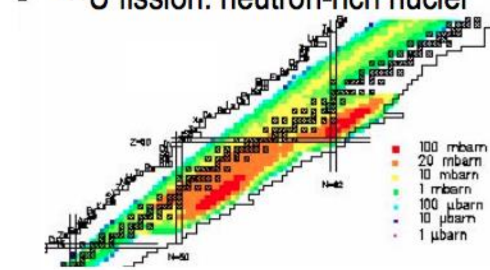
^{105}Sn ^{135}Sn

Two reactions to produce a wide range of tin isotopes.

^{132}Xe fragmentation: neutron-defficient nuclei



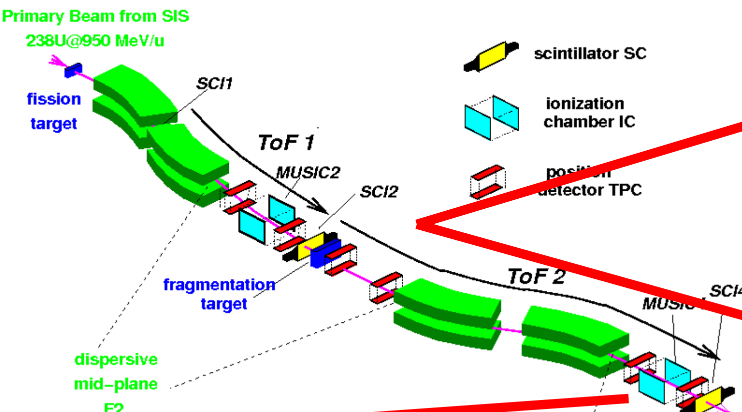
^{238}U fission: neutron-rich nuclei

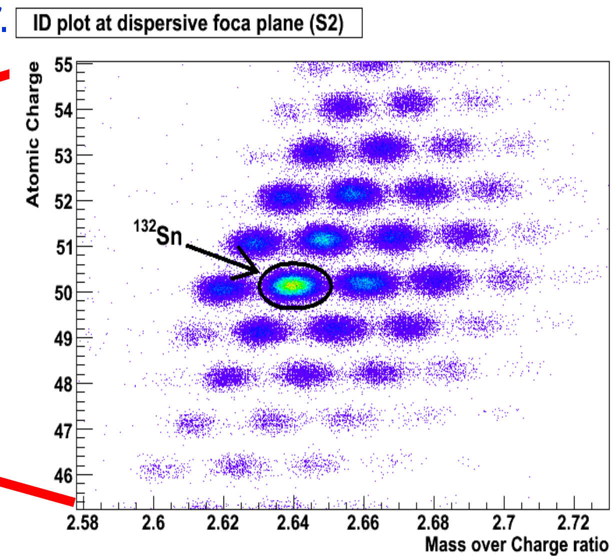


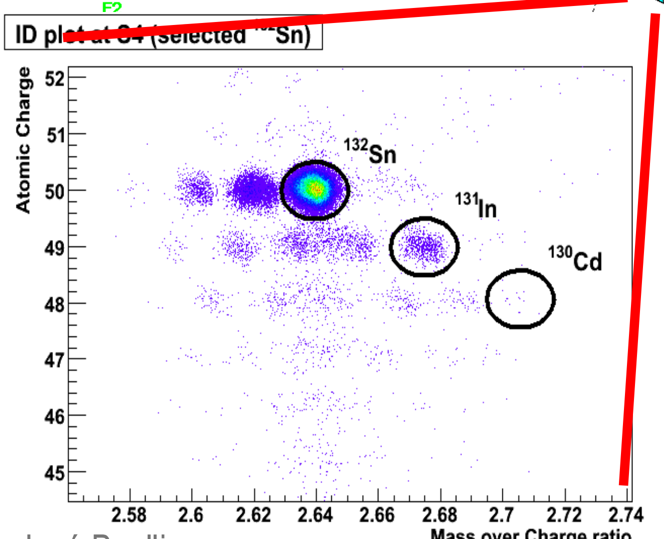
Systematic investigation of nucleon removal

New measurements on proton and neutron knockout in medium-mass nuclei

The FRagment Separator used as a double spectrometer.







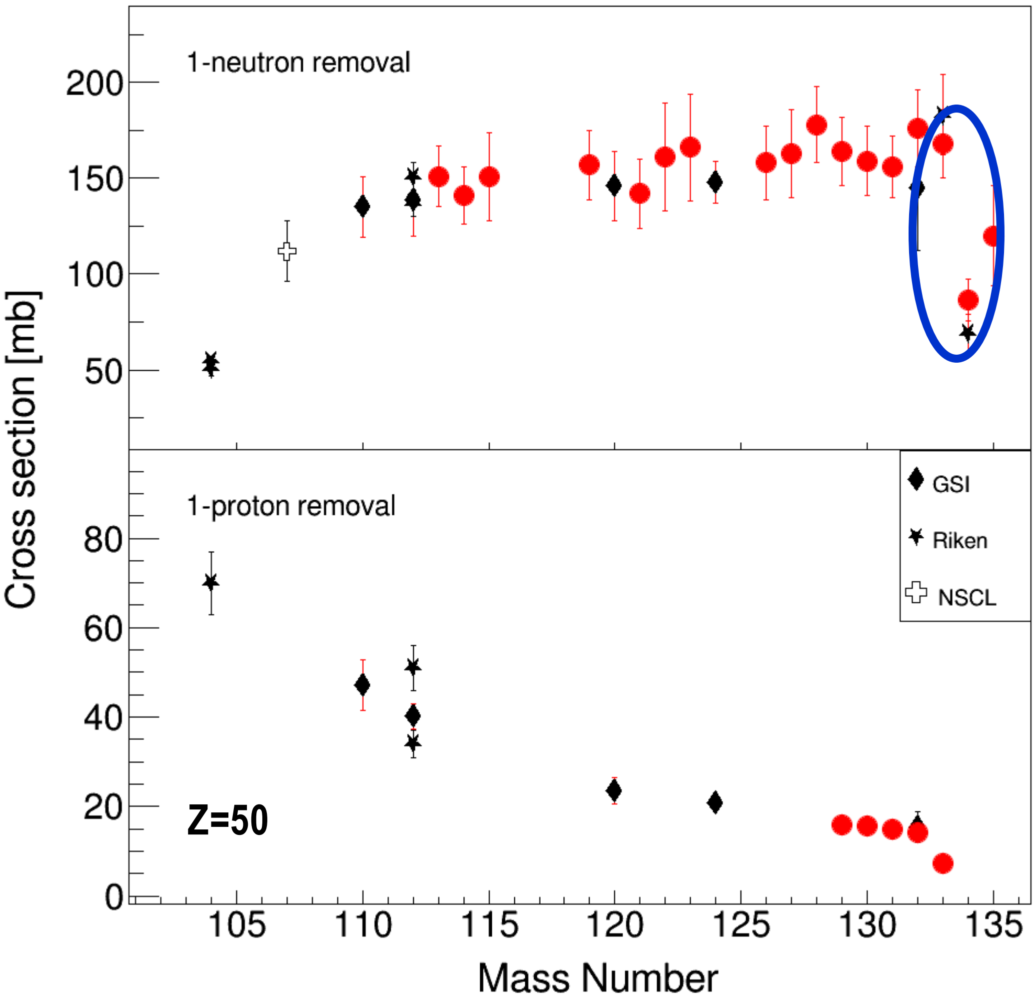
^{238}U(950A MeV)+Be

^{136}Xe(1200A MeV)+Be

Secondary beams around 1000A MeV

Systematic investigation of nucleon removal

Previous and new measurements



- Systematic measurement of neutron and proton removal cross sections over a broad range of neutron excess.

- The quenching of the proton removal is confirmed for neutron-rich nuclei but it reverses for neutron-deficient ones.

- Clear reduction of the neutron removal cross section at N=84 in good agreement with recent measurements at RIKEN.

Previous data:

GSI: D. Pérez et al., PLB 703, 552 (2011)
J.L. Rodríguez et al., PRC 96, 034303 (2017)

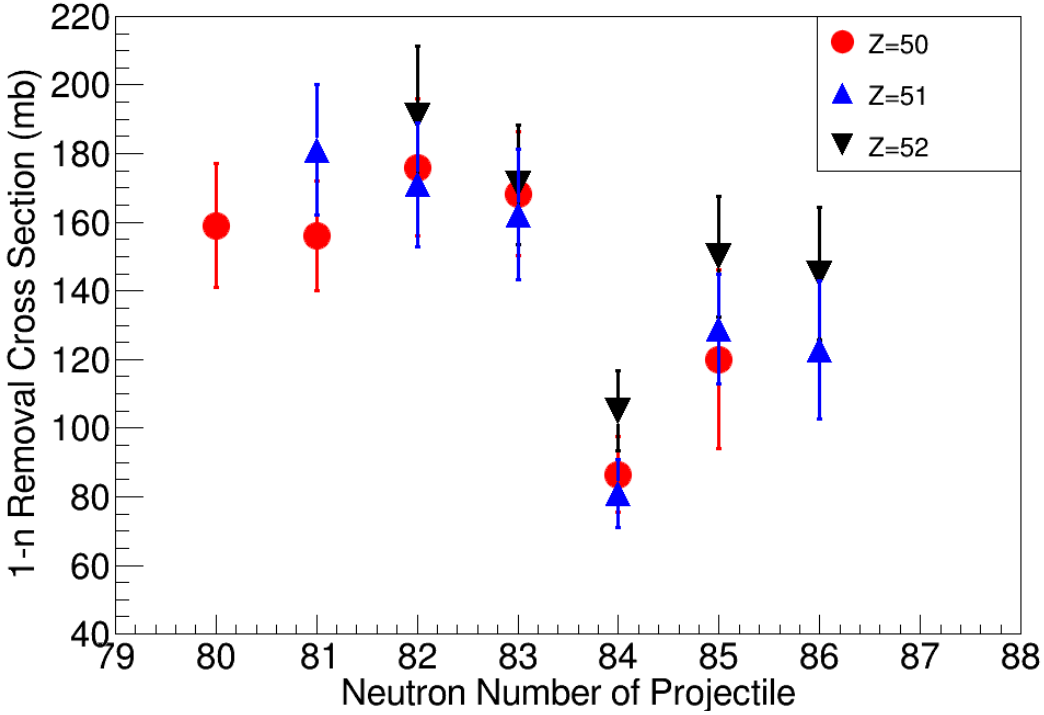
Riken: L. Audirac et al., PRC 88, 041602 (2017)
V. Vaquero et al., PRL 118, 202502 (2017)

NSCL: G. Cerizza et al., PRC 93, 021601 (2016)

Systematic investigation of nucleon removal

Neutron removal

Neutron-removal cross sections do not seem to change much for the different isotopic chains, and all present a strong reduction at N=84.



The description of these data requires complete model calculations describing not only the reaction mechanism but also the structure of the involved nuclei.

Systematic investigation of nucleon removal

Mechanisms involved in the nucleon-removal process

- Direct nucleon-knockout producing hole excitations.

- Initial and final state interactions (IFSI).
  - -- Collective excitations (GDR and GQR) contributing mostly to neutron removal.
  - -- Multiple scattering and NN inelastic collisions decreasing the survival probability of the knockout remnants.

Model description

- Advanced intra-nuclear cascade model (INC) with a realistic description of the neutron and proton radial densities (HFBRAD with Skyrme Sly5). J.L. Rodríguez et al., PRC96, 054602 (2017)

- Collective excitations (GDR and GQR). C.A. Bertulani

- The excitation energy gained by the remnants due to:
  - Hole excitations based on realistic shell model orbital energies and spectroscopic factors. A. Gargano
  - Final-state interactions (multiple scattering, NN inelastic collisions) obtained with the INC model.

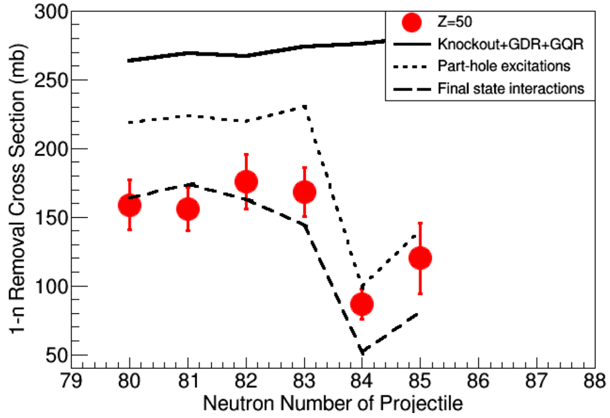
Systematic investigation of nucleon removal

Neutron removal: model calculations

Final one-neutron removal cross sections:

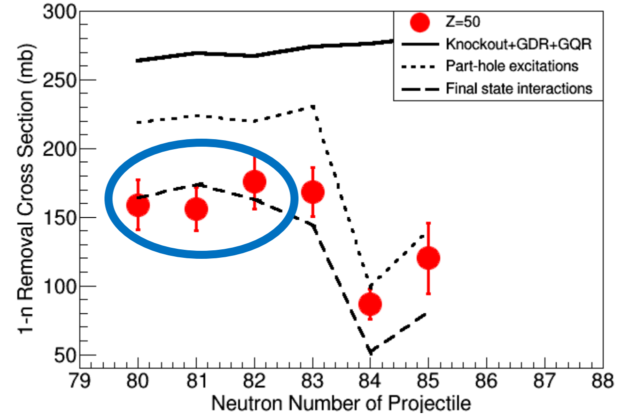
\+ Direct knockout and collective excitations (GDR+GQR).

\- Remnant survival against particle-hole excitations, multiple-scattering, and NN inelastic collisions.



Systematic investigation of nucleon removal

Neutron removal: model calculations



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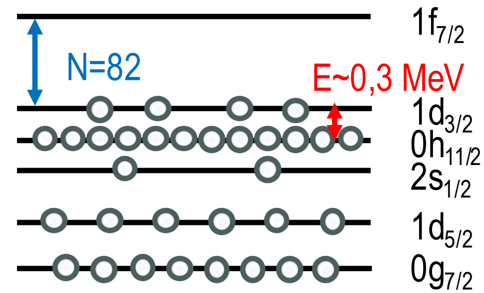
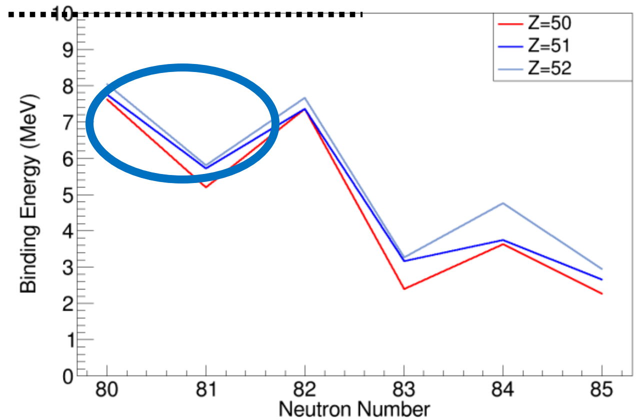


Particle-hole excitations and binding energies explain the observed decrease of the cross sections for N=84 nuclei.

→ For N≤82 large occupation of orbitals close to the Fermi level: low excitation energy, E*~0,5 MeV.

$^{132}Sn \rightarrow {}^{131}Sn$: core with large binding energy (~6 MeV): bound core.



Systematic investigation of nucleon removal

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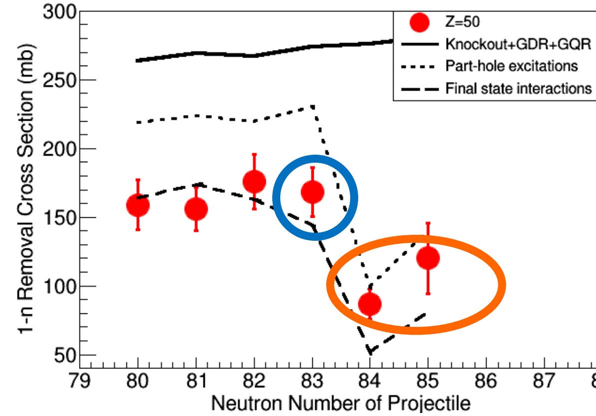

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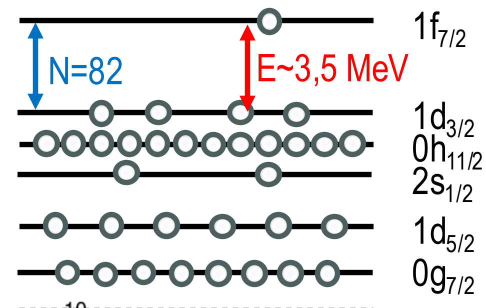
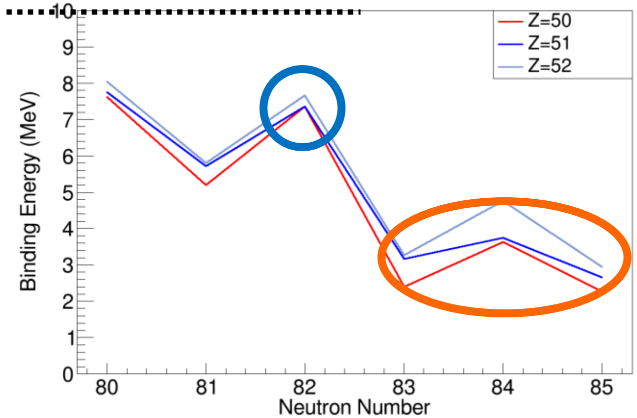
^{132}Sn→^{131}Sn: core with large binding energy (~6 MeV): bound core.

→ For N>82 high probability of deep hole states: higher excitation energy, E*~4,0 MeV.

^{133}Sn→^{132}Sn: core with large binding energy (7.5 MeV): bound core.

^{134}Sn→^{133}Sn: core with small binding energy (2.4 MeV): unbound core.

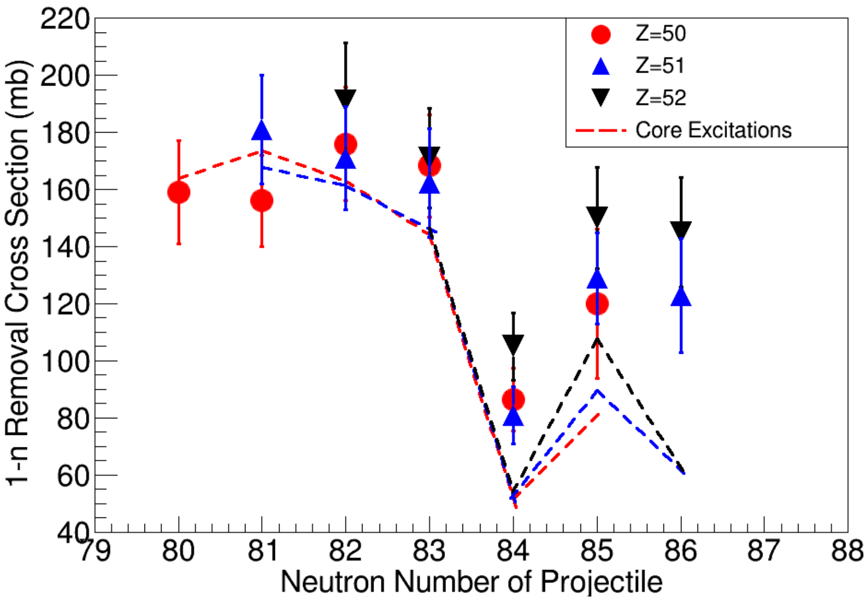




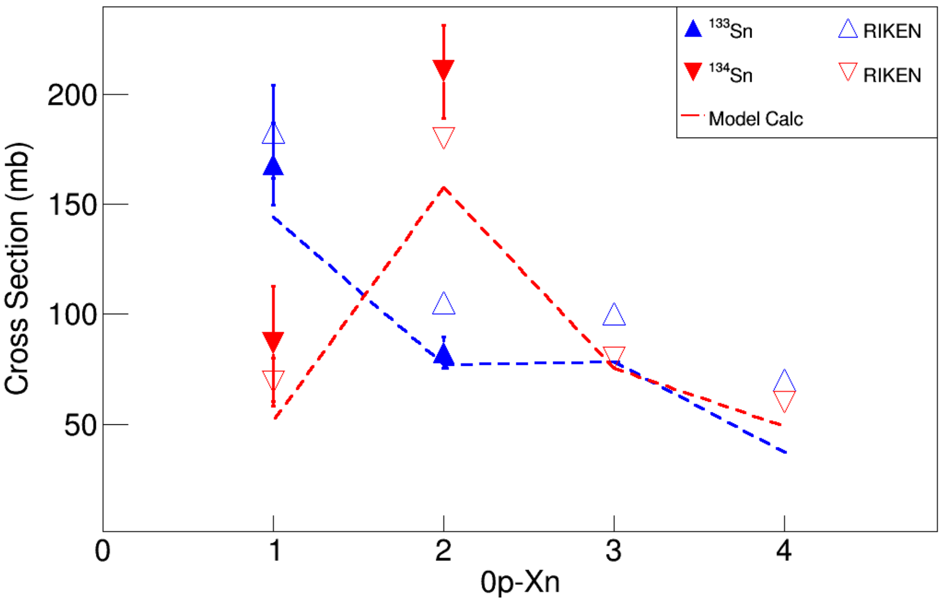
Systematic investigation of nucleon removal

Neutron removal: model calculations

Calculations provide a correct description of single and multiple neutron-removal cross sections



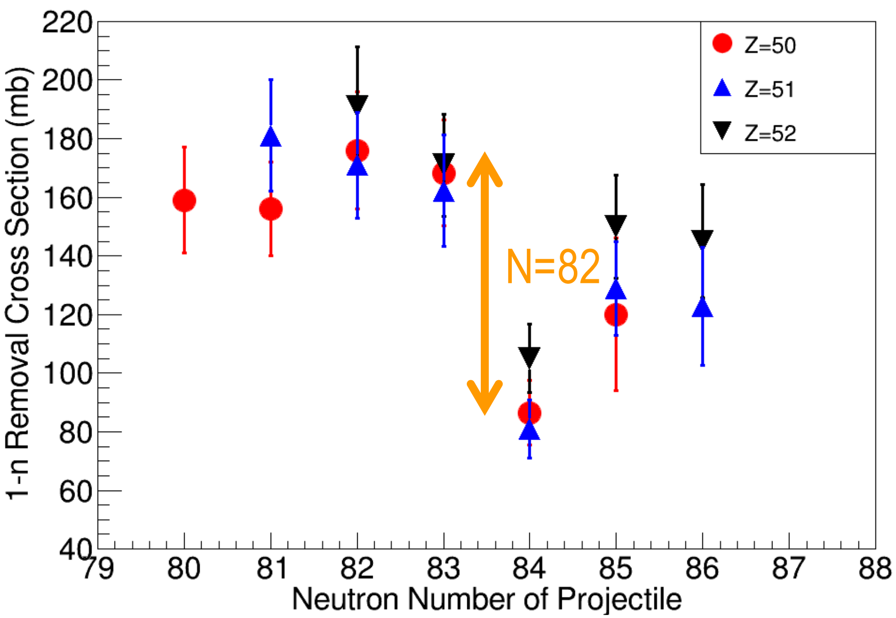
J. Díaz-Cortés et al., PLB 811, 135962 (2020)

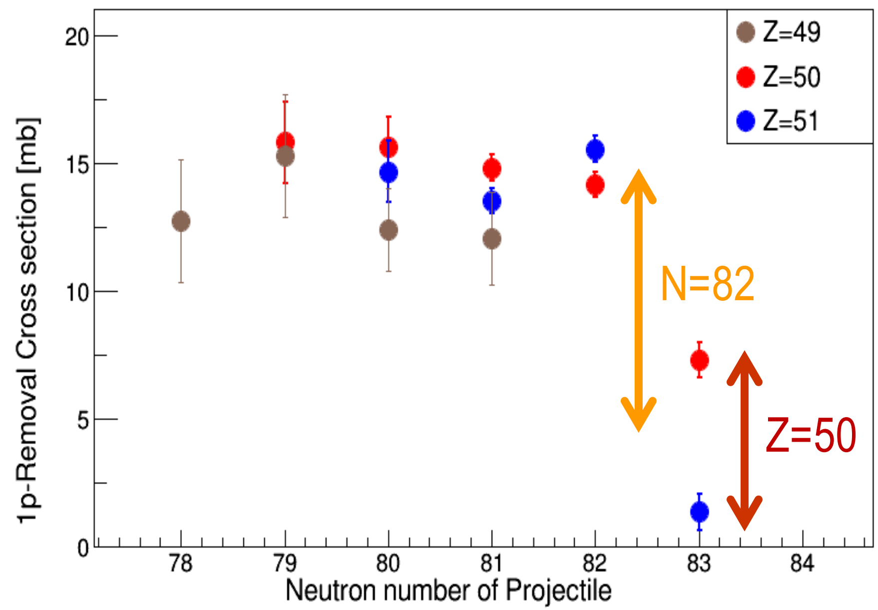


Riken data: V. Vaquero et al., PRL 118, 202502

Proton-removal around ^{132}Sn: measurements

Neutron versus proton removal



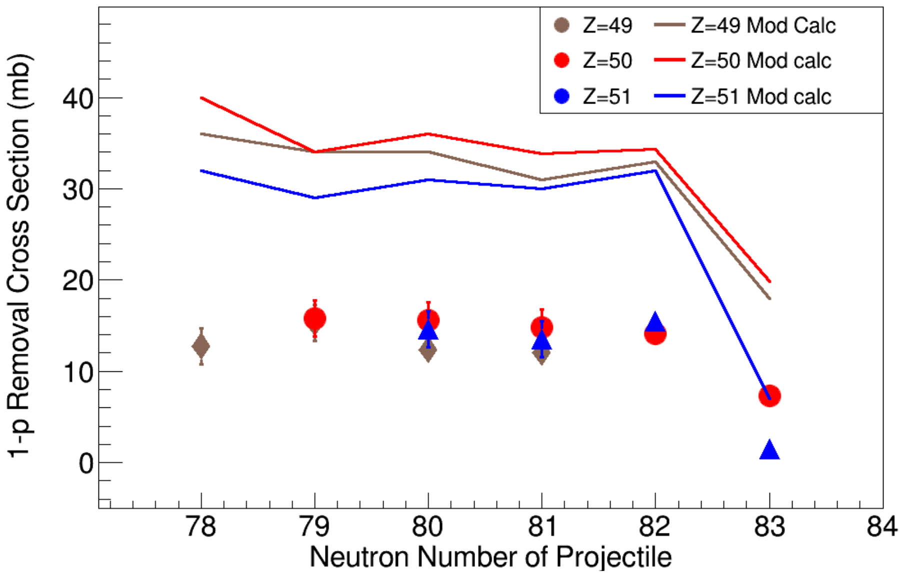


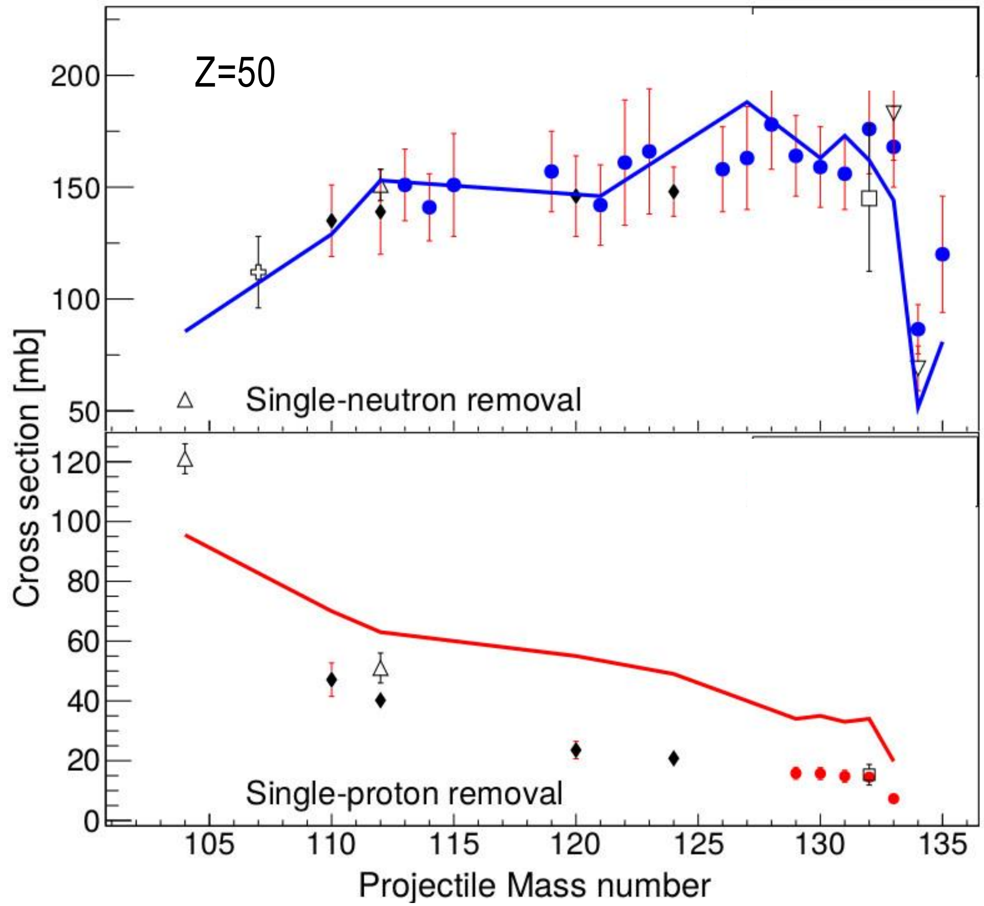
- Proton removal cross sections are significantly smaller (proton removal quenching).
- A stronger reduction of the cross section is observed for the proton removal at N=83 due to N=82 shell.
- Differences in the proton removal cross sections due to the Z=50 shell are only observed at N=83.

Systematic investigation of nucleon removal

Proton removal: model calculations

Calculations describing the neutron removal over-predict the proton-removal cross sections.





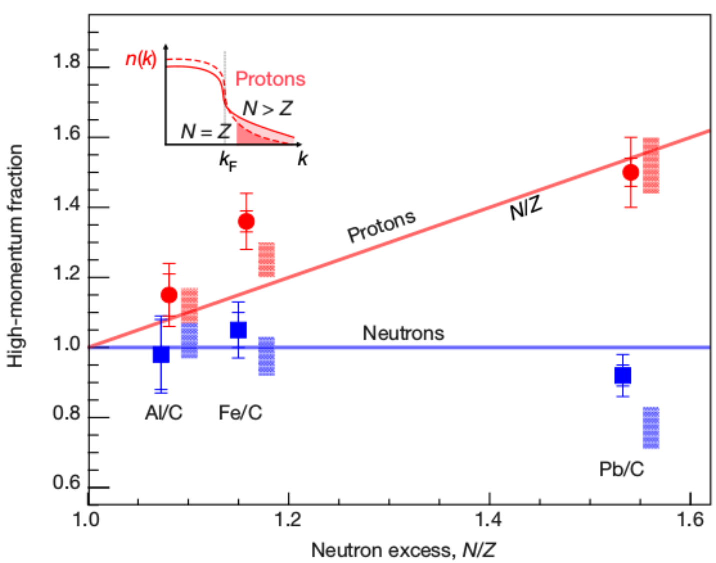
These calculations only consider long range correlations between nucleons (pairing).

Systematic investigation of nucleon removal

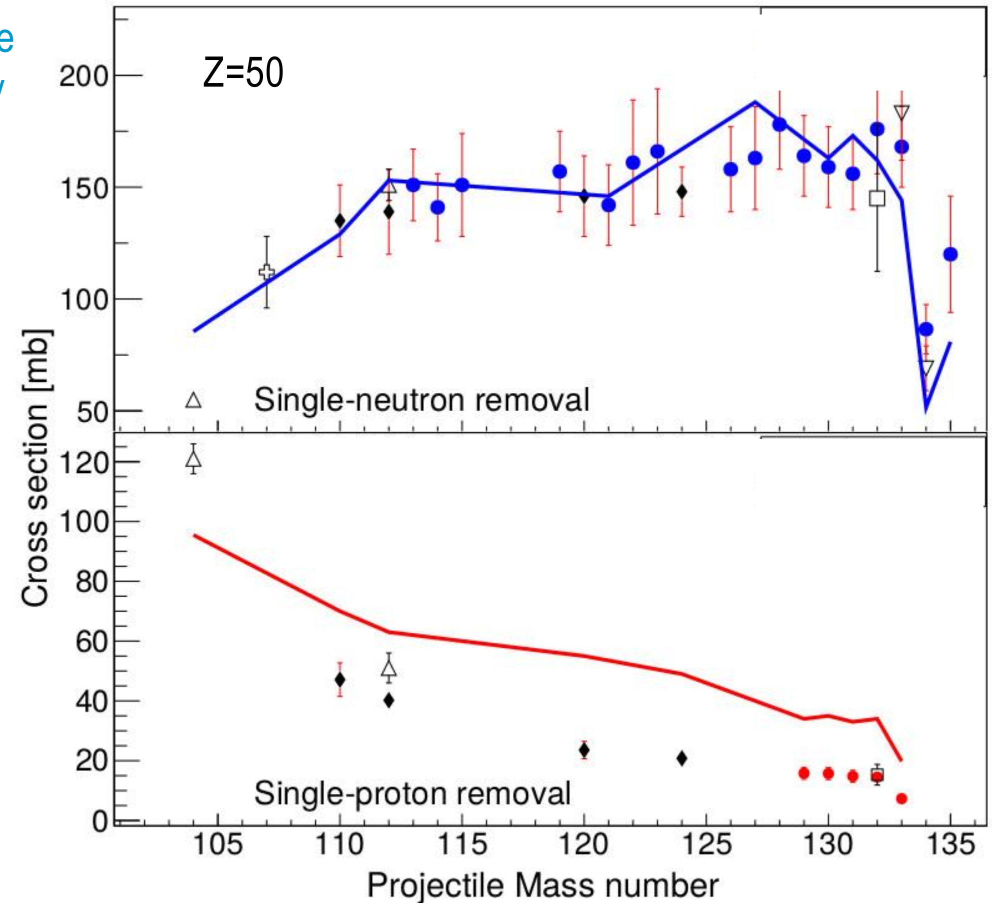
Proton removal: model calculations

Calculations describing the neutron removal over-predict the proton-removal cross sections.

The results obtained by the CLAS collaboration have shown the existence of SRC NN pairs dominated by n-p pairs with an increase of the relative fraction of protons in short-range correlated p-n with the neutron excess.



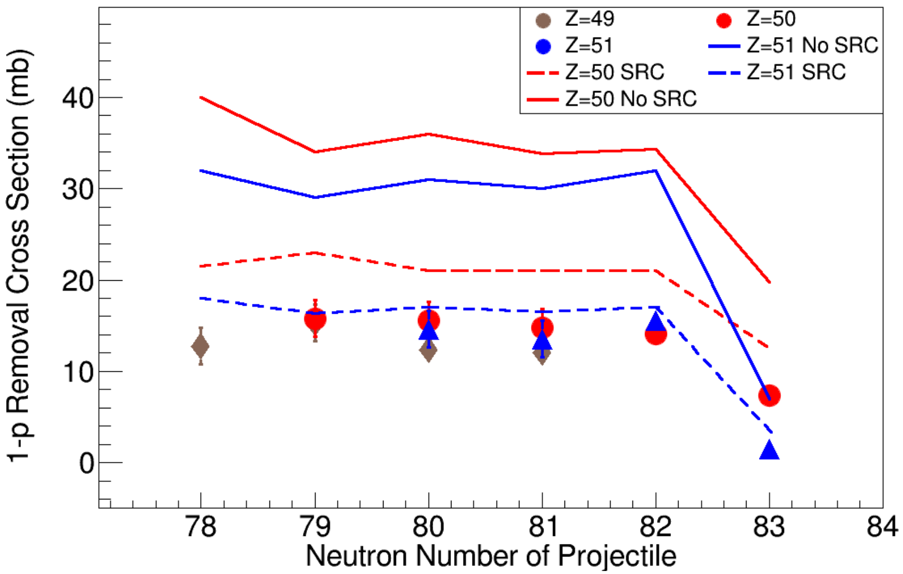
CLAS collaboration, Nature 560, 617 (2018)

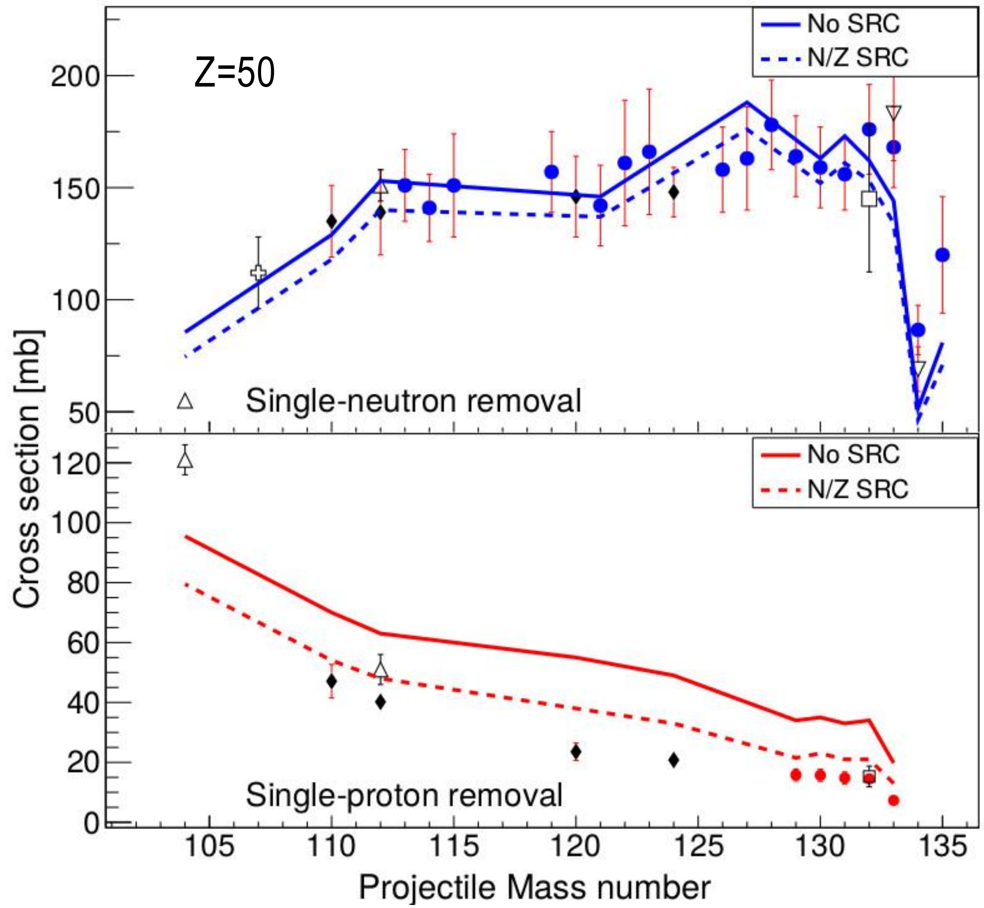


Systematic investigation of nucleon removal

Proton removal: model calculations

The knockout of short-correlated protons would reduce the cross section of the (A-1,Z-1) residues.





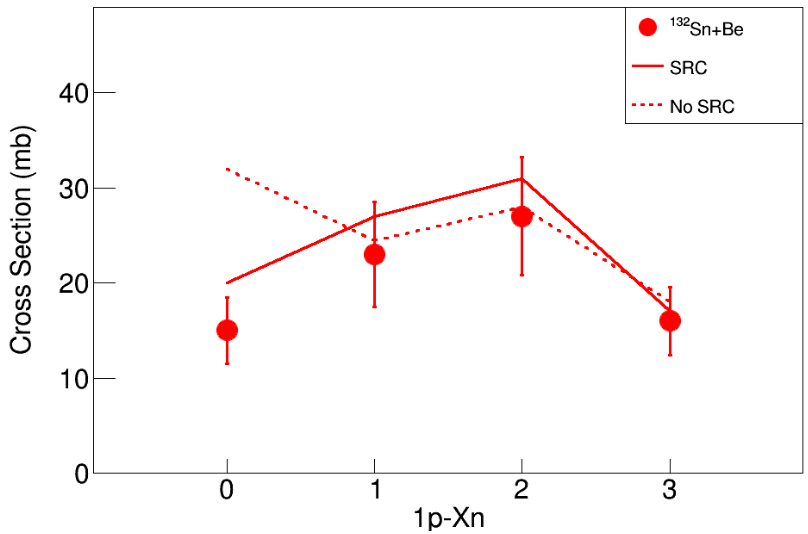
Calculations considering 20% SRC n-p pairs where the proton knockout produces the emission of the neutron partner provide a rather good description of the proton removal channels over a wide range of tin isotopes.

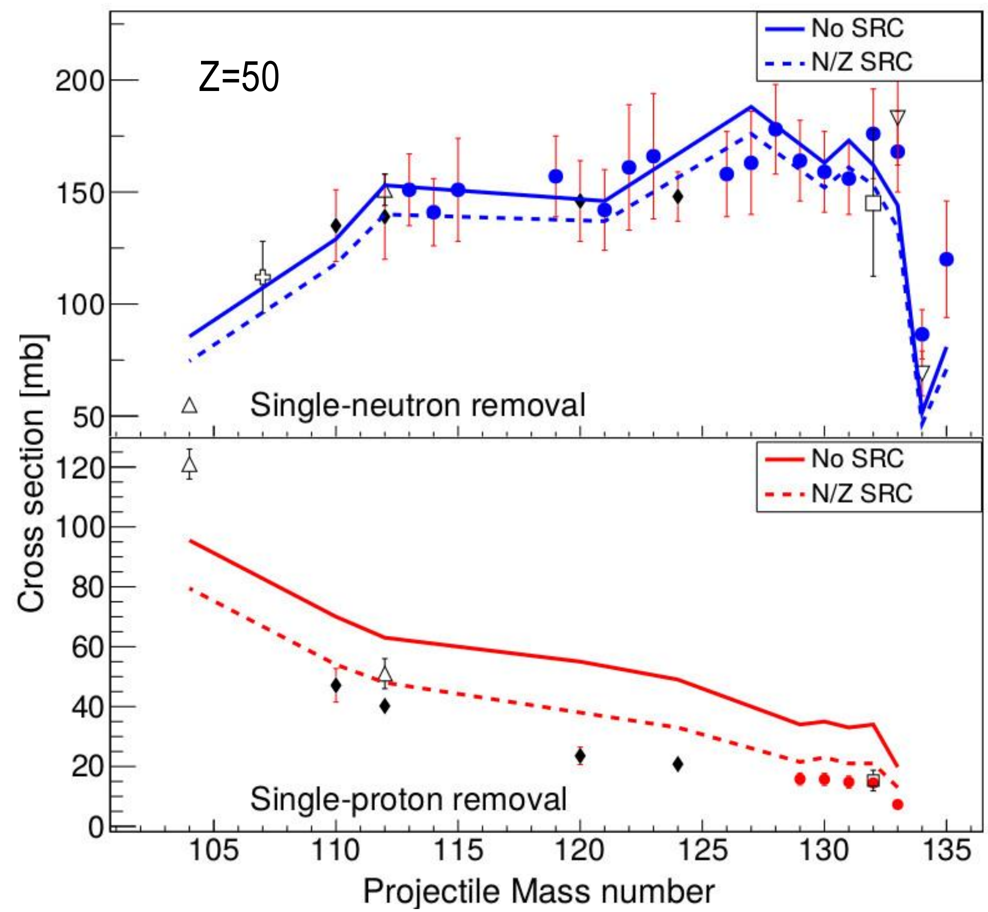
J. Díaz-Cortés et al., PLB 811, 135962 (2020)

Systematic investigation of nucleon removal

Proton removal: model calculations

The knockout of short-correlated protons would reduce the cross section of the (A-1,Z-1) residues.





Calculations considering 20% SRC n-p pairs where the proton knockout produces the emission of the neutron partner provide a better description of the -1p and the 1p-Xn channels.

J. Díaz-Cortés et al., PLB 811, 135962 (2020)

Summary and future perspectives

- ✓ Nucleon knockout (quasi-free nucleon scattering) is a powerful tool that provides access to low-lying and deeply-bound single-particle states, but also to nucleon correlations.
- ✓ The quenching of the proton knockout has been systematically investigated.
  - → The presence of SRC neutron-proton pairs may explain part of the quenching.
  - → Other possible contributions are the knockout of deeply bound nucleons or the role of final-state interactions.
- ✓ Final evidence for the role of correlations in nucleon knockout will require complete kinematic measurements where the knocked-out nucleons are detected (previous talk by V. Panin).