Deeply-bound nucleon stripping

An update on recent results

Alexandre Obertelli
TU Darmstadt

ECT* Workshop
Trento, March 9th, 2018

Outline

TECHNISCHE UNIVERSITÄT DARMSTADT

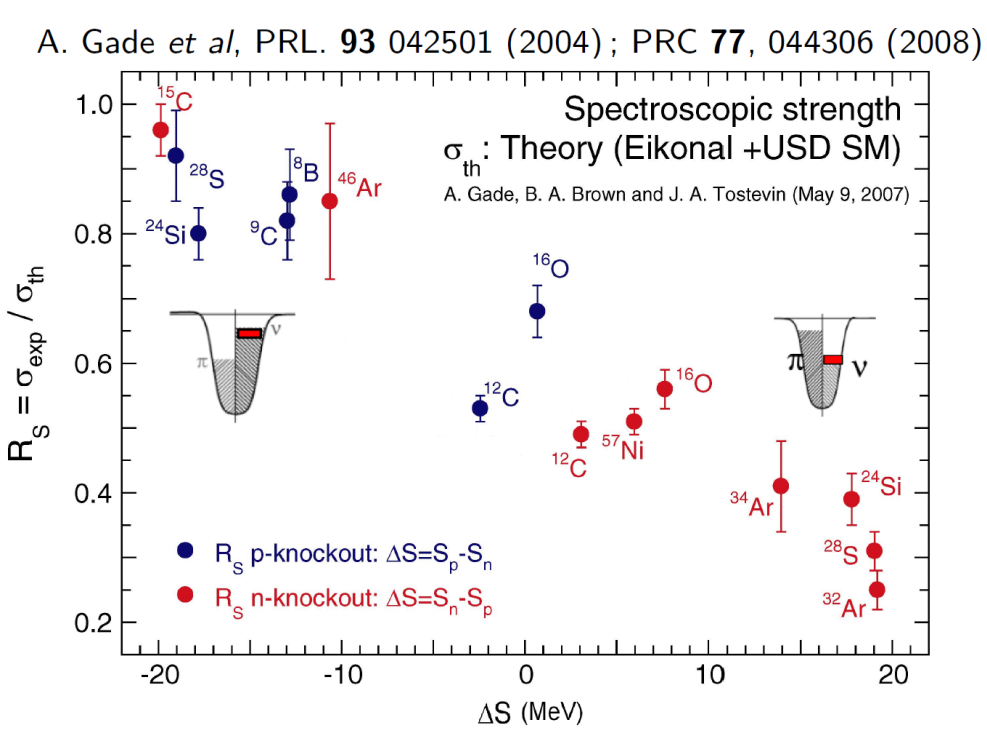
1) Introduction

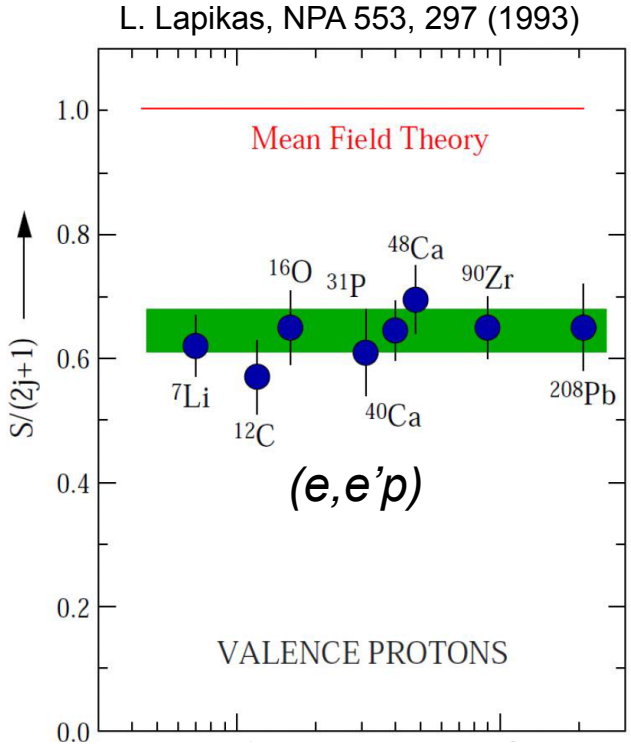
2) Transfer reactions: trend with binding energies and sensitivity
F. Flavigny *et al.,* Phys. Rev. Lett. **100**, 122503 (2013)
F. Flavigny *et al.,* Phys. Rev. C **97**, 034601 (**2018**)

3) Intermediate energies: role of inelastic excitations and evaporation
C. Louchart *et al.,* Phys. Rev. C **83**, 011601(R) (2011)
L. Audirac *et al.,* Phys. Rev. C **88**, 041602(R) (2013)
J. L. Rodriguez-Sanchez *et al.,* Phys. Rev. C **96**, 034303 (**2017**)
N. Paul *et al.,* under preparation (**2018**)

4) Why does it matter? Future related experimental plans

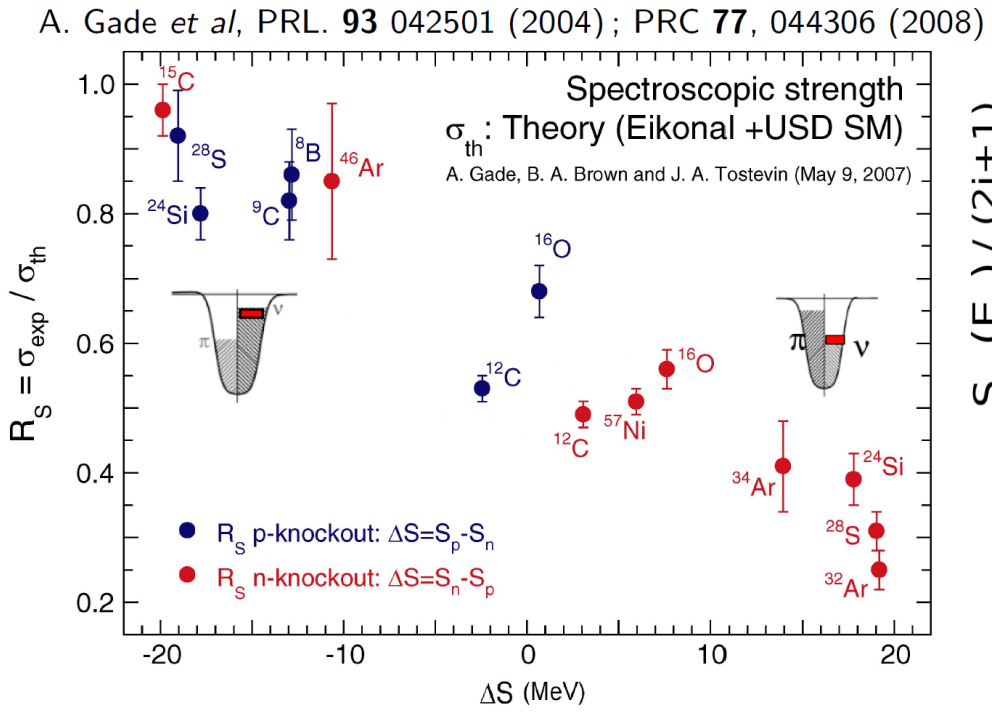
Introduction



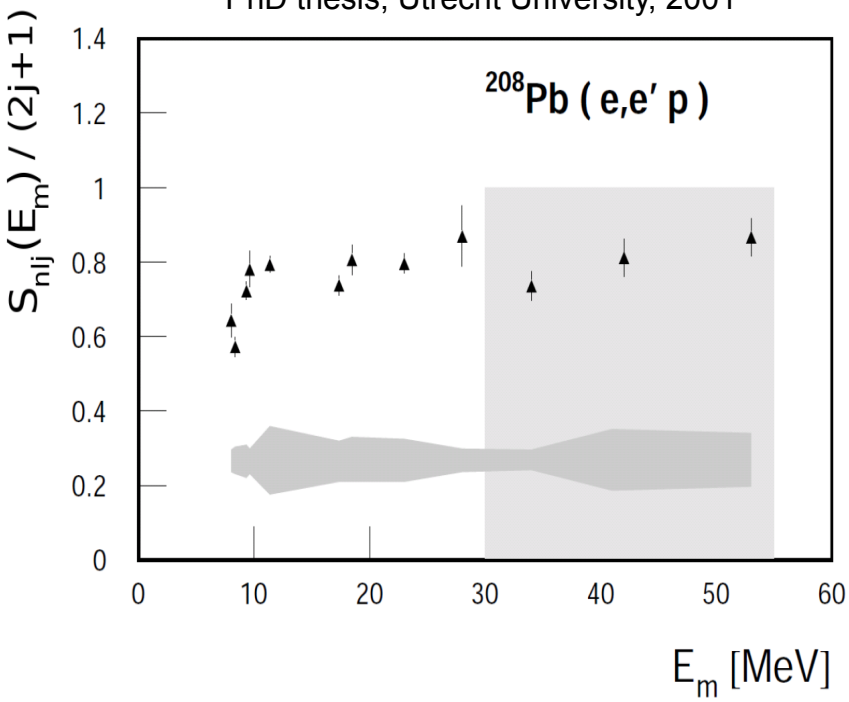


Intermediate-energy (100 MeV/nucleon) heavy-ion induced nucleon removal
Disagreement between eikonal theory / shell model and experiment

Introduction



M. van Batenburg,
Deeply bound states in ^{208}Pb
PhD thesis, Utrecht University, 2001

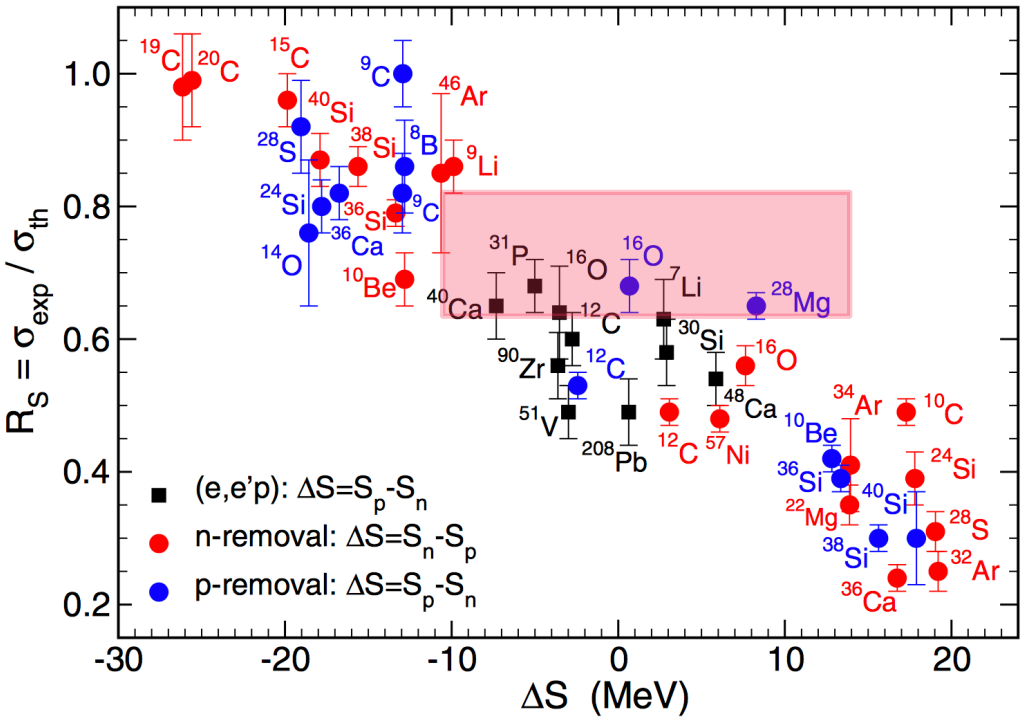


Ab initio approaches do not predict such a “reduction” for asymmetric nuclei

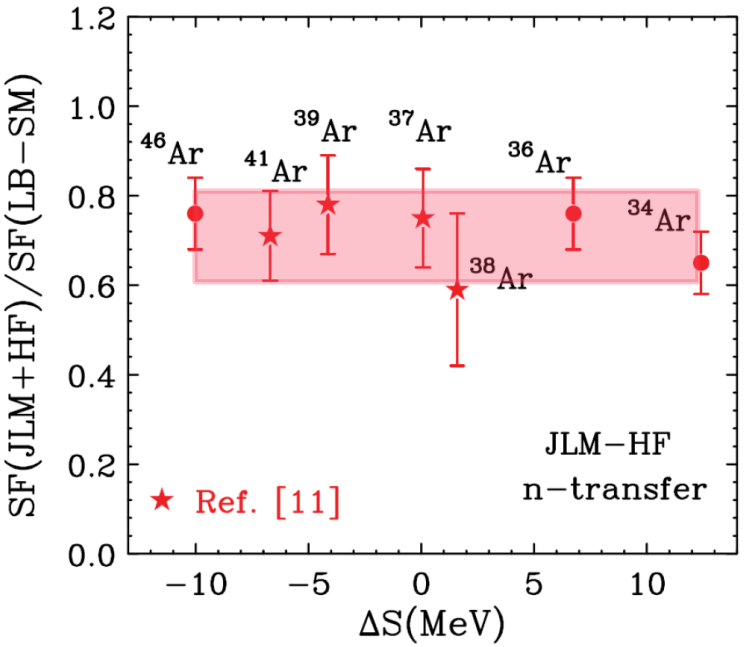
C. Barbieri, W.H. Dickhoff, Int. Jour. Mod. Phys. A **24**, 2060 (2009)
O. Jensen et al., Phys. Rev. lett. **107**, 032501 (2011)

Introduction

J. A. Tostevin and A. Gade, Phys. Rev. C **90**, 057602 (2014)



J. Lee *et al*, PRC **83**, 014606 (2011).



Low energy transfer
Data up to ΔS=13 MeV

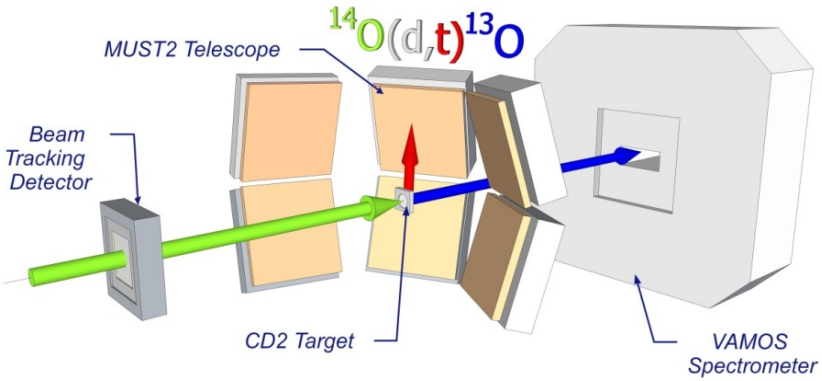
Low energy stripping (transfer)

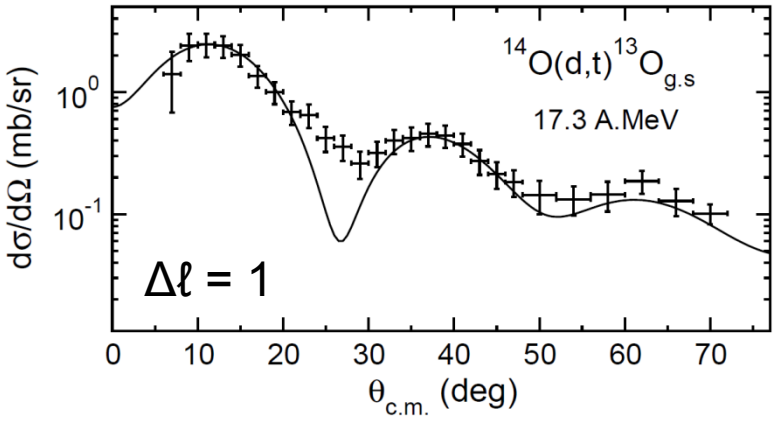
TECHNISCHE UNIVERSITÄT DARMSTADT

^{14}O(d,t) , (d,^{3}He) and elastic scattering, 19 MeV/nucleon, SPIRAL (GANIL)

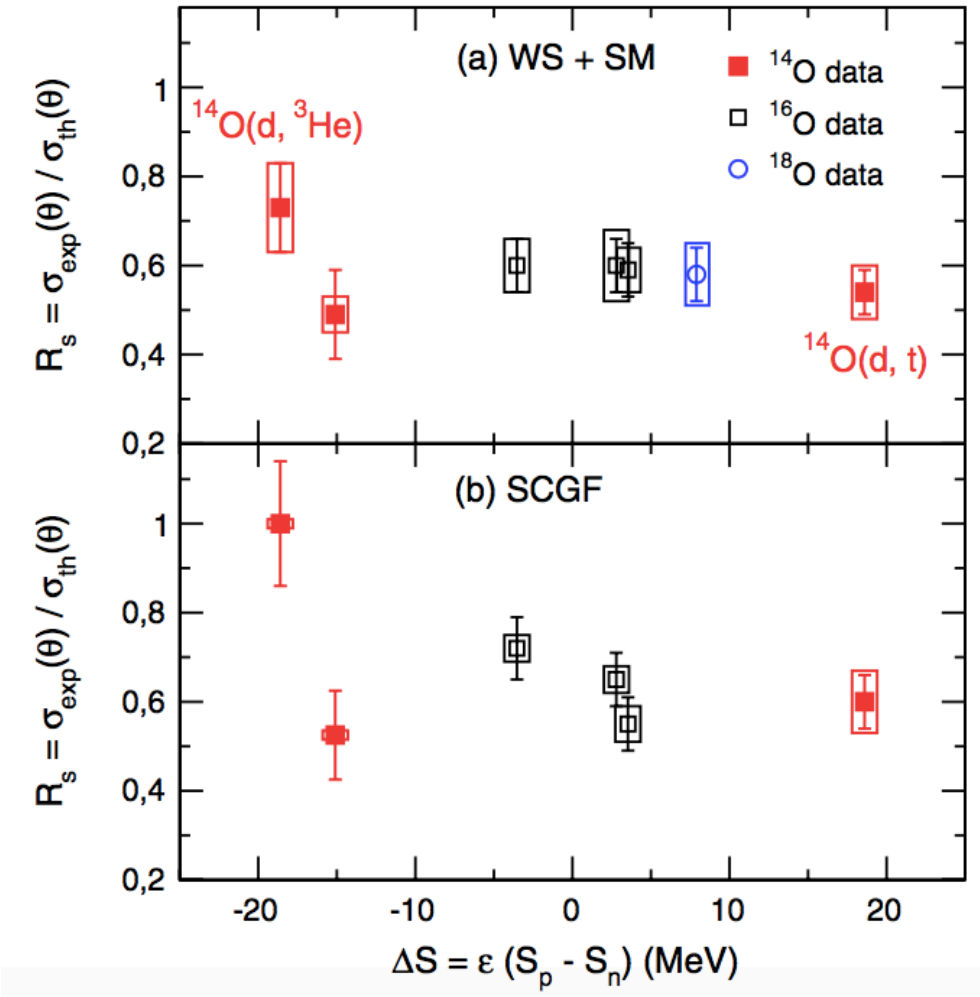
- Span over a large range of ΔS (19 MeV for ^{14}O)
- spherical nuclei with large C2S for low lying states, known structure
- Few bound states
- Reference isotopic chain (see recent work from quasifree scattering)

F. Flavigny, IPNO

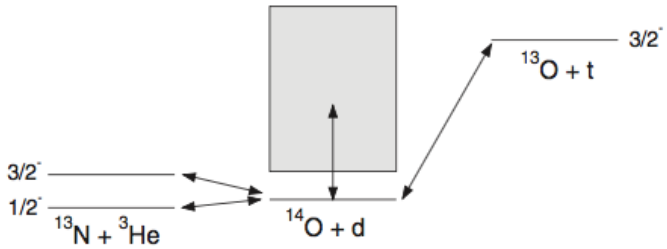




Low energy stripping (transfer)



- analysis via CRC
- CDCC for deuteron breakup

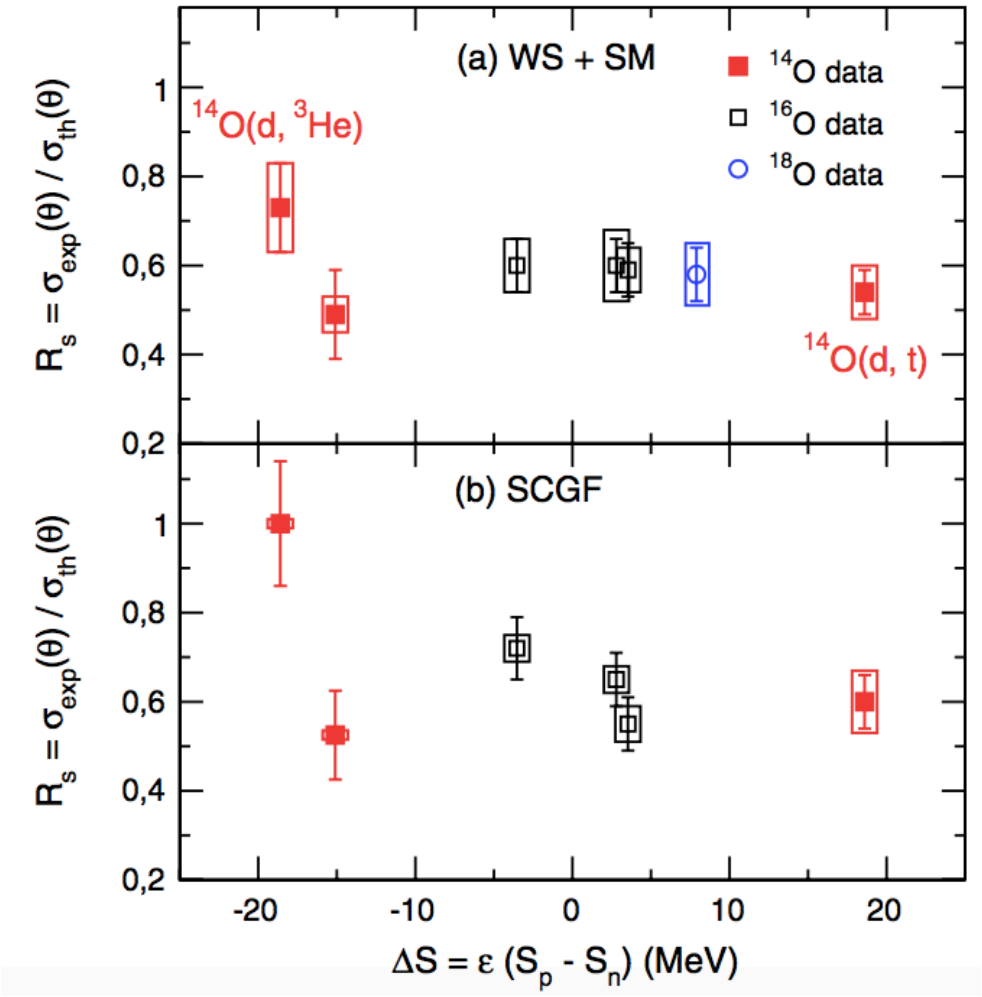


- Re-analysis of stable beam data

Uncertainties from theory:
- radii constrained by HF (as in eikonal)
- use of different potentials (in, out)
- several SM interactions considered
- All combinations considered

F. Flavigny *et al.,* Phys. Rev. Lett. **100**, 122503 (2013)

Low energy stripping (transfer)



48 analysis:

- **2 sets of C^2S_{th}:**
  - WBT Interaction 0p shell + 2ħΩ
  - Utsuno int. 0p1s0d space
- **3 HF calculations** for radii
- **8 combinations of optical potentials** for entrance and exit channels

χ^2_{min}

$$R_s = \alpha \cdot \Delta S + \beta$$

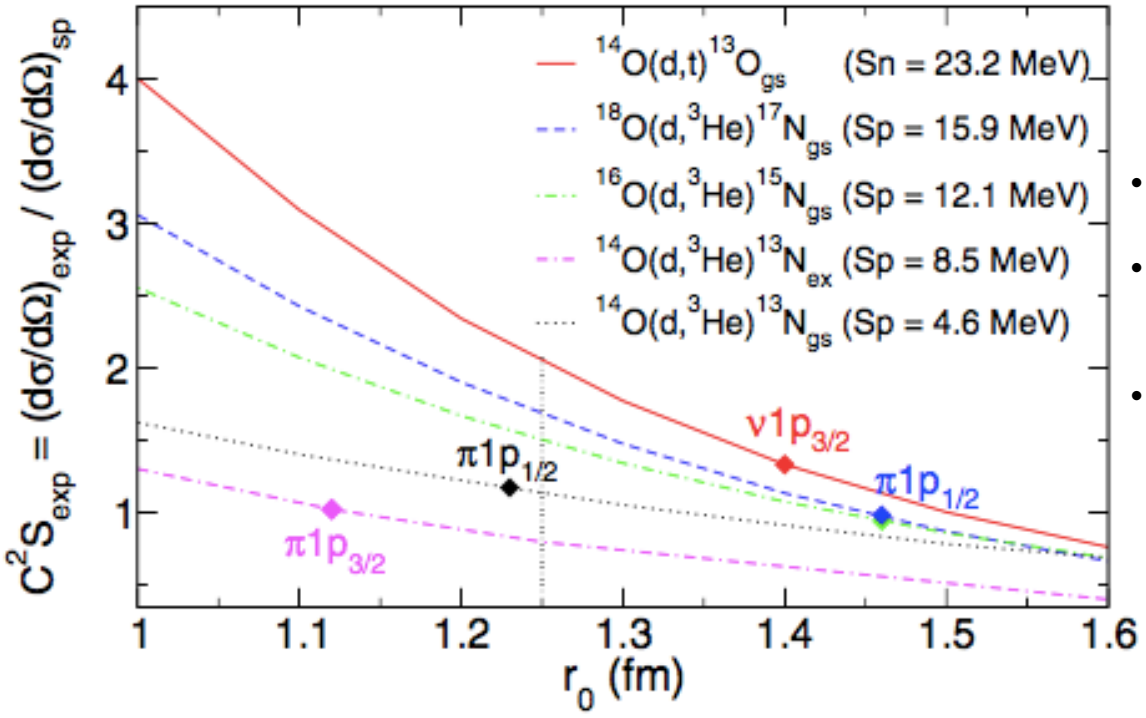
α = +0.0004(24)(12) MeV^{-1}

$\beta = R_s(0) = 0.538(28)(18)$

Exp. Error (1 set)

Systematic error from 48 data sets

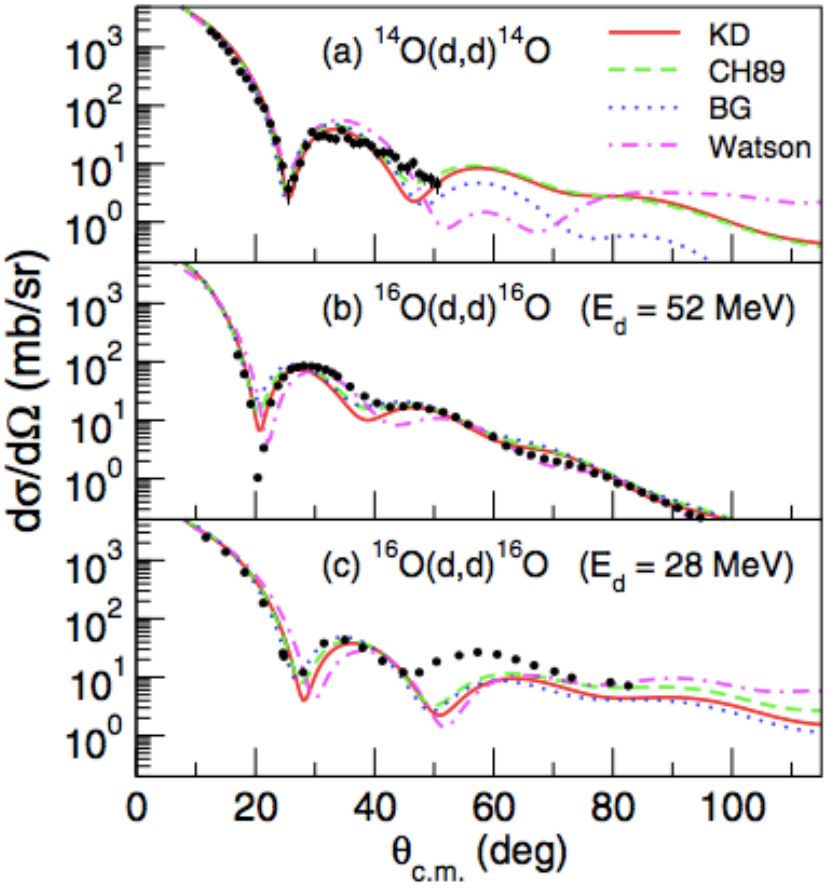
Low energy stripping (transfer)

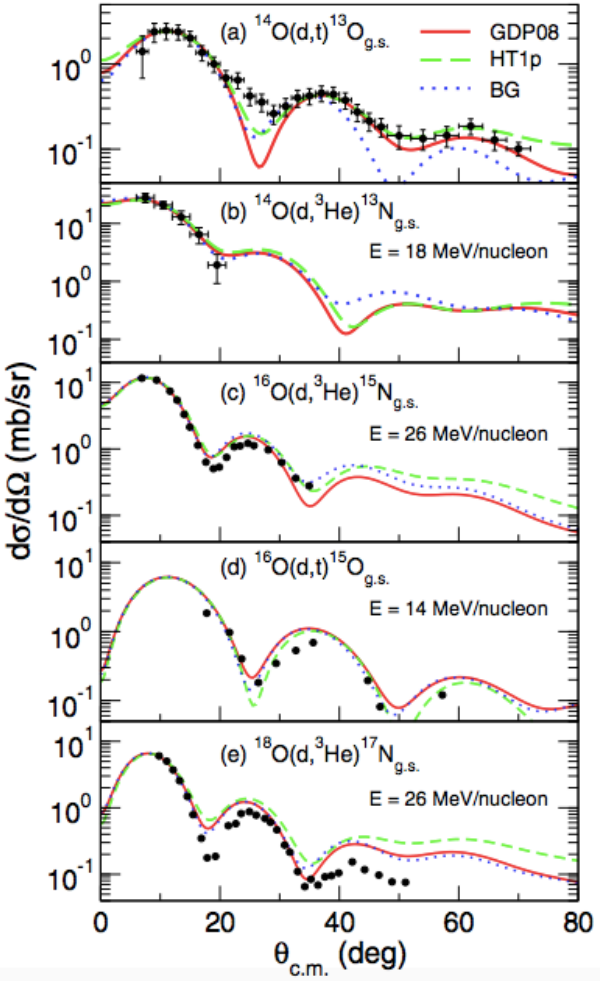


- Strong sensitivity to the form factor
- **Ansatz**: constrain from HF calculations (as done for eikonal Be-induced reactions)
- Similar dependence than found in eikonal

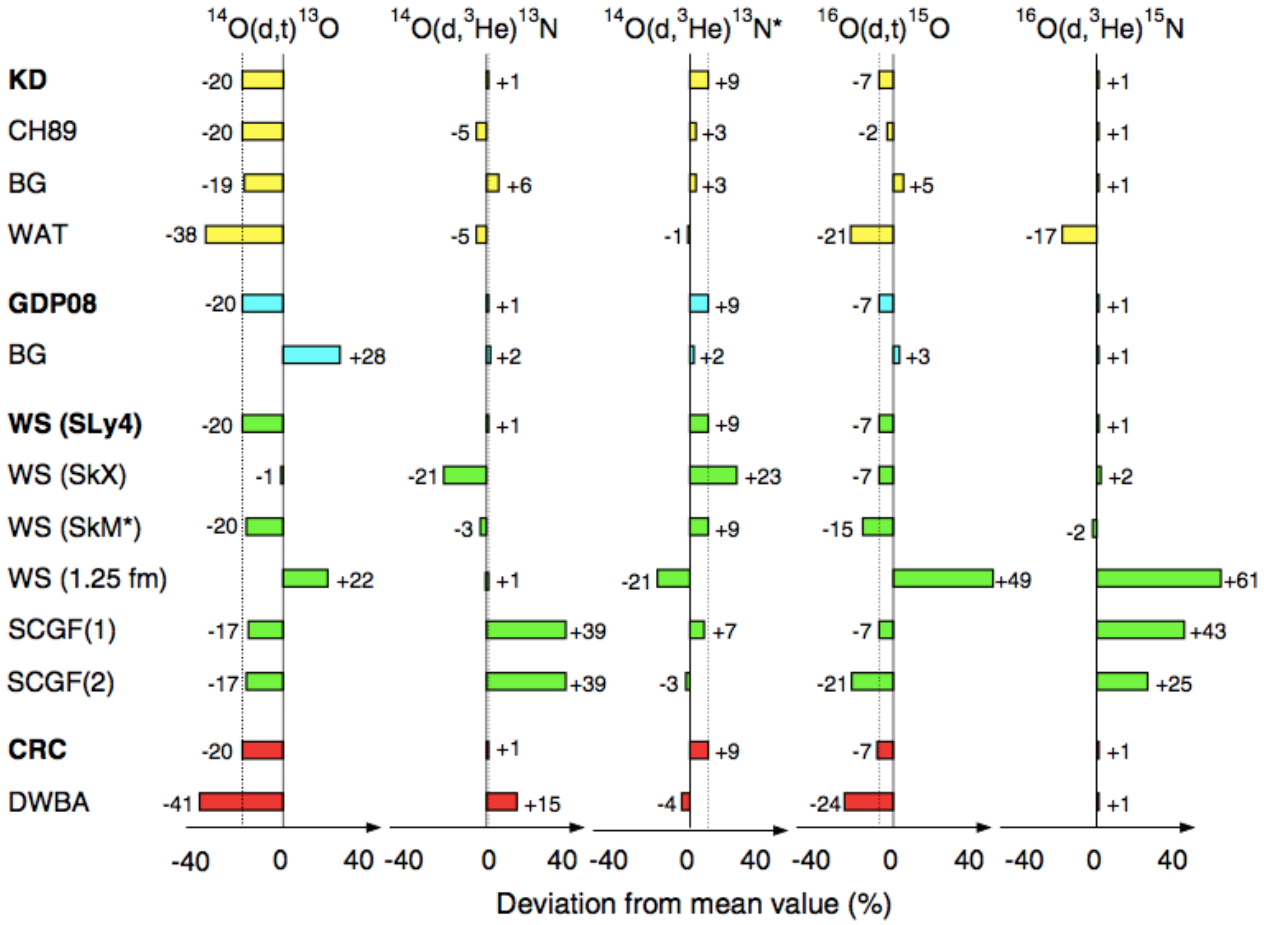
F. Flavigny *et al.,* Phys. Rev. C **97**, 034601 (2018)

Low energy stripping (transfer)





Low energy stripping (transfer)



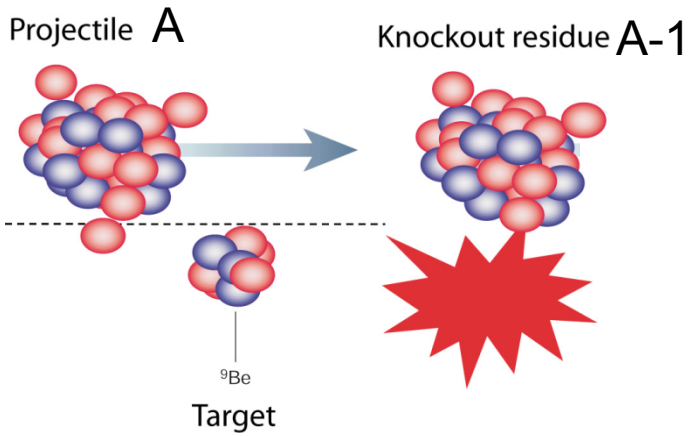
F. Flavigny *et al.,* Phys. Rev. C **97**, 034601 (2018)

Intermediate-energy removal: questioning the sudden approximation

TECHNISCHE UNIVERSITÄT DARMSTADT

Sudden approximation: Projectile energy large enough to consider that the intrinsic degrees of freedom are frozen

Eikonal / sudden approximation



Probability to leave the core intact

Probability to remove the nucleon

$$\sigma_{st} = 2\pi \int bdb\,|\phi_0|^2 |S_C|^2 (1 - |S_N|^2)$$

$$\hat{S}_C(b) = exp(i\chi_C(b))$$

$$\chi_C(b) = -\sigma_{NN}(E) \int d^2\vec{r}_\perp \bar{\rho}_C(\vec{r}_\perp)\bar{\rho}_T(|\vec{b} - \vec{r}_\perp|)$$

NN cross section

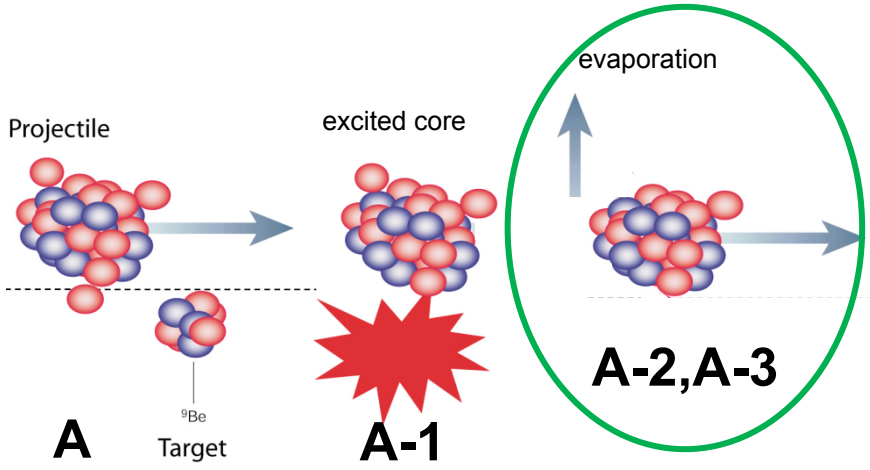
Core density

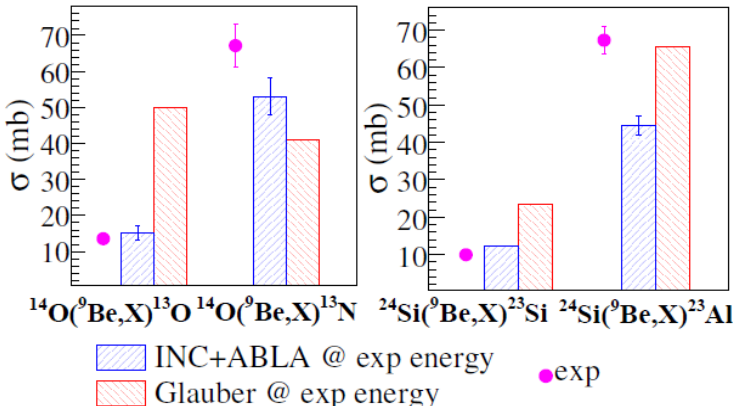
No explicit treatment of core excitations

Intermediate-energy removal: questioning the sudden approximation

TECHNISCHE UNIVERSITÄT DARMSTADT

Intranuclear Cascade Model (*INC*)
(*with nuclear-structure input)*





Reduction of the -1 nucleon removal cross section

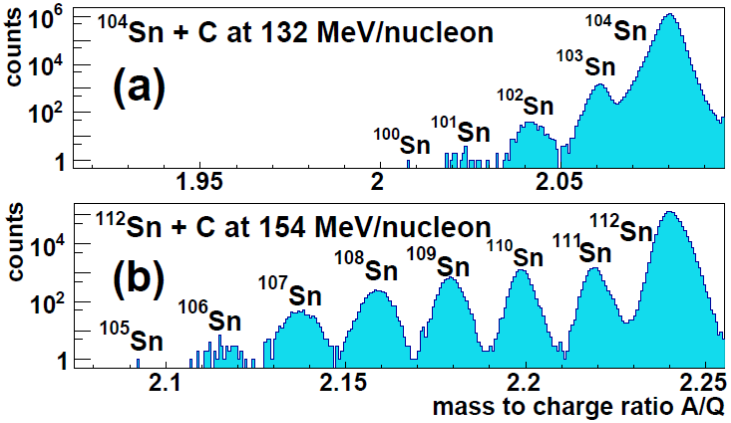
⇒ Importance of **core excitations** for loosely-bound cores and deeply-bound nucleons?

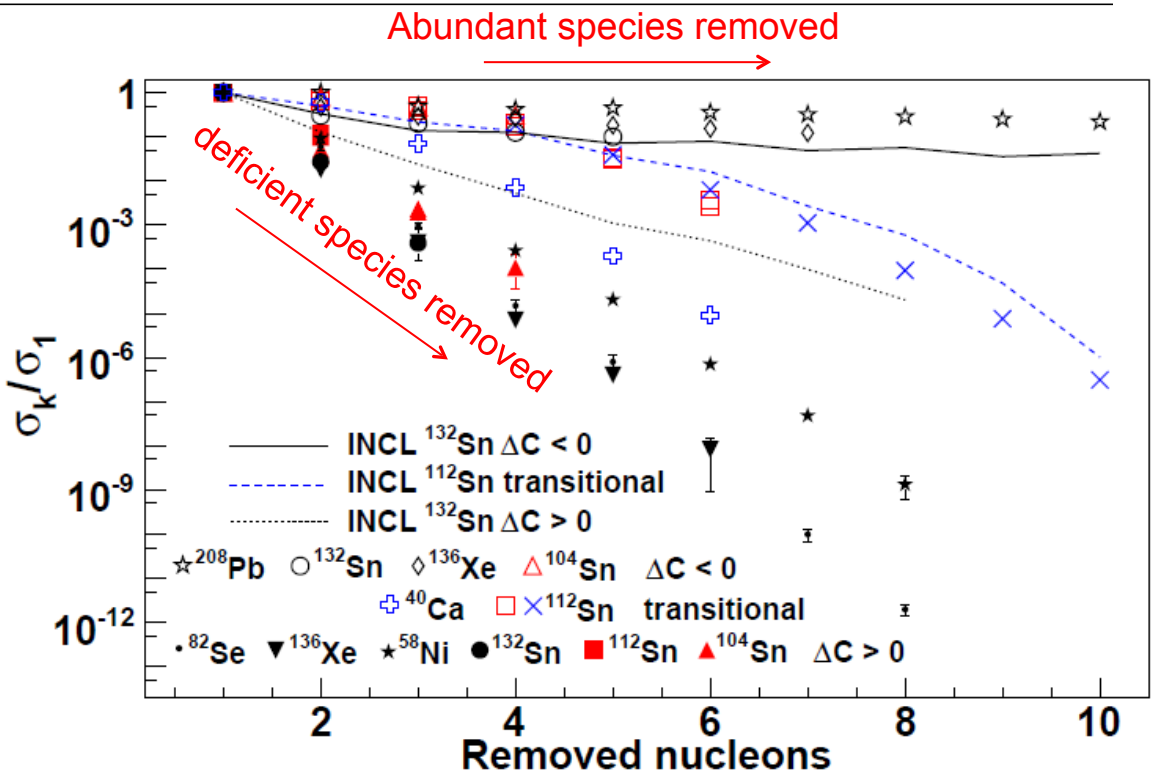
C. Louchart *et al.,* Phys. Rev. C **83**, 011601 (R) (2011).

Multi-deeply bound nucleon removal

TECHNISCHE UNIVERSITÄT DARMSTADT

^{104}Sn, ^{112}Sn + ^{12}C, CH_2
at 140 MeV/nucleon, RIBF





Important role of the "Evaporation cost":

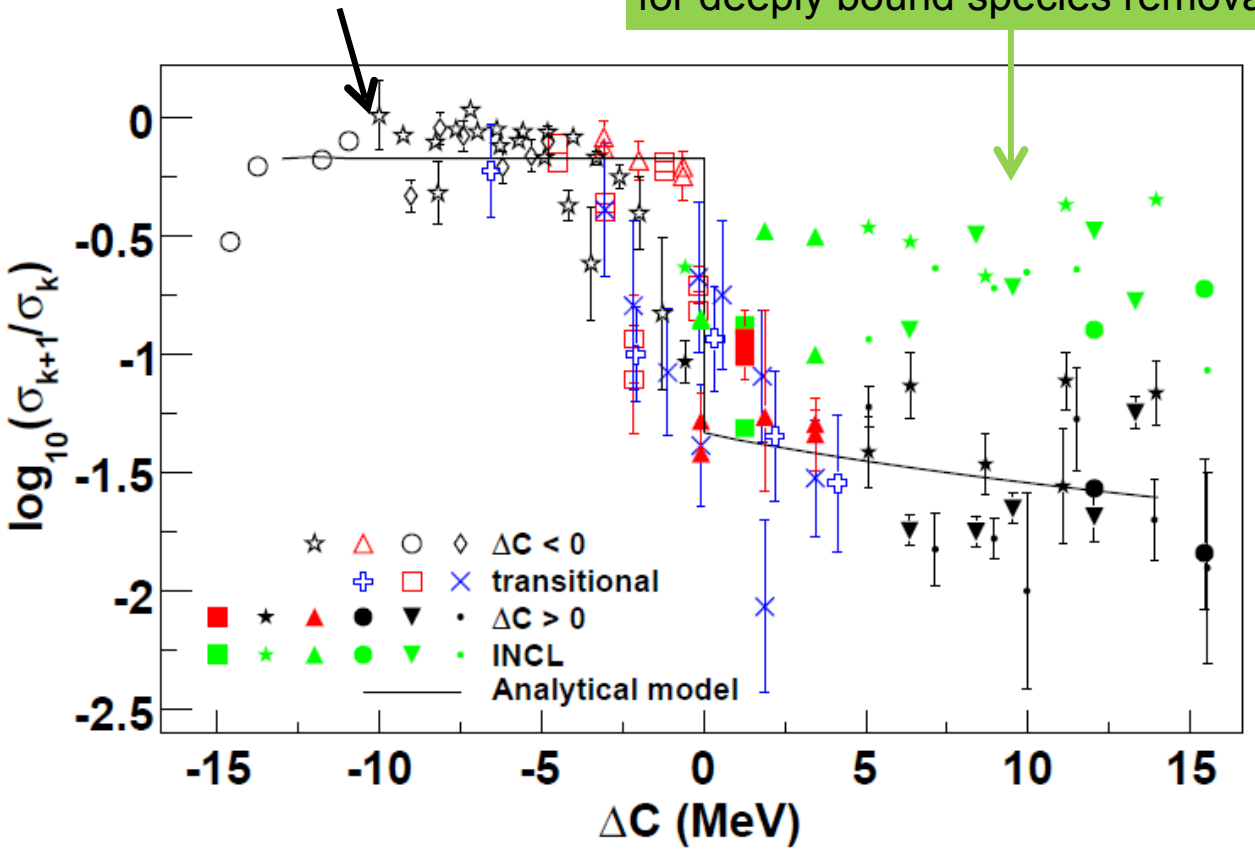
$\Delta C = S_p - S_n + B$ (if n removed) of the final nucleus (remnant)

L. Audirac *et al.*, Phys. Rev. C **88**, 041602 (2013).

Multi-deeply bound nucleon removal

Neutrons from ^{132}Sn, ^{112}Sn, protons from ^{104}Sn

Overestimated “slope” (and cross sections) for deeply bound species removal



L. Audirac *et al.,* Phys. Rev. C **88**, 041602 (2013)

Improving one-nucleon removal in INC

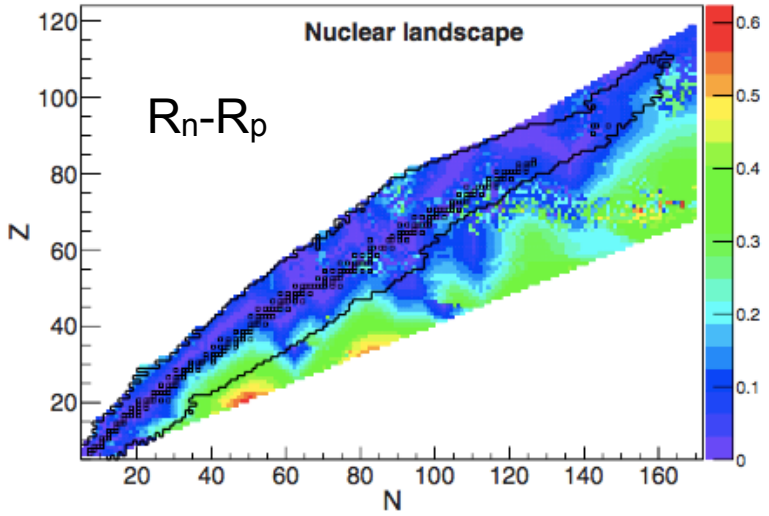
TECHNISCHE UNIVERSITÄT DARMSTADT

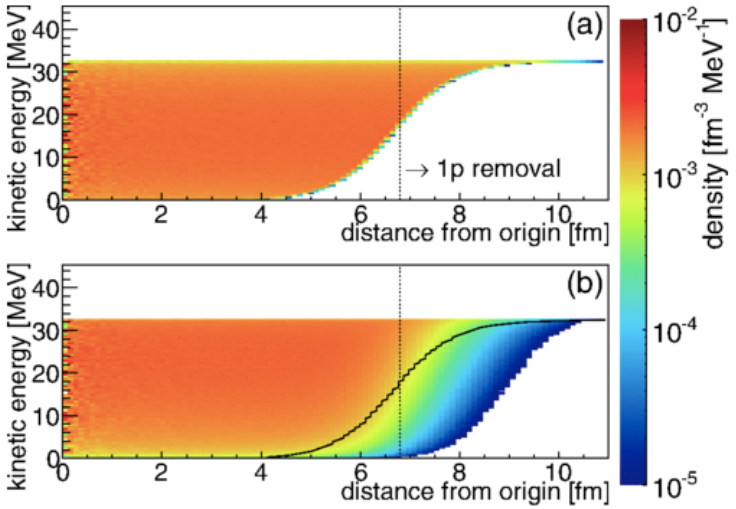
PHYSICAL REVIEW C **96**, 054602 (2017)

Improvement of one-nucleon removal and total reaction cross sections in the Liège intranuclear-cascade model using Hartree-Fock-Bogoliubov calculations

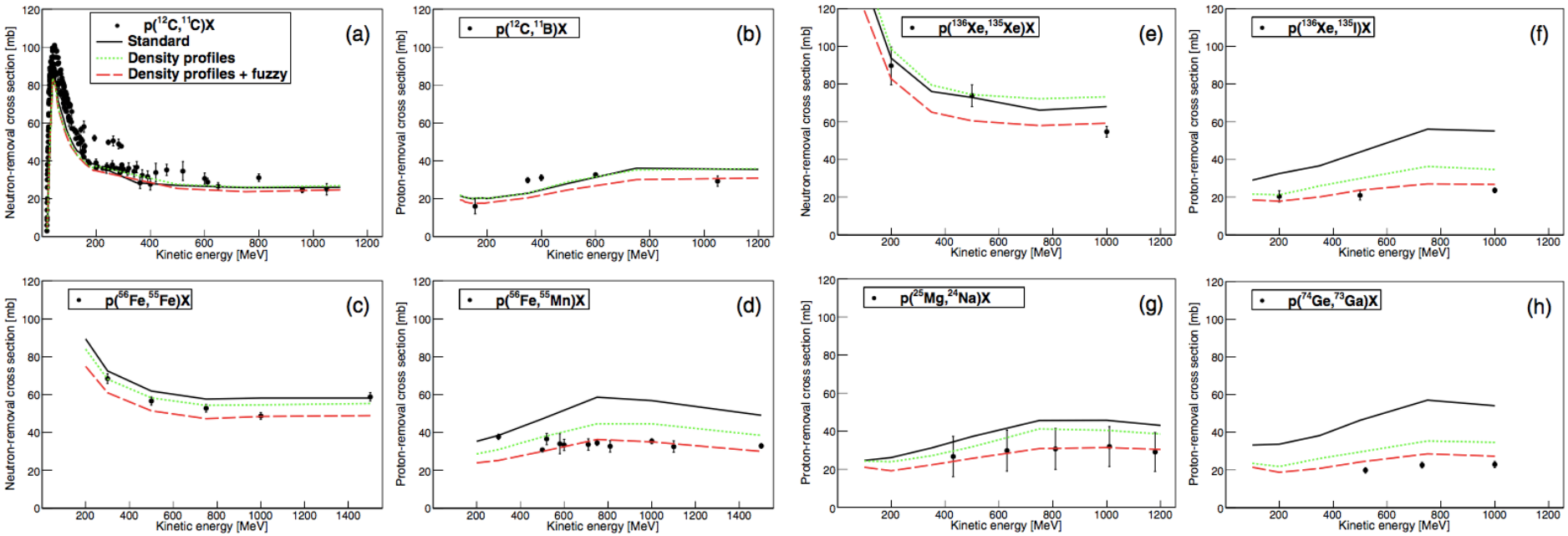
Jose Luis Rodríguez-Sánchez,[1,*] Jean-Christophe David,[1] Davide Mancusi,[2] Alain Boudard,[1]
Joseph Cugnon,[3] and Sylvie Leray[1]

1) proton and neutron radial densities constrained by Hartree-Fock
2) fluctuations of intrinsic nucleonic momentum distributions





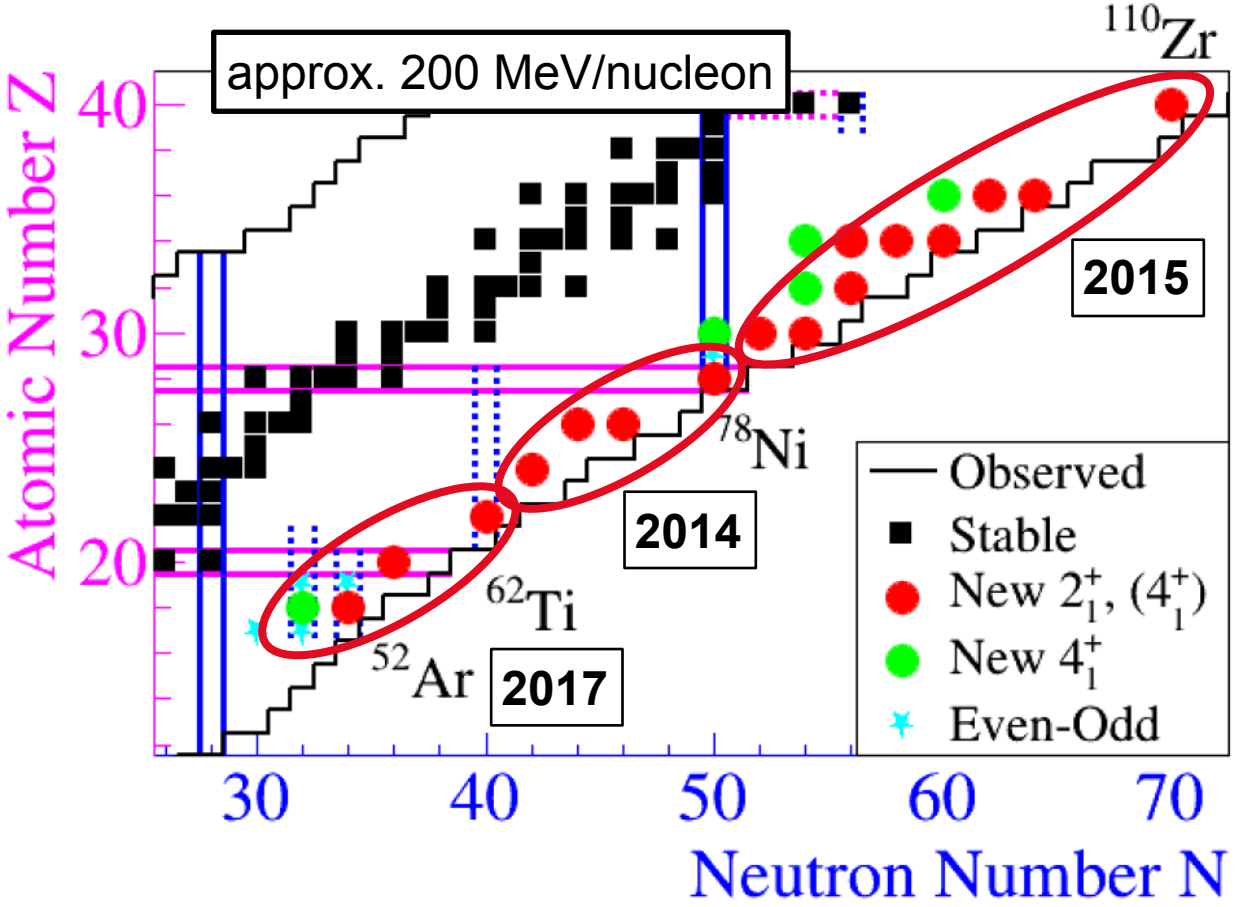
Improving one-nucleon removal in INC



- Overall improvement of one-nucleon removal from stable nuclei
- Maintained good prediction of reaction cross sections (not shown)

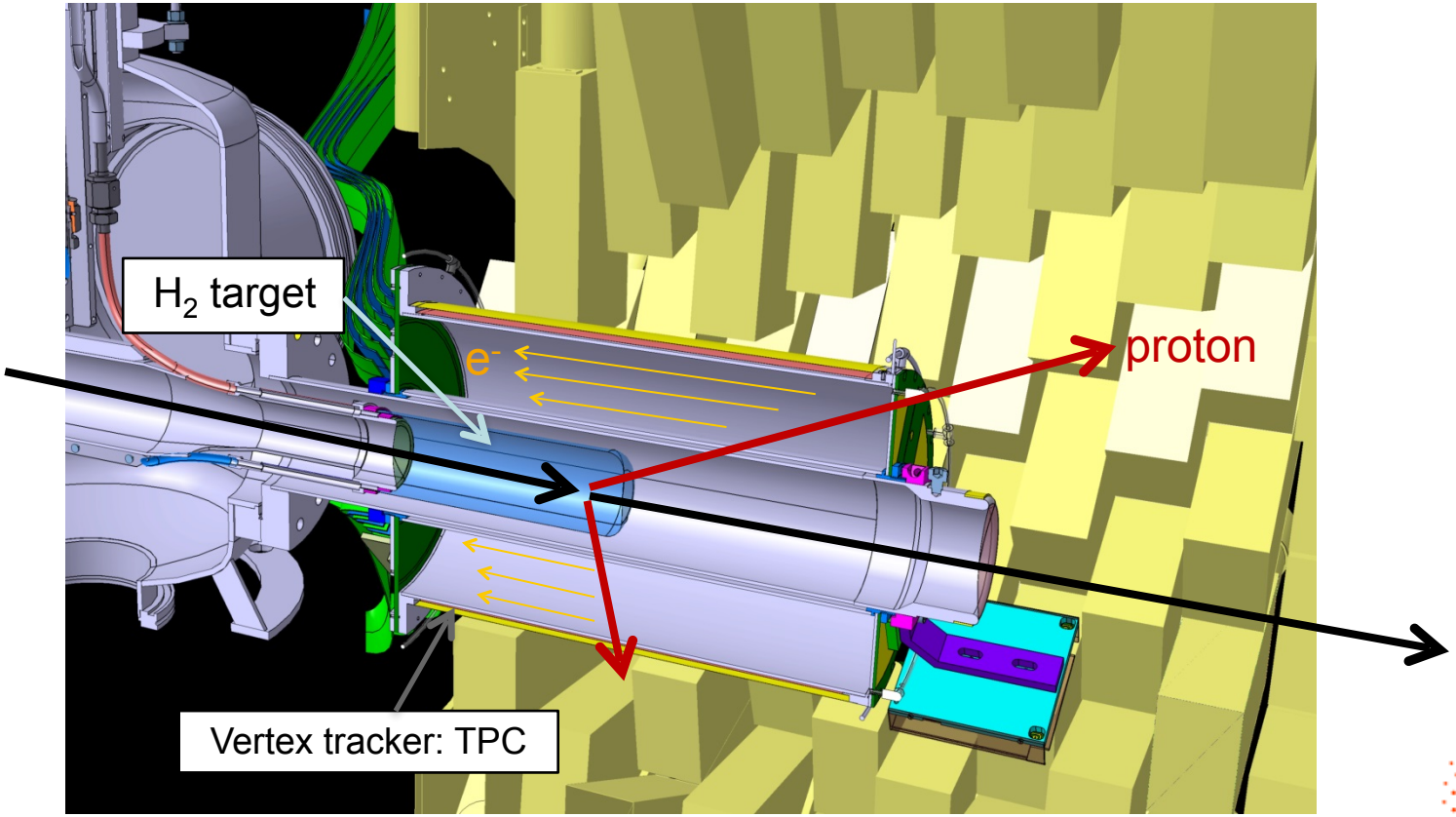
Nucleon-removal data from the RIBF

SEASTAR: In-flight gamma spectroscopy program for 2^+ state energies



SEASTAR spokespersons: P. Doornenbal (RIKEN), A. Obertelli

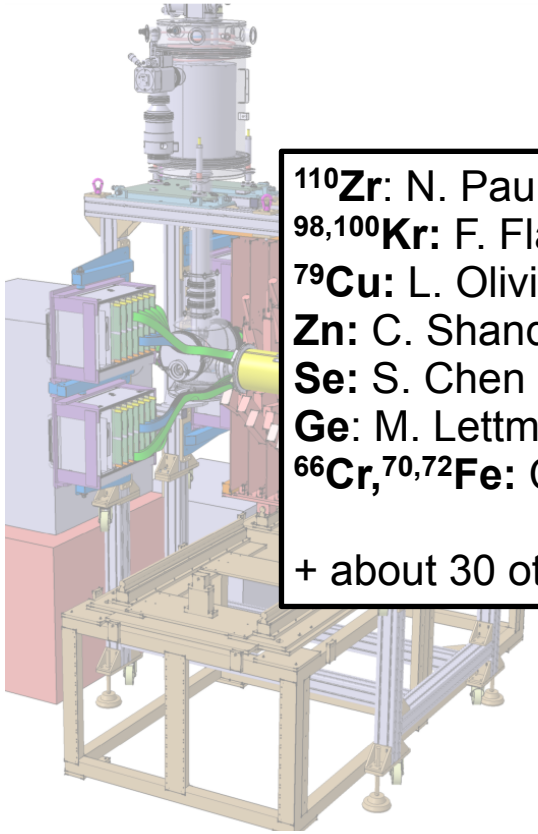
DALI2 and MINOS at the RIBF



A. Obertelli *et al.,* Eur. Phys. Jour. A **50**, 8 (2014)

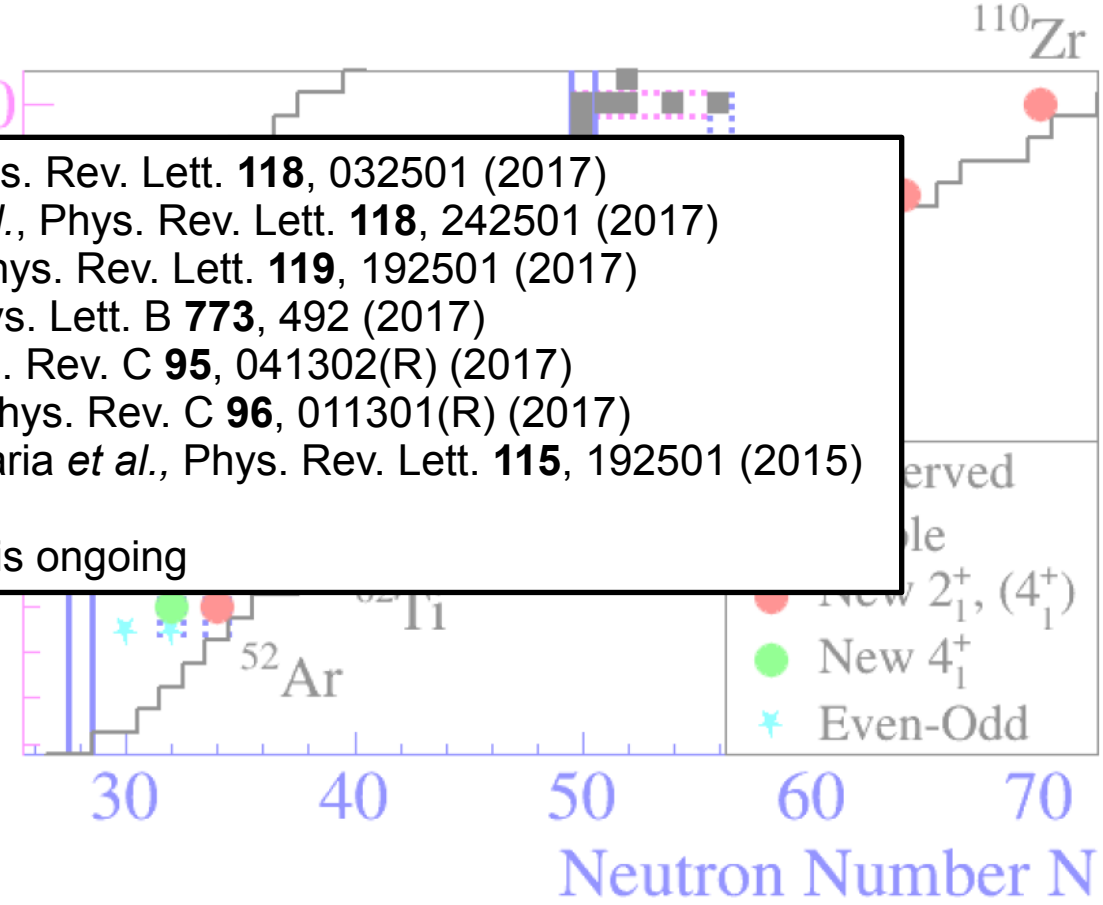
SEASTAR physics program: 2014 - 2017

TECHNISCHE UNIVERSITÄT DARMSTADT



^{110}Zr: N. Paul *et al.*, Phys. Rev. Lett. **118**, 032501 (2017)
^{98,100}Kr: F. Flavigny *et al.*, Phys. Rev. Lett. **118**, 242501 (2017)
^{79}Cu: L. Olivier *et al.,* Phys. Rev. Lett. **119**, 192501 (2017)
Zn: C. Shand et *al.,* Phys. Lett. B **773**, 492 (2017)
Se: S. Chen *et al.*, Phys. Rev. C **95**, 041302(R) (2017)
Ge: M. Lettman *et al.,* Phys. Rev. C **96**, 011301(R) (2017)
^{66}Cr,^{70,72}Fe: C. Santamaria *et al.,* Phys. Rev. Lett. **115**, 192501 (2015)

+ about 30 other analysis ongoing



SEASTAR spokespersons: P. Doornenbal (RIKEN), A. Obertelli

Collaboration (expt)

TECHNISCHE UNIVERSITÄT DARMSTADT

L. Achouri, O. Aktas, G. de Angelis, N. Aoi, T. Aumann, H. Baba, F. Brown, D. Calvet, S. Chen, N. Chiga, L. Chung, M.L. Cortes, A. Corsi, F. Delaunay, A. Delbart, Z. Dombradi, P. Doornenbal, F. Flavigny, S. Franchoo, I. Gasparic, R.-B. Gerst, J.-M. Gheller, J. Gibelin, A. Gillibert, S. Go, M. Gorska, A. Gottardo, K. Hahn, C. Hilaire, A. Jungclaus, D. Kim, N. Kobayashi, T. Kobayashi, T. Koiwai, Y. Kondo, W. Korten, P. Koseglou, Y. Kubota, V. Lapoux, J. Lee, B.D. Linh, H. Liu, T. Lokotko, G. Lorusso, C. Louchart, R. Lozeva, M. Marques, M. Mc Cormick, K. Matsui, Y. Matsuda, M. Matsushita, S. Michimasa, T. Miyazaki, S. Momiyama, K. Moschner, I. Murray, D. Napoli, F. Naqvi, M. Niikura, A. Obertelli, , N. Orr, S. Ota, H. Otsu, V. Panin, S.-Y. Park, N. Paul, N. Pietralla, Z. Podolyak, E.C. Pollacco, G. Randisi, F. Recchia, W. Rodriguez, E. Sahin, M. Sasano, Y. Shiga, Y. Shimuzu, P.-A. Soderstrom, D. Sohler, I. Stefan, D. Steppenbeck, L. Stuhl, Y. Sun, M. Tanaka, R. Taniuchi, S. Takeuchi, Y. Togano, V. Vaquero, H. Wang, S. Wang, V. Werner, K. Wimmer, Z. Xu, H. Yamada, D. Yan, M. Yasuda, K. Yoneda, Y. Zaihong

TECHNISCHE UNIVERSITÄT DARMSTADT

Preliminary / unpublished results from the RIBF removed

Nucleon removal from Tin isotopes / GSI

TECHNISCHE UNIVERSITÄT DARMSTADT

PHYSICAL REVIEW C **96**, 034303 (2017)

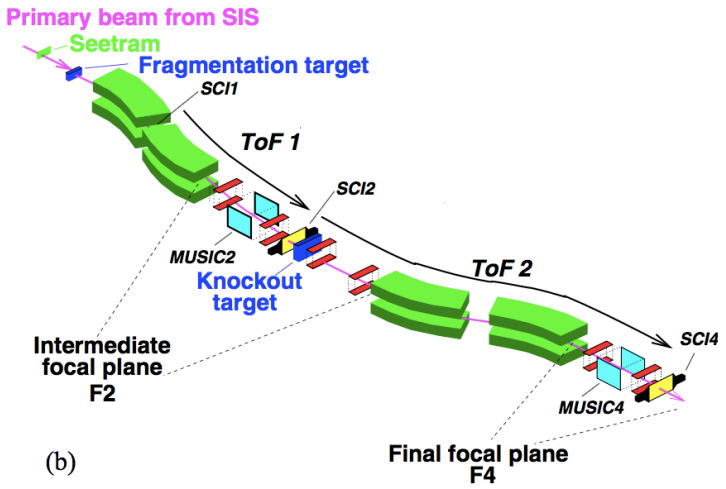
Knockout and fragmentation reactions using a broad range of tin isotopes

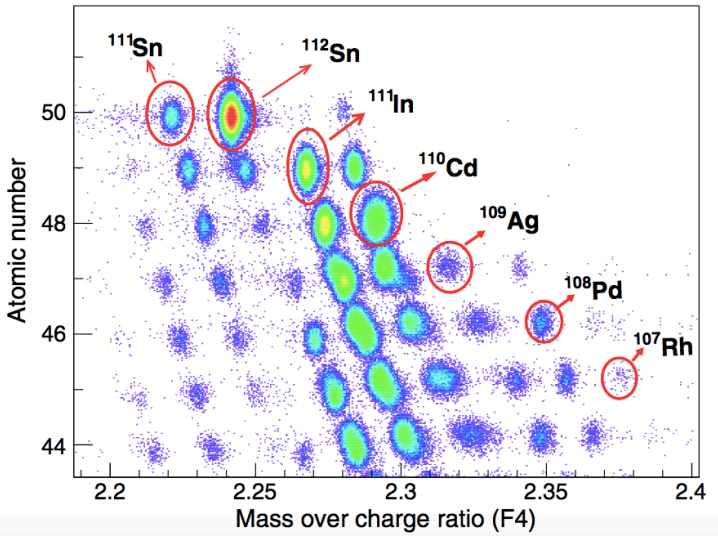
J. L. Rodríguez-Sánchez,[1,*] J. Benlliure,[1] C. A. Bertulani,[2] J. Vargas,[1,†] Y. Ayyad,[1,‡] H. Alvarez-Pol,[1] J. Atkinson,[3] T. Aumann,[3,4] S. Beceiro-Novo,[1,§] K. Boretzky,[3] M. Caamaño,[1] E. Casarejos,[5] D. Cortina-Gil,[1] J. Díaz-Cortes,[1] P. Díaz Fernández,[1,‖] A. Estrade,[3,6,¶] H. Geissel,[3] A. Kelić-Heil,[3] Yu. A. Litvinov,[3] M. Mostazo,[1] C. Paradela,[1,#] D. Pérez-Loureiro,[1,**] S. Pietri,[3] A. Prochazka,[3] M. Takechi,[3,††] H. Weick,[3] and J. S. Winfield[3]

[1]*Universidad de Santiago de Compostela, E-15782 Santiago de Compostela, Spain*

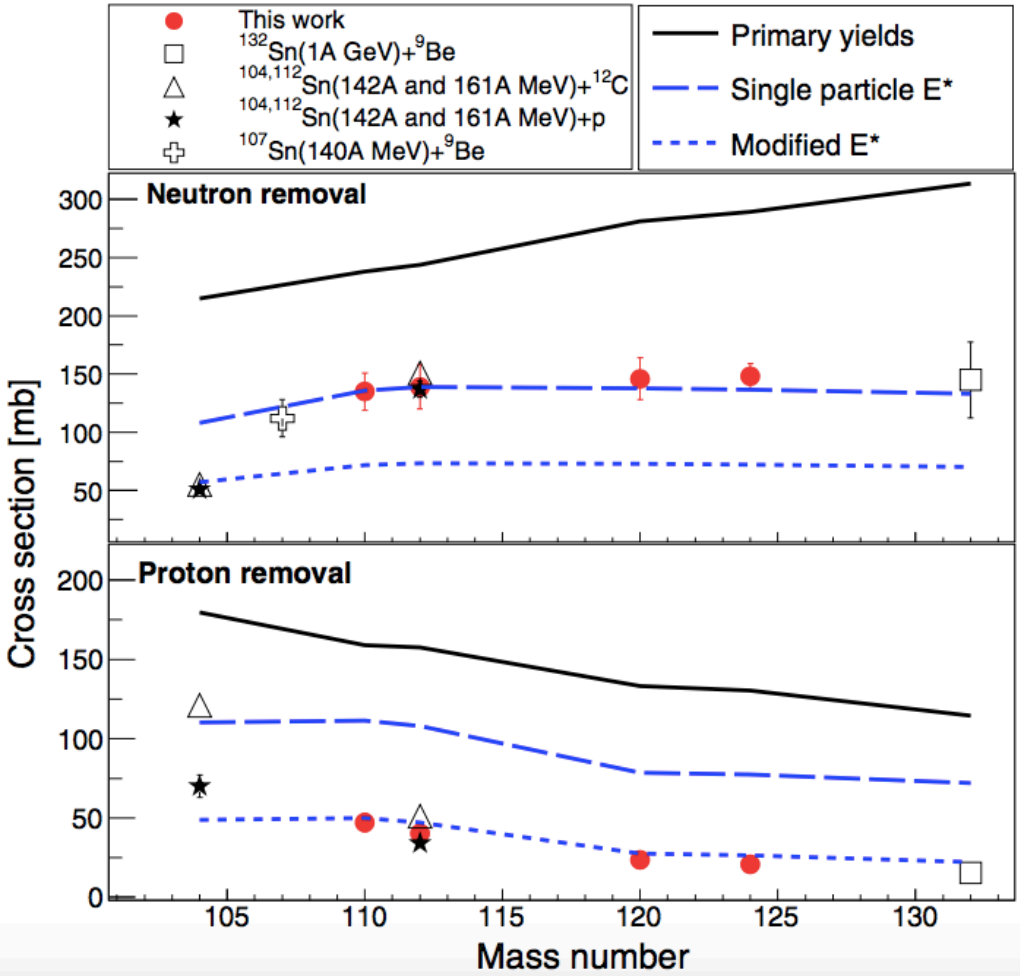
[2]*Department of Physics and Astronomy, Texas A&M University–Commerce, Commerce, Texas 75429, USA*

[3]*GSI-Helmholtzzentrum für Schwerionenforschung GmbH, D-64291 Darmstadt, Germany*





Glauber followed by evaporation

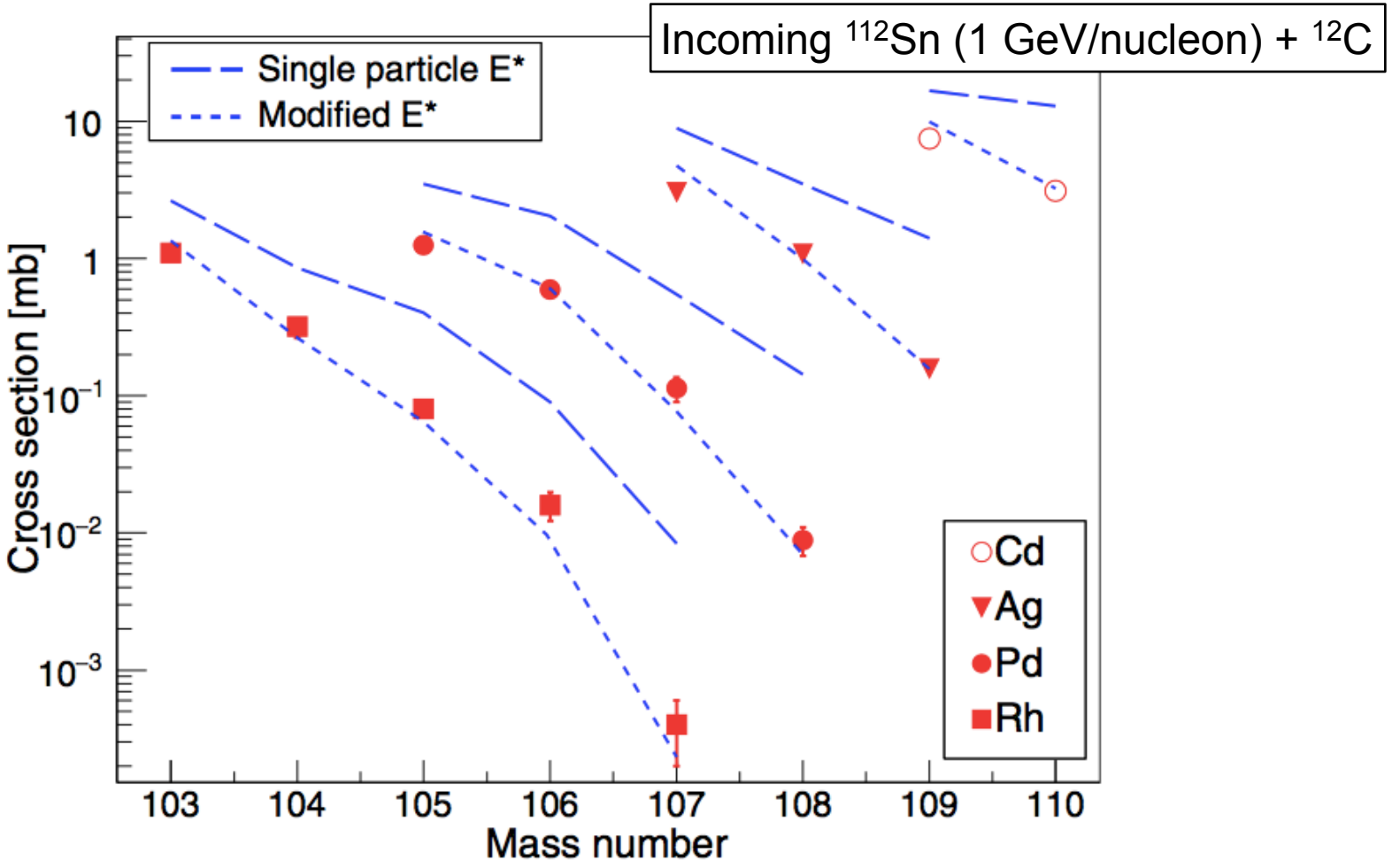


Experiment
- Beams of ^{110}Sn, ^{112}Sn, ^{120}Sn, ^{124}Sn
- Energy: 1 GeV/nucleon
- ^{12}C target
- combined with other data (RIKEN, GSI)

Model
- Glauber
- Excitation energy from HF
- (s.-p. state density)
- De-excitation of remnants by ABLA07
- Assumes exit. separation energies + Bass potential Coulomb barriers

Modification of E* (arbitrary):
- + 7 MeV for protons
- + 4 MeV for neutrons

General improvement from E* corrections



Future related plans

TECHNISCHE UNIVERSITÄT DARMSTADT

Proposal for an EMMI Rapid Reaction Task Force

Direct reactions and nuclear structure: the need of a consistent theoretical treatment of structure and reactions

T. Aumann[1], C. Barbieri[2], D. Bazin[3] and A. Obertelli[1]

[1]TU Darmstadt, Germany, [2]University of Surrey, England, [3]NSCL, MSU, USA

- Dedicated “task force” to :
- overview and summarise the theoretical and experimental situation
- think and determine next steps for improvement

- People who published about the “quenching problem” will participate
- July 2018, Darmstadt, Germany

- Similar workshop will follow later in 2018 in the USA (APS meeting)
  Organizer: A. Machiavelli, LBNL

Future related plans

TECHNISCHE UNIVERSITÄT DARMSTADT

1) **Two-proton removal** from hydrogen induced reactions
   > Sensitivity to structure / complementarity to one-proton removal seen in SEASTAR data

2) **Short range correlation** studied at 1-2 GeV/nucleon
   > Plans at R3B collaboration under discussion

3) **Strangeness production** from hydrogen induced reactions from few-body
   > Currently discussed within NUSTAR / R3B collaboration

Summary

TECHNISCHE UNIVERSITÄT DARMSTADT

- Discrepancy between experimental and eikonal theory for heavy-ion induced well-bound nucleon removal at E ~ 60 - 100 MeV/nucleon
  A. Gade *et al.,* Phys. Rev. C **77**, 044306 (2008)
  J. Tostevin, A. Gade, Phys. Rev. C **90**, 057602 (2014)

- No such effect for low-energy transfer **despite model uncertainties**
  J. Lee *et al.,* Phys. Rev. C. **83**, 014606 (2011)
  F. Flavigny *et al.,* Phys. Rev. Lett. **110**, 122503 (2013)
  F. Flavigny *et al.,* Phys. Rev. C **97**, 034601 (**2018**)

- Latest results show **agreement between transfer and quasi free scattering**
  L. Atar *et al.,* Phys. Rev. Lett. **120**, 052501 (2018)
  S. Kawase *et al.,* Prog. Theo. Exp. Phys. 021D01 (2018)

- **Similar discrepancy with intra-nuclear cascade** for high-energy nucleon stripping cross sections
  L. Audirac *et al.,* Phys. Rev. C **88**, 041602 (2013)
  N. Paul *et al.,* in preparation (**2018**)

- **hypothesis for a "strong" core-target inelastic excitation** in deeply bound nucleon removal
  C. Louchart *et al.,* Phys. Rev. C **83**, 011601(R) (2011)
  J. L. Rodriguez-Sanchez *et al.,* Phys. Rev. C **96**, 034303 (**2017**)