Nucleon Stripping from Exotic Nuclei

Some recent developments and open questions

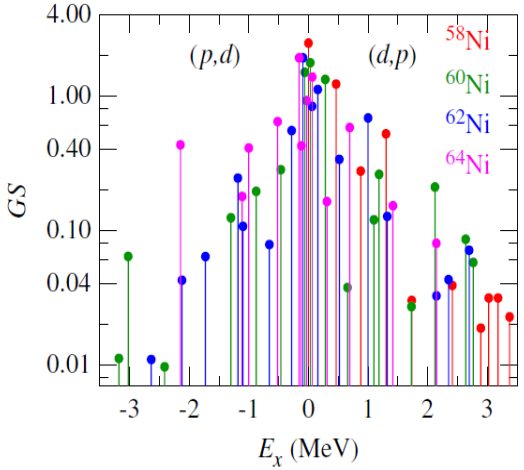
A. Obertelli

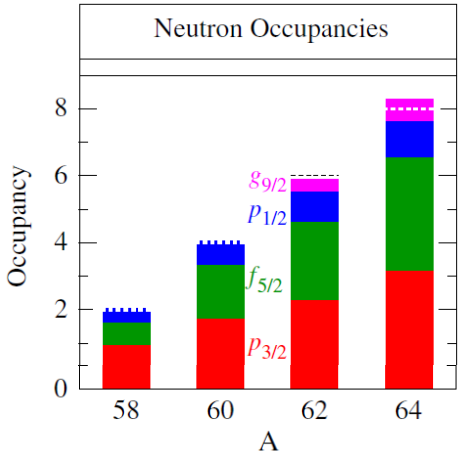
CEA Saclay

Direct Nucleon Stripping and Pickup Reactions

Reason of interest / belief: sensitive to shell occupancy / overlap from initial to final states

DWBA formalism, finite range





Renormalization
by 0.5-0.6 for correlations
beyond the shell model

J.P. Schiffer *et al.*, Phys. Rev. Lett. **108**, 022501 (2012).

Major assumption in treatment : separation of reaction mechanism and structure inputs

Cross section
to populate a final state μ

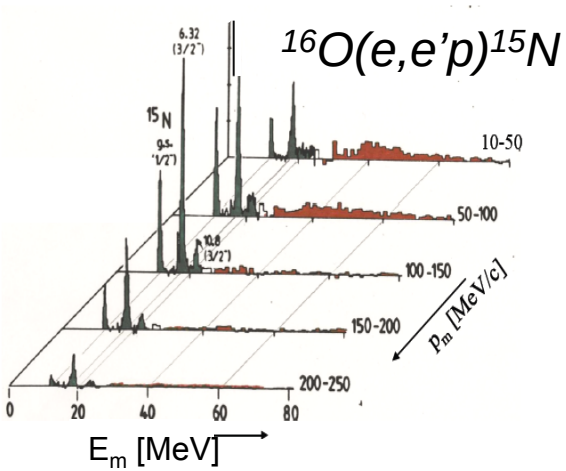
$$\sigma_\mu = \sum_{p \in H < H_1} \left| \left\langle \varphi_\mu{}^{A-1} \middle| a_p \middle| \varphi_0{}^{A} \right\rangle \right|^2 \times \sigma_p$$

σ_p → **reaction**

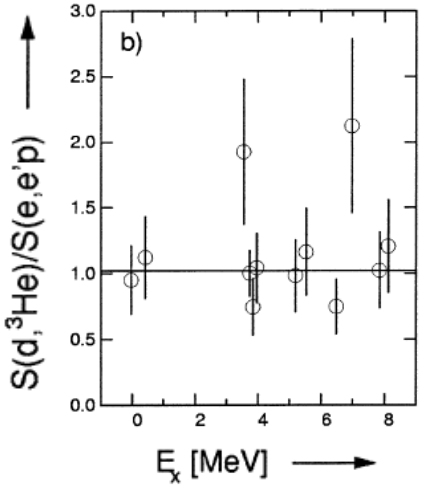
$\left\langle \varphi_\mu{}^{A-1} \middle| a_p \middle| \varphi_0{}^{A} \right\rangle$ → **Structure**

Counter-examples: ex. transfer: coupled channels mandatory in some cases

Comparison of probes for stripping



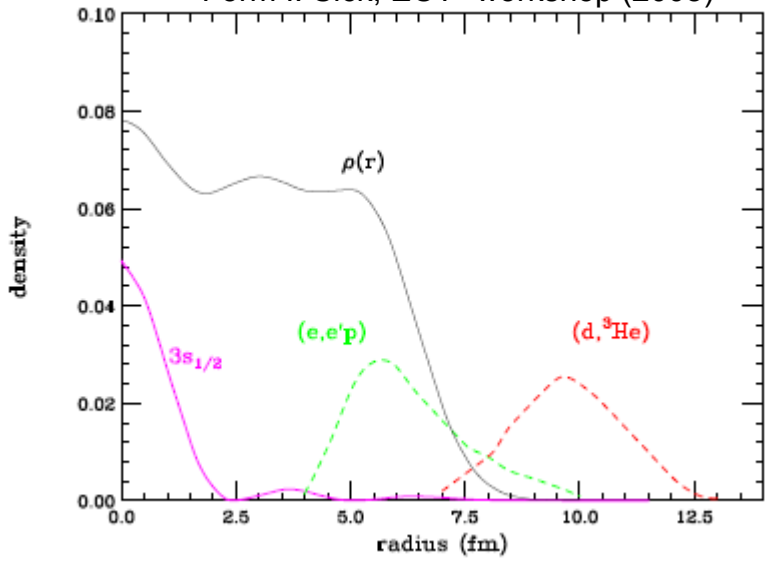
J. Mougey *et al.,* CEA Saclay (1980)



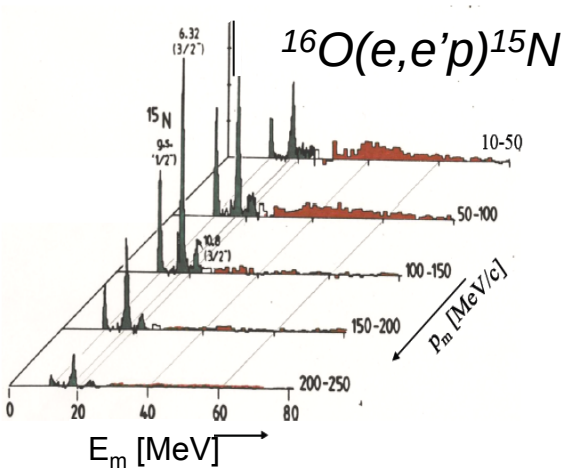
Consistency of *(e,e'p)* and *(d,^{3}He)* analysis

G.J. Kramer *et al.,*
Nucl. Phys. A **679**, 267 (2001).

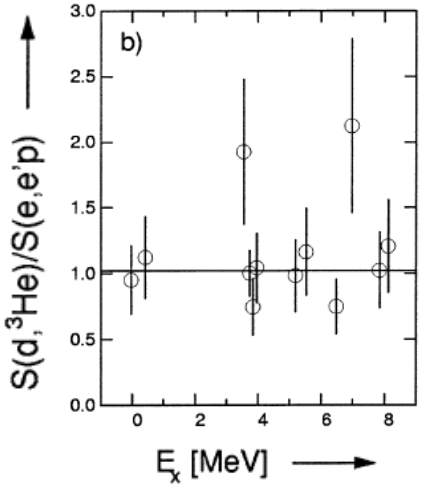
Form I. Sick, ECT* workshop (2008)



Stripping reactions at intermediate energies



J. Mougey *et al.,* CEA Saclay (1980)



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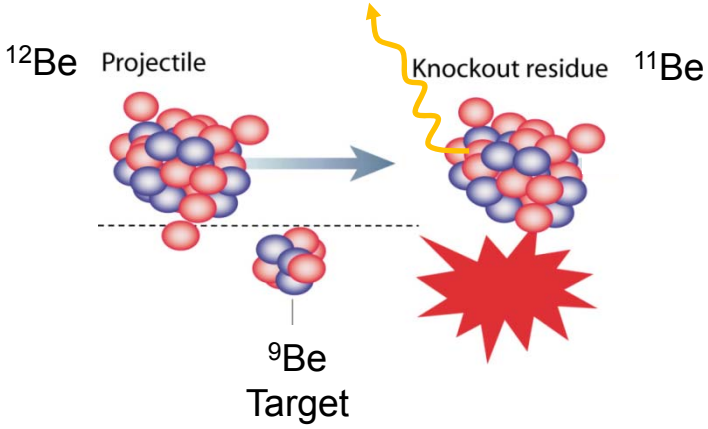
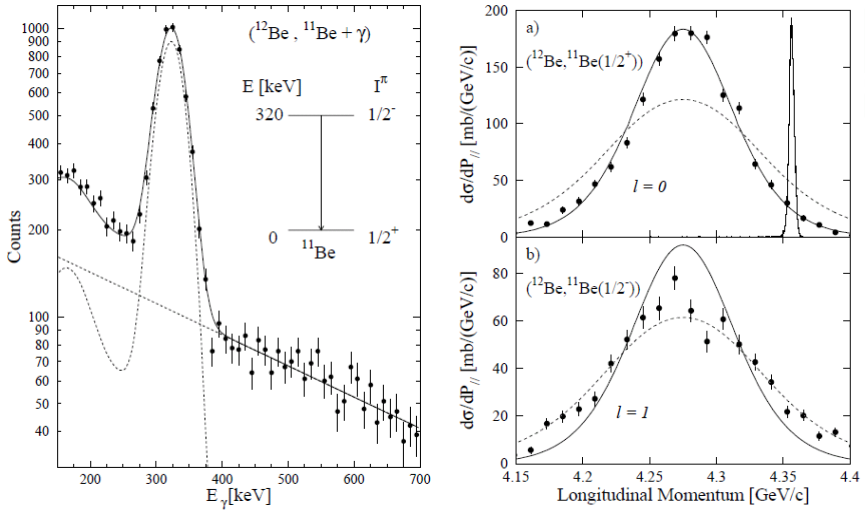
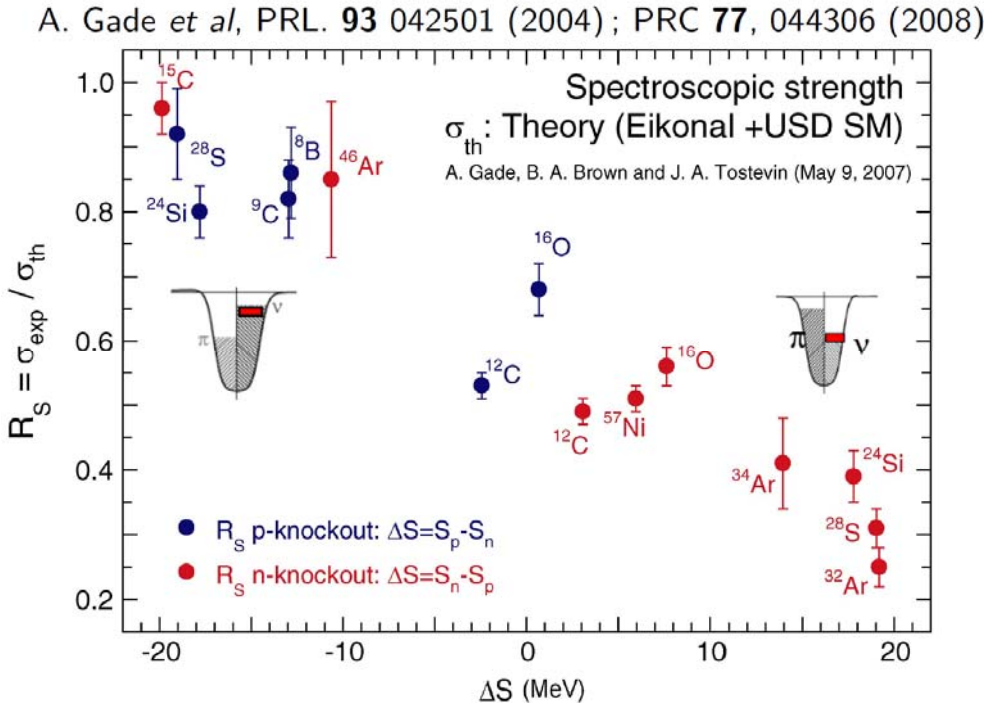


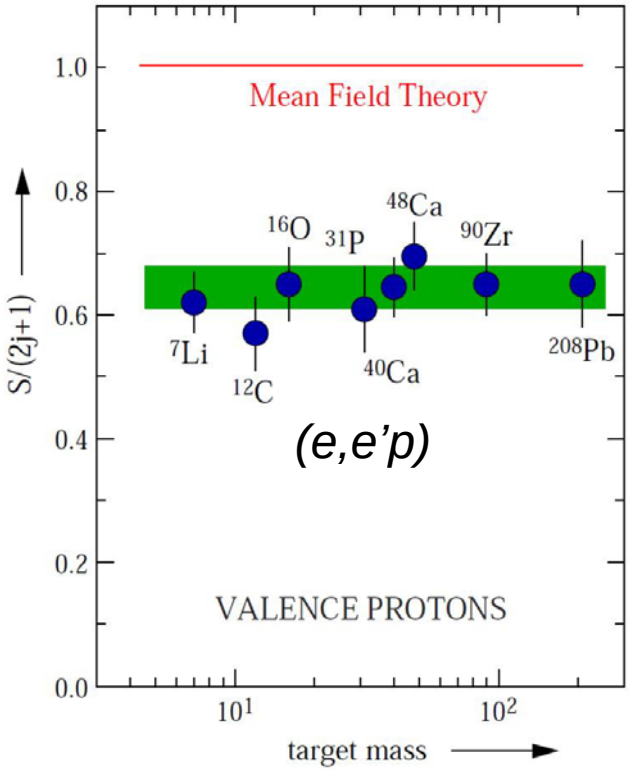
Exotic nuclei = inverse kinematics



A. Navin *et al.,* Phys. Rev. Lett. **85**, 266 (2000)

Deeply-bound nucleon removal

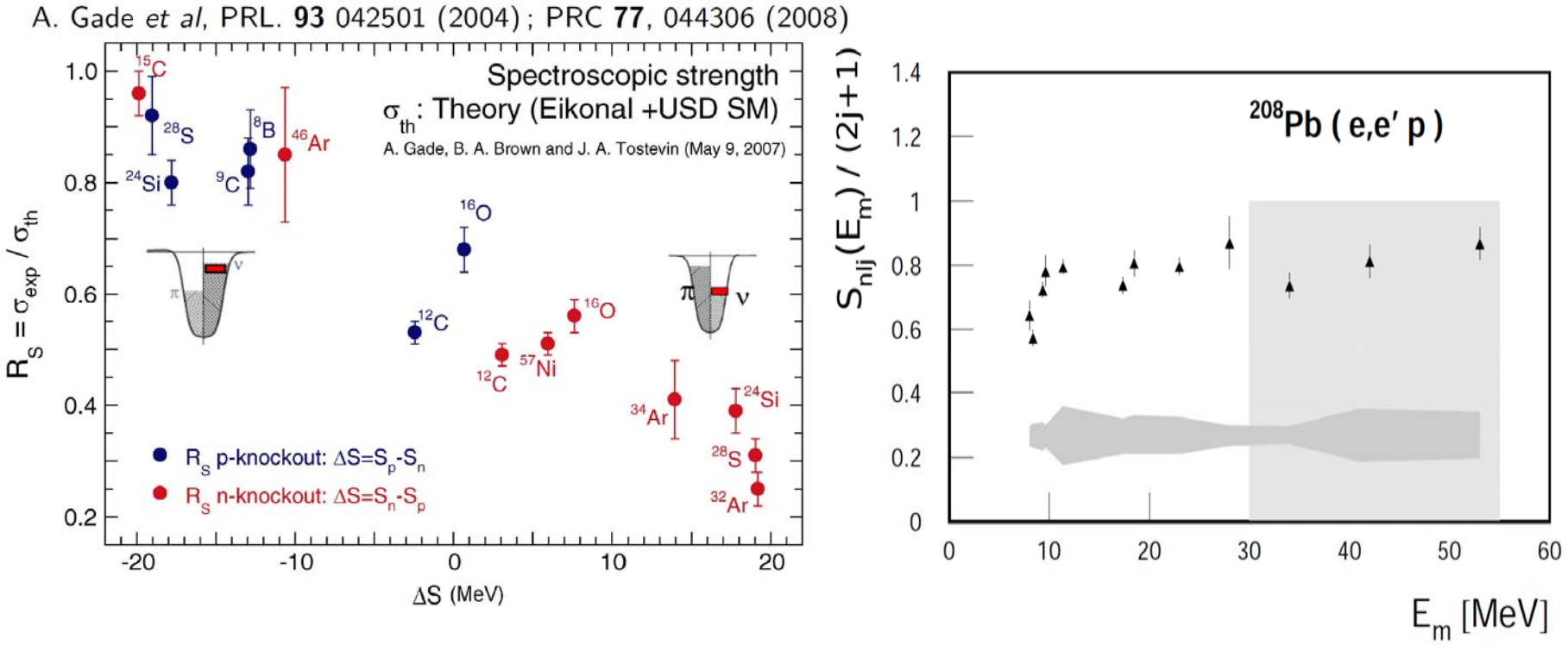




Intermediate-energy knockout

Disagreement between theory and experiment

Deeply-bound nucleon removal



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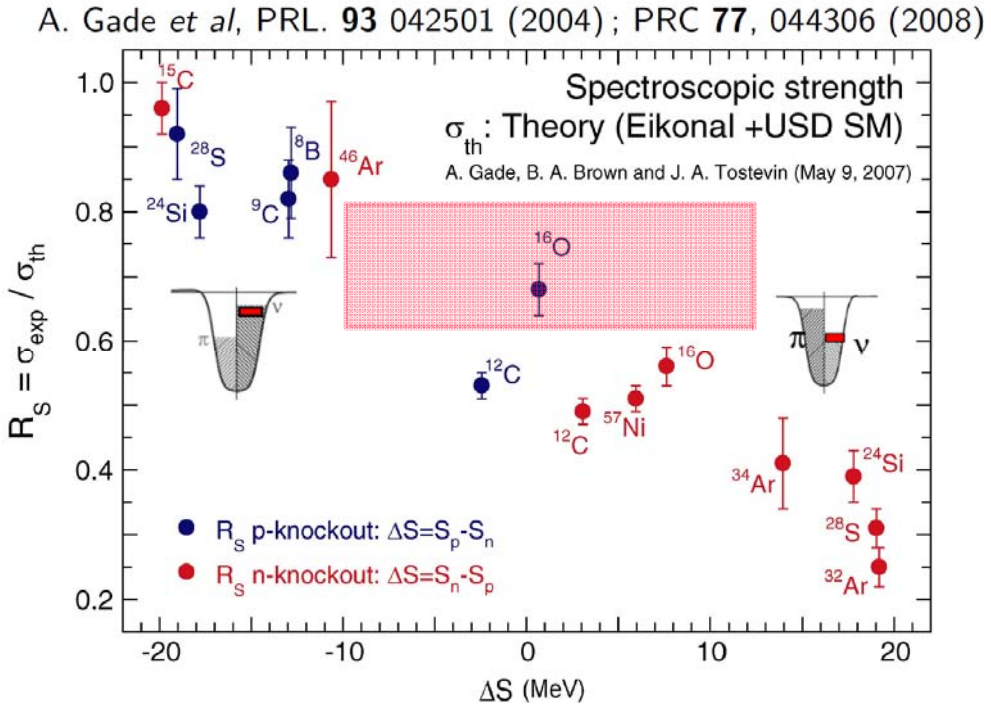
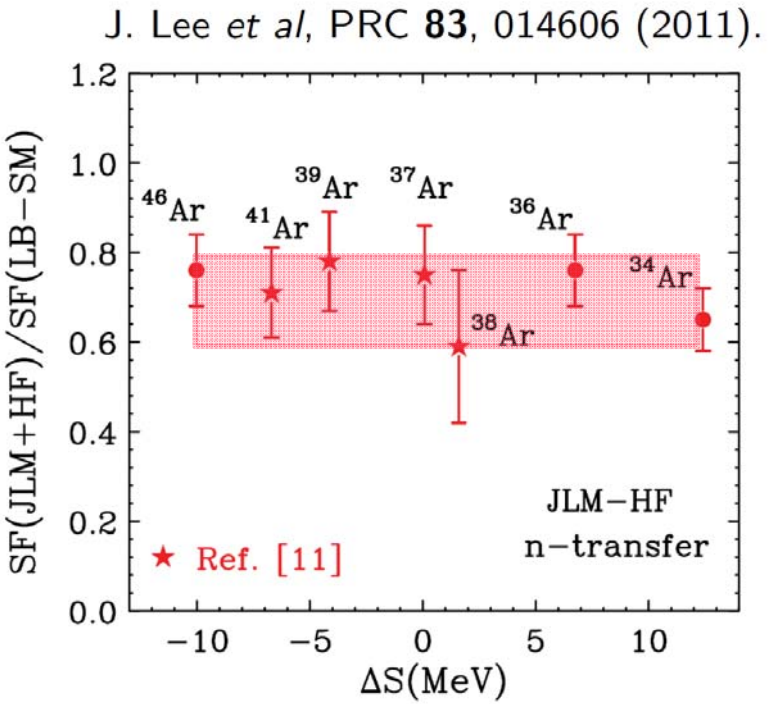




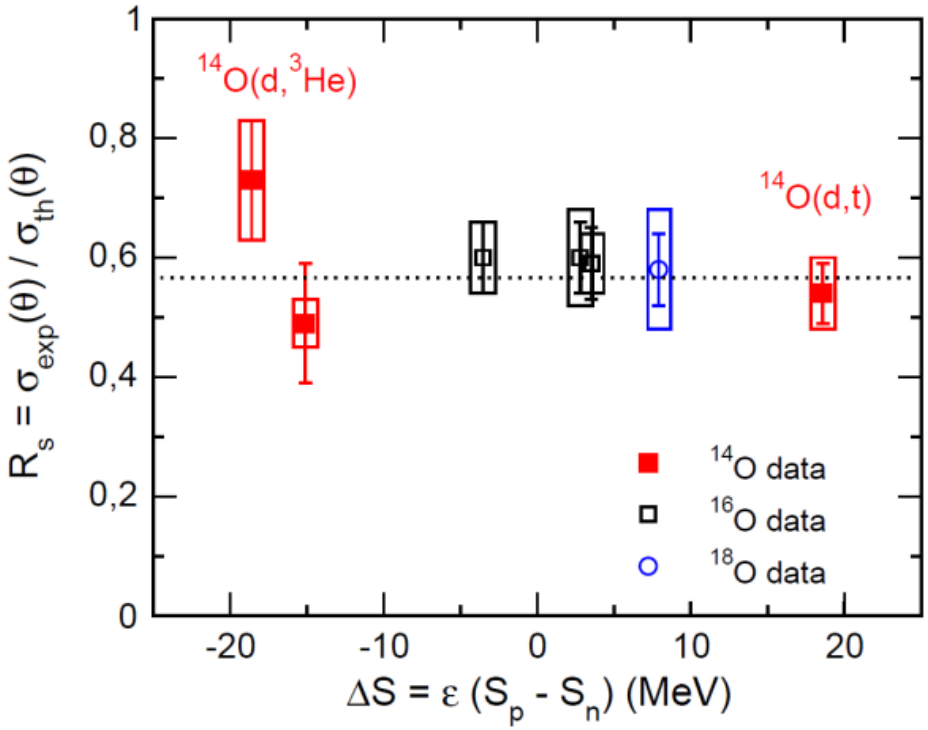
Intermediate-energy knockout
Disagreement between theory and experiment

Low energy transfer
Data up to ΔS=13 MeV

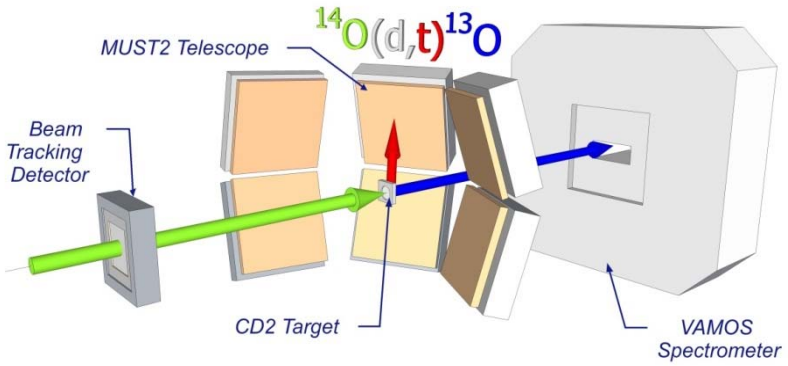
Applicability of reaction models to deeply-bound nucleon stripping?

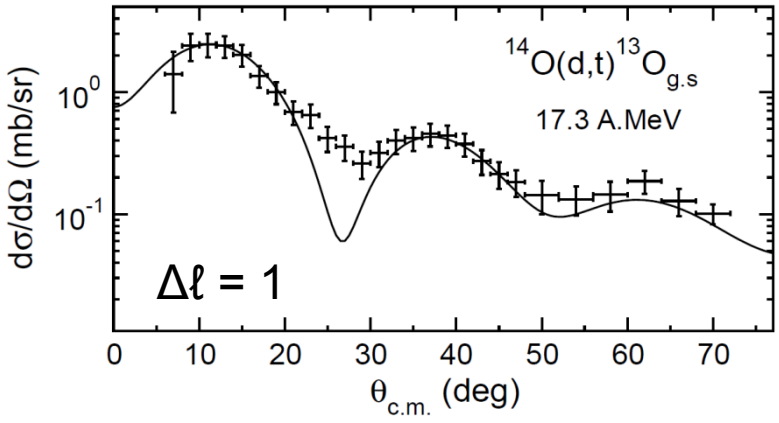
Oxygen isotopes via transfer

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



F. Flavigny *et al.,* Phys. Rev. Lett. **110**, 122503 (2013)



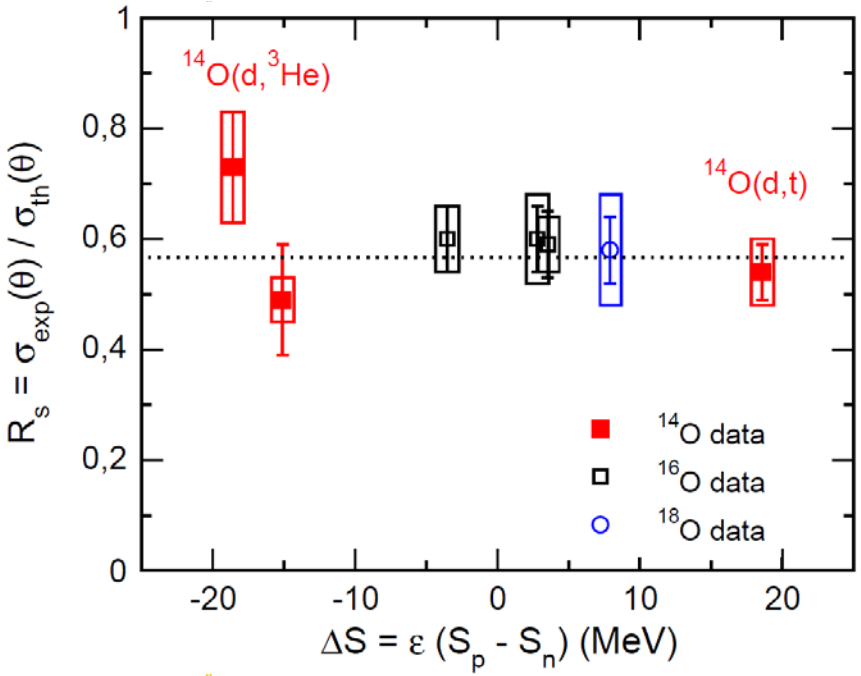


Conclusions

- **weak ΔS dependence**
- **Disagreement** between intermediate-energy nucleon removal and transfer analysis

Oxygen isotopes via transfer, results overview

F. Flavigny *et al.*, Phys. Rev. Lett. **110**, 122503 (2013)



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

$\Downarrow$ χ^2_{min}

$$R_s = \alpha \, . \, \Delta S + \beta$$

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

Oxygen isotopes via transfer, results overview

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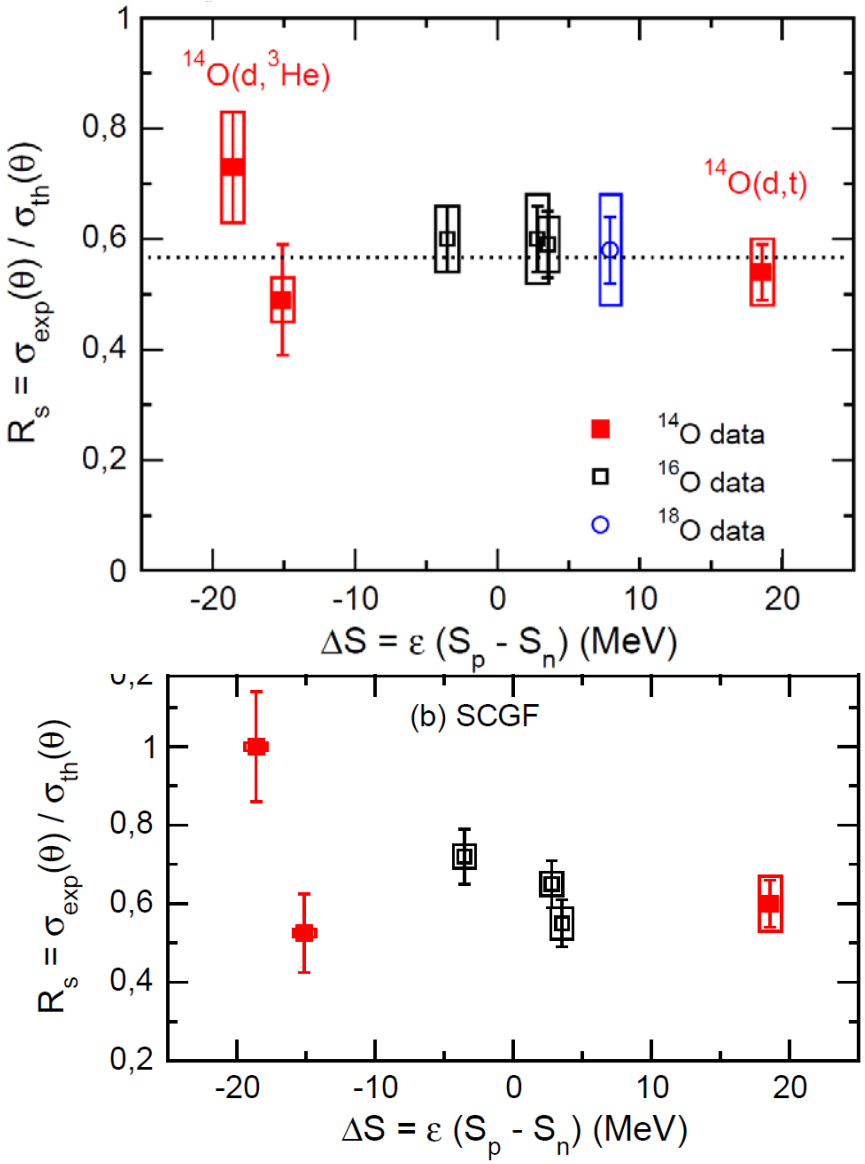

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Systematic error from 48 data sets

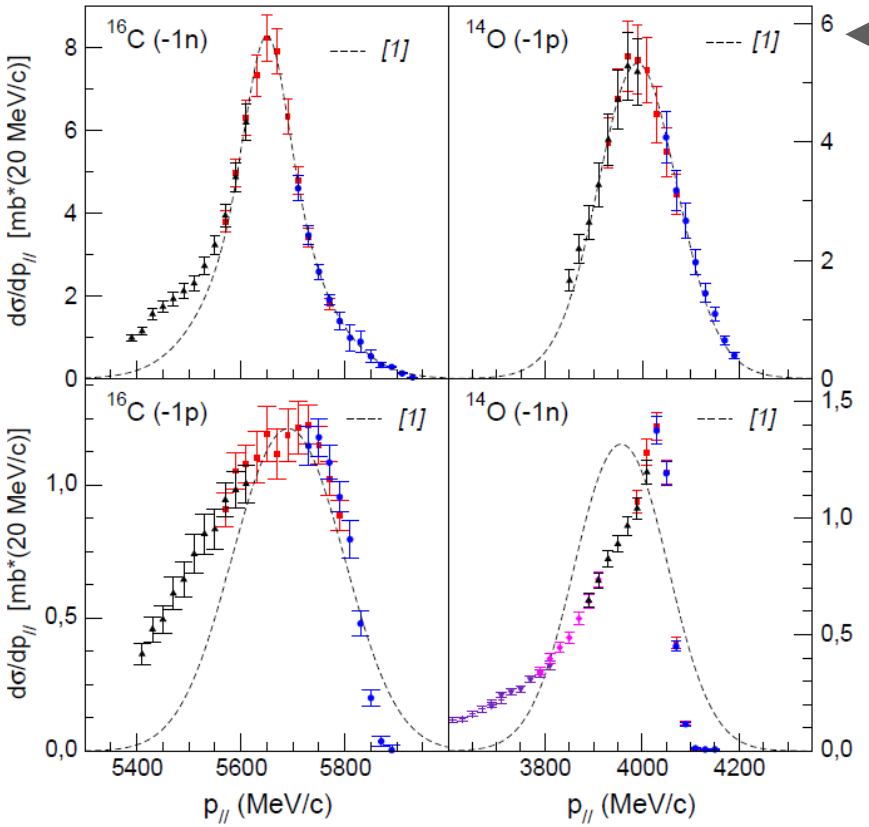
SCFG: α = -0.0042(28)(36) MeV^{-1}

More details on the analysis to be published, F. Flavigny *et al.* (2014) / new data from ^{18}Ne under analysis

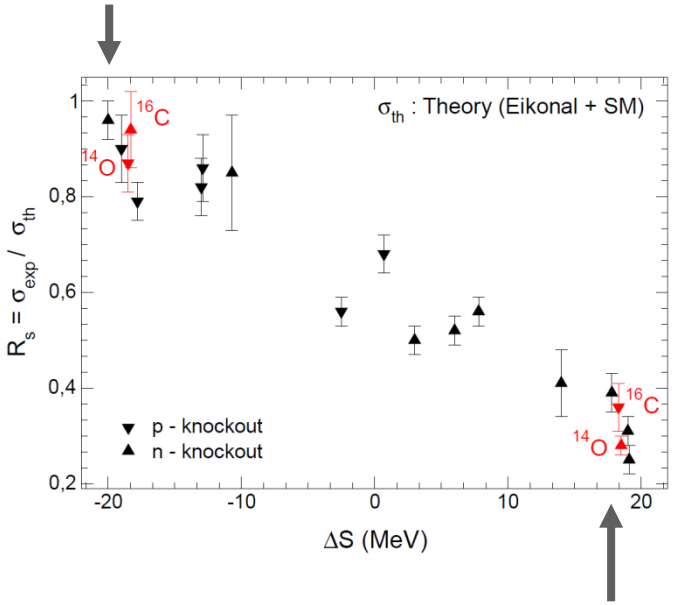
Intermediate-energy nucleon removal from ^{14}O,^{16}C (ΔS~19 MeV)

F. Flavigny *et al.*, Phys. Rev. Lett. **108,** 252501 (2012)

^{9}Be target, ^{14}O: 53 MeV/u, ^{16}C: 70 MeV/u, NSCL



← *Loosely-bound valence nucleon*



← *Deeply-bound valence nucleon*

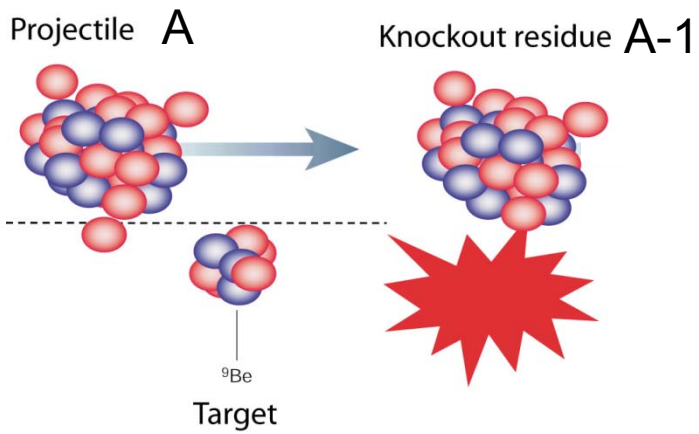
Open questions

- Microscopic origin of the observed **dissipative processes ?**
- **Incident-energy** dependence of the reaction process ?

Hypothesis: inelastic core-target processes

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

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

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

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

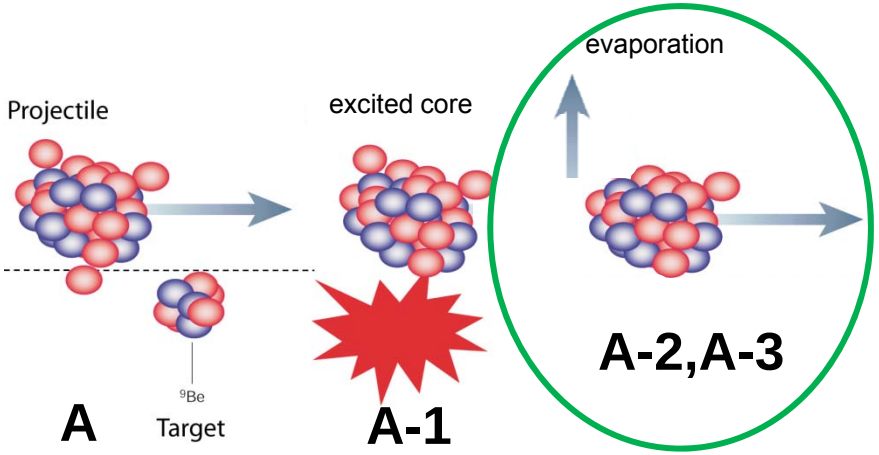
NN cross section

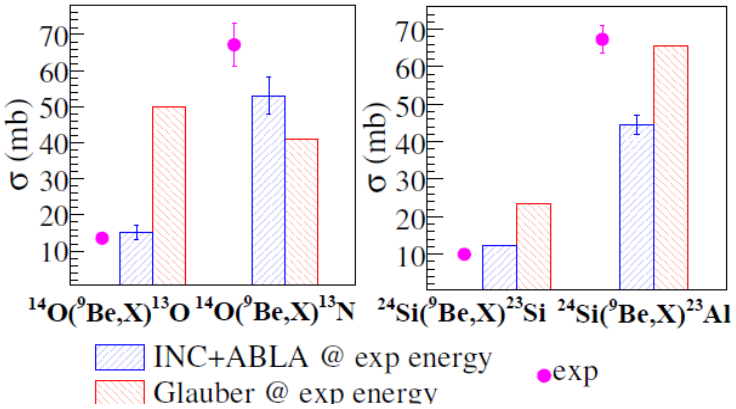
Core density

No explicit treatment of core excitations

Questioning the « inert core » approximation

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





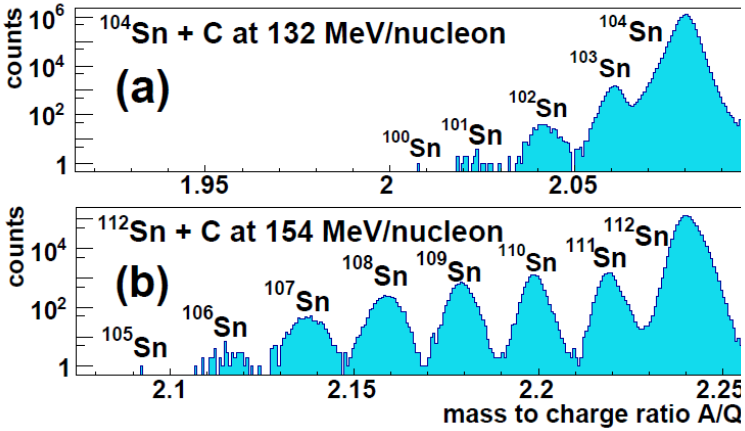
Reduction of the -1 nucleon removal cross section

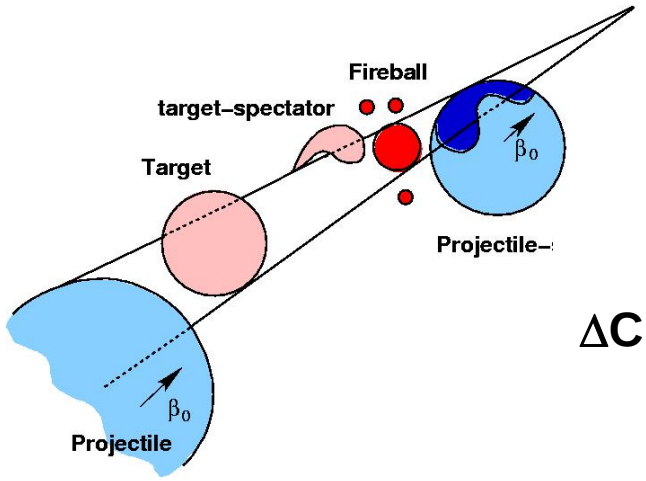
⇒ Importance of **core excitations** for loosely-bound cores and deeply-bound nucleons?

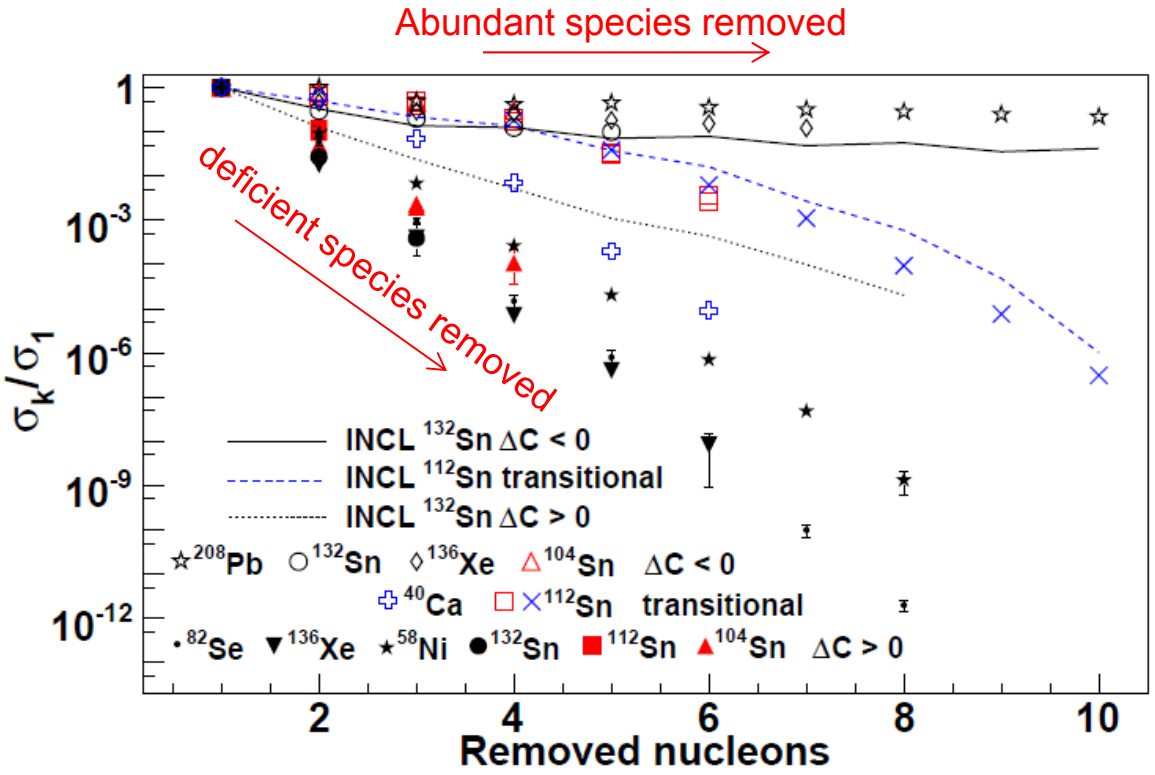
C. Louchart *et al.,* Phys. Rev. C **83**, 011601 (R) (2011).

Nucleon stripping from Sn isotopes at the RIBF - RIKEN

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







Important role of the “Evaporation cost”:

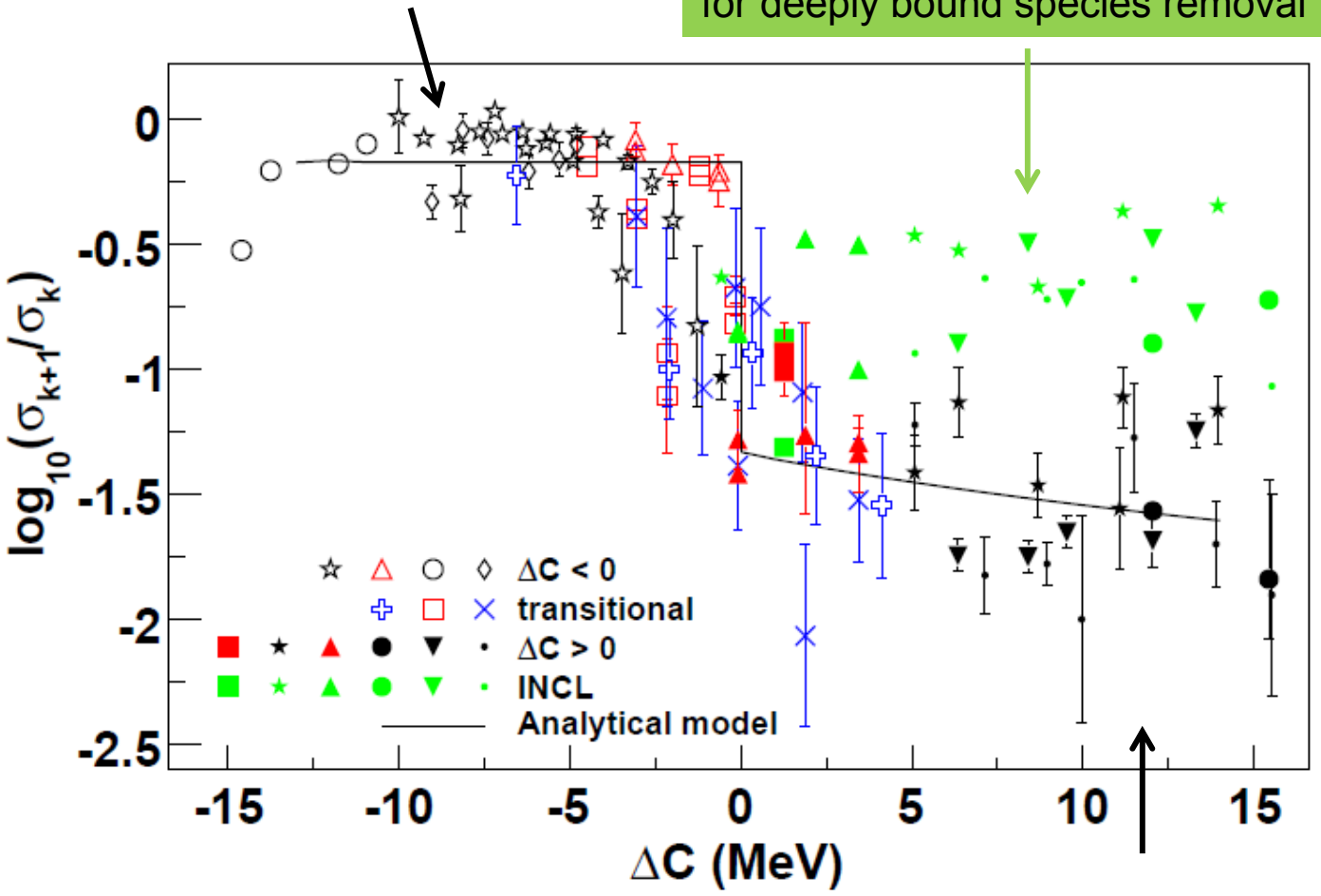
$\Delta C = S_p - S_n$ (if n removed) of the final nucleus (remnant)

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

Failure of intra-nuclear cascade for deeply-bound nucleon stripping

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

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

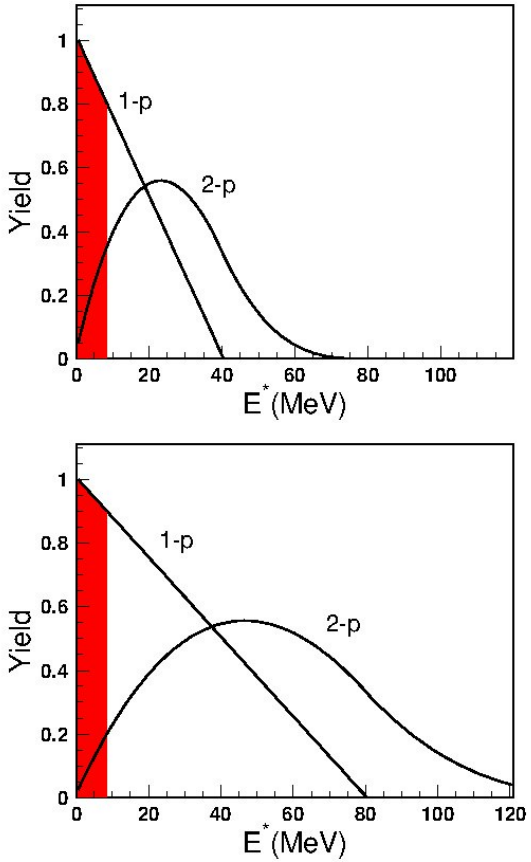


Neutrons from ^{104}Sn, ^{58}Ni

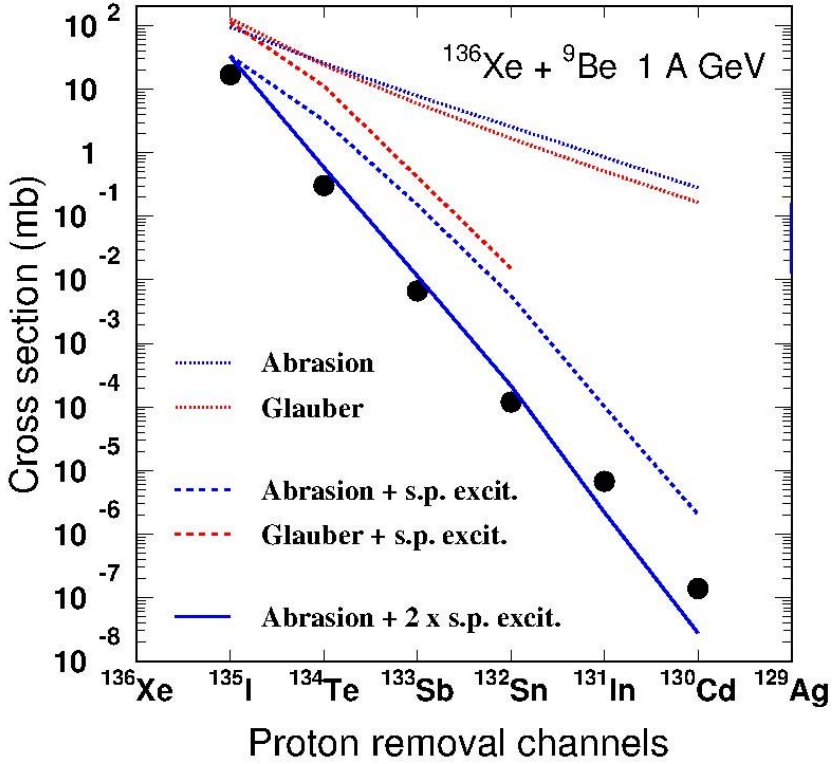
Nuclear excitation in proton knockout

Data interpretation

Slide from J. Benlliure, USC Spain



Abrasion – evaporation model

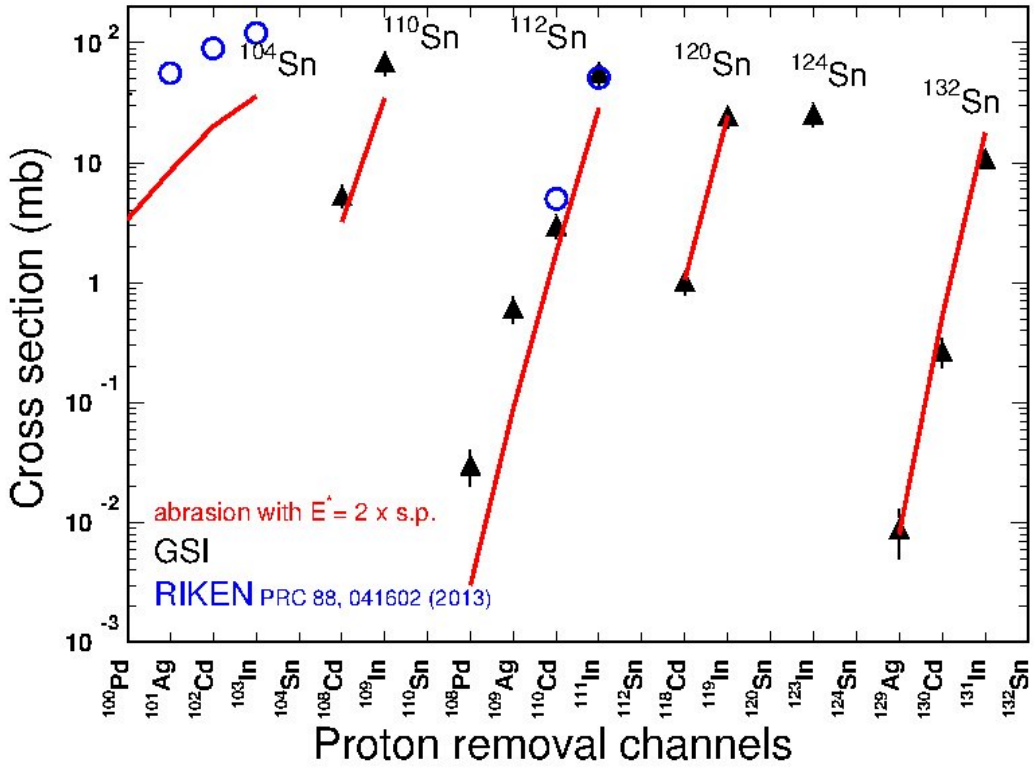


Excitation energy gained by the remnants seems to be larger than expected from particle-hole excitations

K.-H. Schmidt et al., PLB 300, 313 (1993)

Nuclear excitation in proton knockout

Isospin dependence of the proton-removal process



Slide from J. Benlliure, USC Spain

Nucleon Stripping from Exotic Nuclei

- Discrepancy between experimental and eikonal theory for well-bound nucleon removal at E ~ 60 - 100 MeV/nucleon

  A. Gade *et al.,* Phys. Rev. C **77**, 044306 (2008).
  F. Flavigny *et al.,* Phys. Rev. Lett. **108**, 252501 (2012).

- No such effect for low-energy transfer

  J. Lee *et al.,* Phys. Rev. C. **83**, 014606 (2011).
  F. Flavigny *et al.,* Phys. Rev. Lett. **110**, 122503 (2013).
  F. Flavigny *et al.,* in preparation (2014).

- hypothesis for a **strong core-target inelastic excitation in asymmetric nuclei** in case of intermediate-energy stripping of deeply bound nucleons

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

- Similar discrepancy with intra-nuclear cascade for high-energy nucleon stripping cross sections

  L. Audirac *et al.,* Phys. Rev. C **88**, 041602 (2013).
  J. Benlliure, DREB conference (2014).

- **Intermediate and low energy analysis give inconsistent structure results in some cases**
- **Specificities of weakly bound nuclei**
- **Inelastic processes in knockout still to be described microscopically and studied**

Irfu

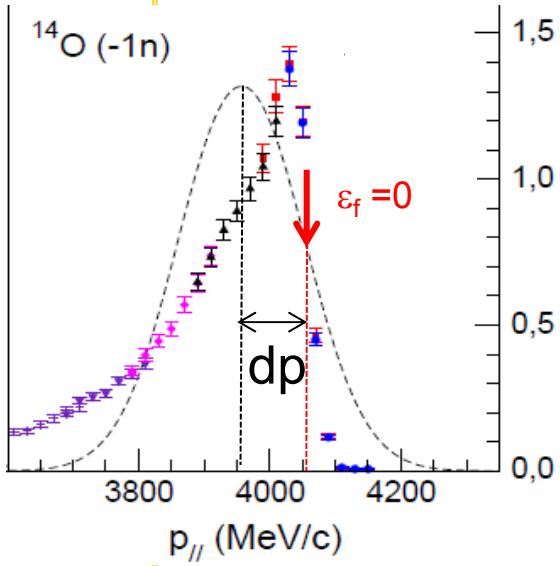
Thank you!

F. Flavigny, S. Boissinot, A. Corsi, A. Gillibert, V. Lapoux, L. Nalpas, A.Obertelli, E.C. Pollacco,
A. Signoracci, CEA Saclay
D. Beaumel, S. Giron, J. Guillot, F. Hammache, B. Lecron, A. Matta, Morfouace, N. de Séreville, *IPN Orsay*
B. Bastin, G. Burgunder, A. Lemasson, R. Raabe, M. Rejmund, A. Shrivastava, *GANIL Caen*
J. Gibelin, *LPC Caen*
N. Keeley, *NCNR Warsaw*
C. Barbieri, A. Cippolone, *U. Of Surrey*
P. Navratil, Triumf

NSCL B.A. Brown, D. Bazin, A. Gade
GANIL G. Grinyer
U. Of Pisa A. Bonaccorso

RIKEN Nishina center H. Baba, P. Doornenbal, T. Isobe, J. Lee, T. Motobayashi, H. Sakurai, S. Takeuchi
CEA Saclay L. Audirac, S. Boissinot, A. Corsi, V. Lapoux, A. Obertelli, E.C. Pollacco, C. Santamaria
CNS M. Matsushita, S. Ota, D. Steppenbeck
RCNP N. Aoi
University of Tokyo K. Matsui, R. Taniuchi
Ryokko University Y. Shiga
ATOMKI D. Sohler
CSIC Madrid A. Jungclaus
SKLNPT, Peking University H. Wang
IFJ Pan Cracow P. Bednarczyk, M. Ciemala

High-momentum cutoff



$$P_{//} = \sqrt{(T_p - S_n - \varepsilon_f)^2 + 2m\ (T_p - S_n - \varepsilon_f)}$$

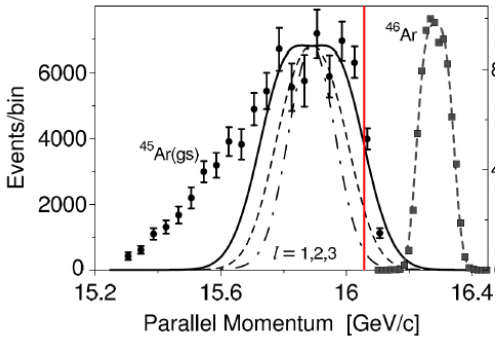
ε_f= kinetic energy of the fragments (nucleon + target) in the lab. frame

Momentum threshold (CUT) for ε_f =0

A. Bonaccorso, Phys. Rev. C **60**, 054604 (1999).

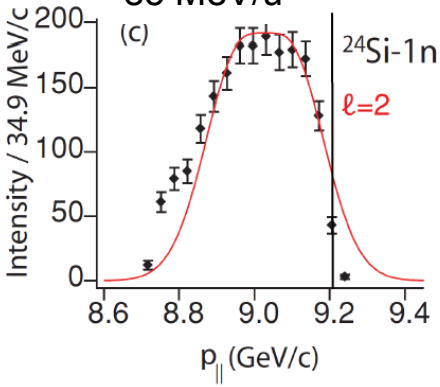
"barely visible" effect in published data

70 MeV/u



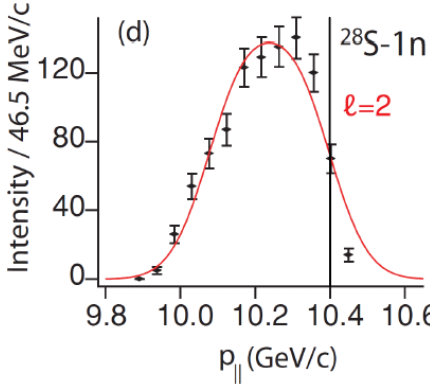
A. Gade *et al.*, PRC **71**, 051301 (2005).

85 MeV/u

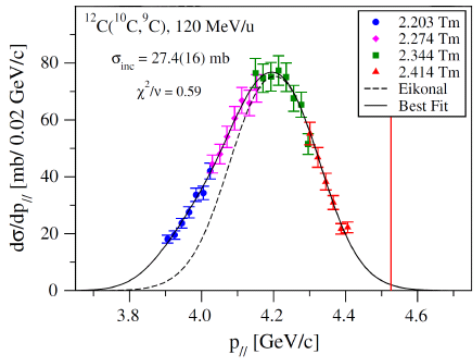


A. Gade *et al.*, PRC **77**, 044306 (2008).

80 MeV/u



120 MeV/u

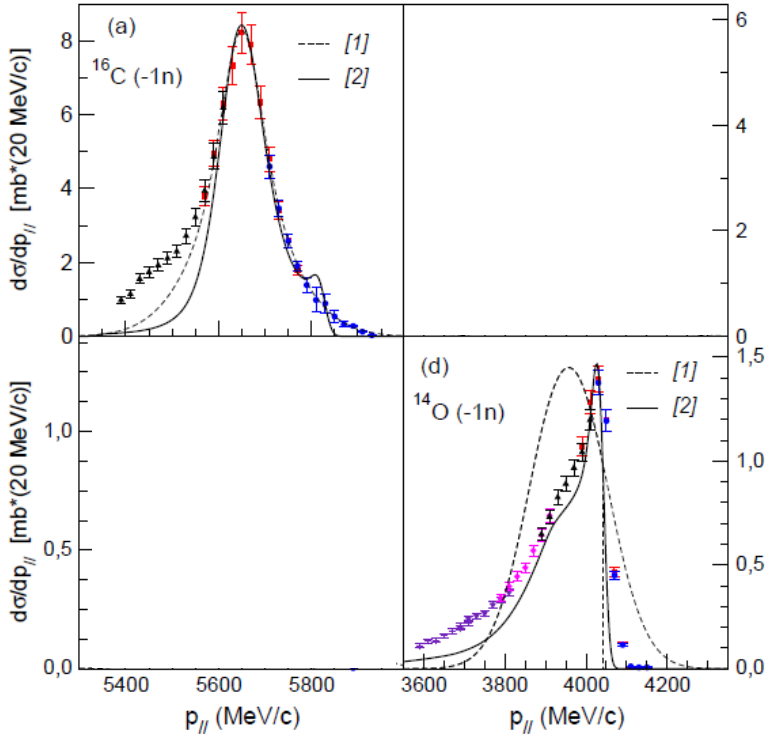


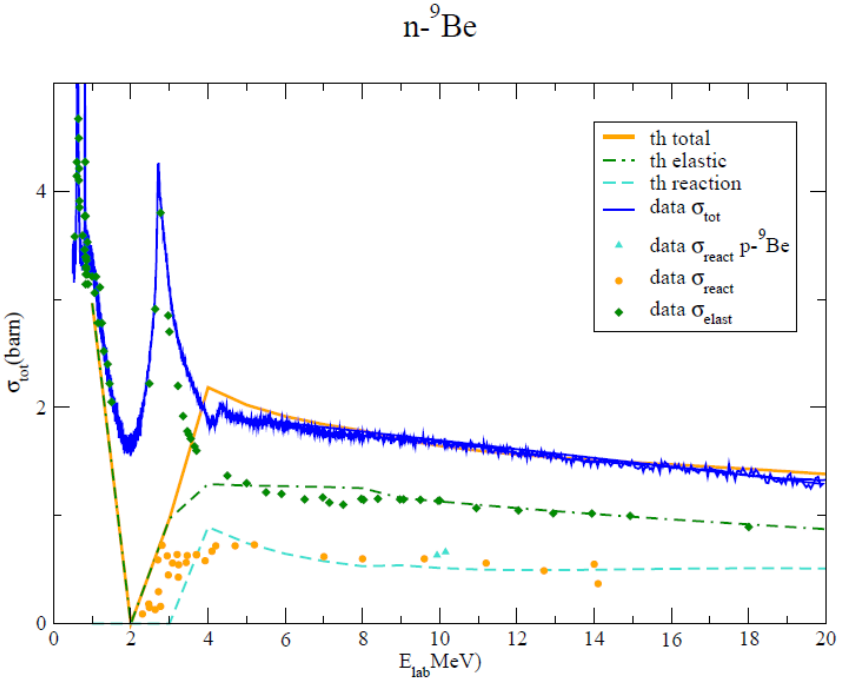
G. Grinyer *et al.*, PRL **106**, 162502 (2011).

Transfer to the continuum model

Intrinsic momentum of the neutron + energy-dependent n-^{9}Be potential taken into account

A. Bonaccorso and D.M. Brink, Phys. Rev. C **43**, 299 (1991); A. Bonaccorso and G.F. Bertsch, Phys. Rev. C **63**, 044604 (2001)





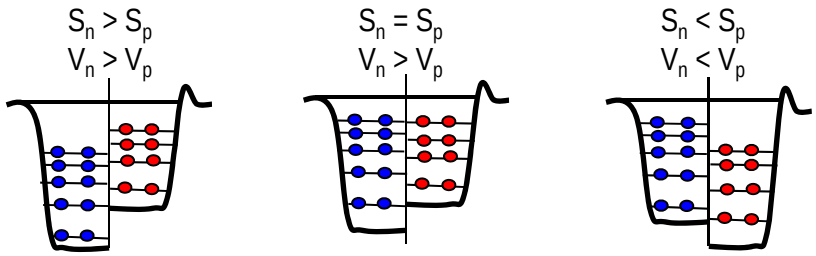
[Courtesy A. Bonaccorso]

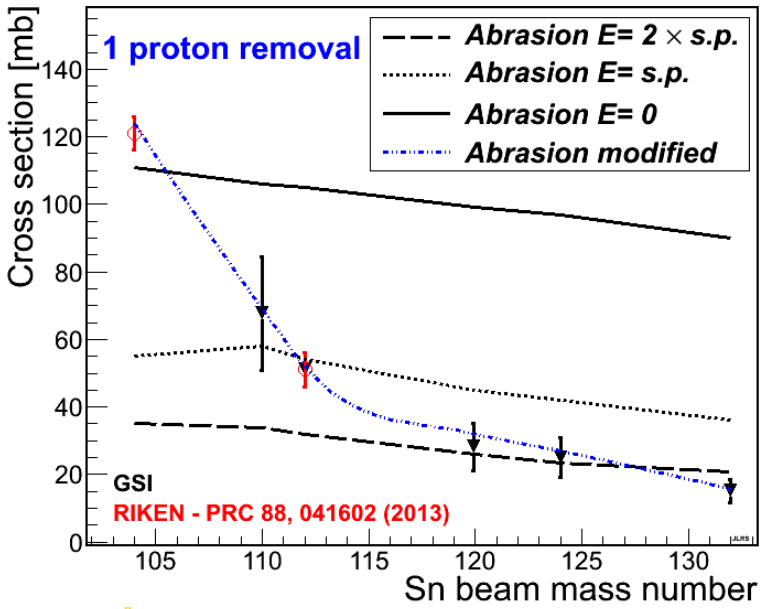
Inputs:

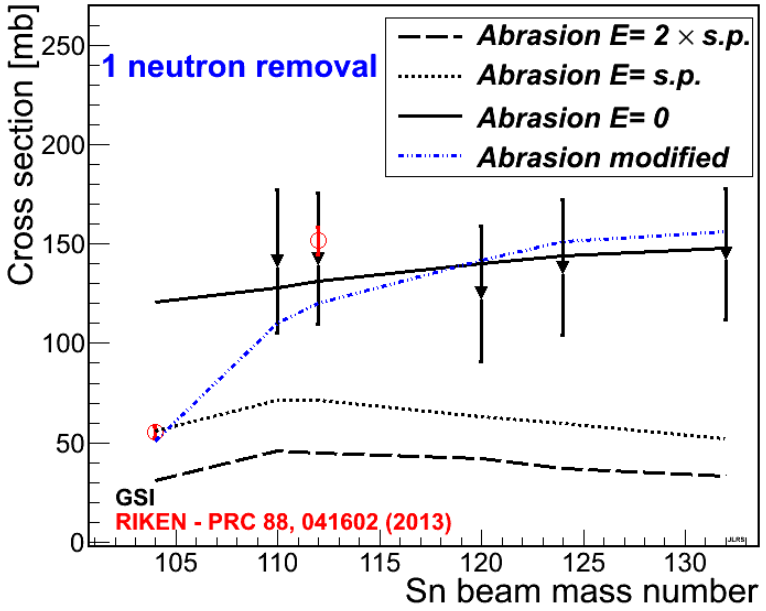
- Neutron single-particle wave function (from HF, Skyrme interaction)
- Core-target S matrix (from eikonal theory)
- n-^{9}Be potential (adjusted on n-^{9}Be cross section data)

Isospin dependence of the nucleon-removal process

Slide from J. Benlliure, USC Spain







The excitation energy induced by nucleon removal seems to be enhanced for the deficient species in systems with large neutron-proton asymmetries.