Probing single-particle properties of nuclei with (*p*,*pN*) reactions

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Reaction Seminar Series 2020
reactionseminar.github.io
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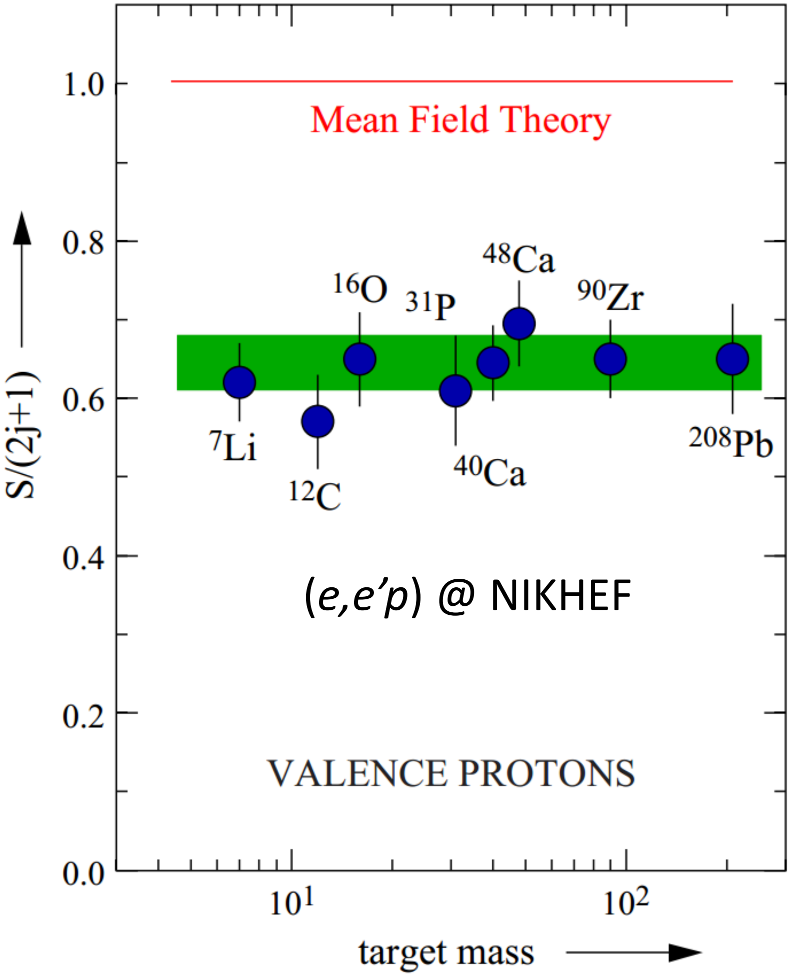
Outline

1. Quenching of spectroscopic factor
2. Knockout reactions (*p,pN*) with DWIA
3. Results with GSI R^{3}B/LAND data
4. Molecular orbital study with ^{9}Be(*p,pn*)^{8}Be

Part 1

Quenching of spectroscopic factor



L. Lapikás, NPA **553**, 297 (1993)

Spectroscopic factor (SF) = norm of the overlap between reality and pure single-particle picture

For stable nucleus, SF is quenched to 60%-70% due to short-range and long-range correlations.

V.R. Pandharipande et al., RMP **69**, 981 (1997)
W. Dickhoff, C. Barbieri, PPNP **52**, 377 (2004)
I. Sick, PPNP **59**, 447 (2007)
W. Dickhoff, JPG **37**, 064007 (2010)

Experimentally, often quantified as the reduction factor

$$R_S = \frac{\sigma_{exp}}{\sigma_{th}} \approx \frac{SF_{exp}}{SF_{th}}$$

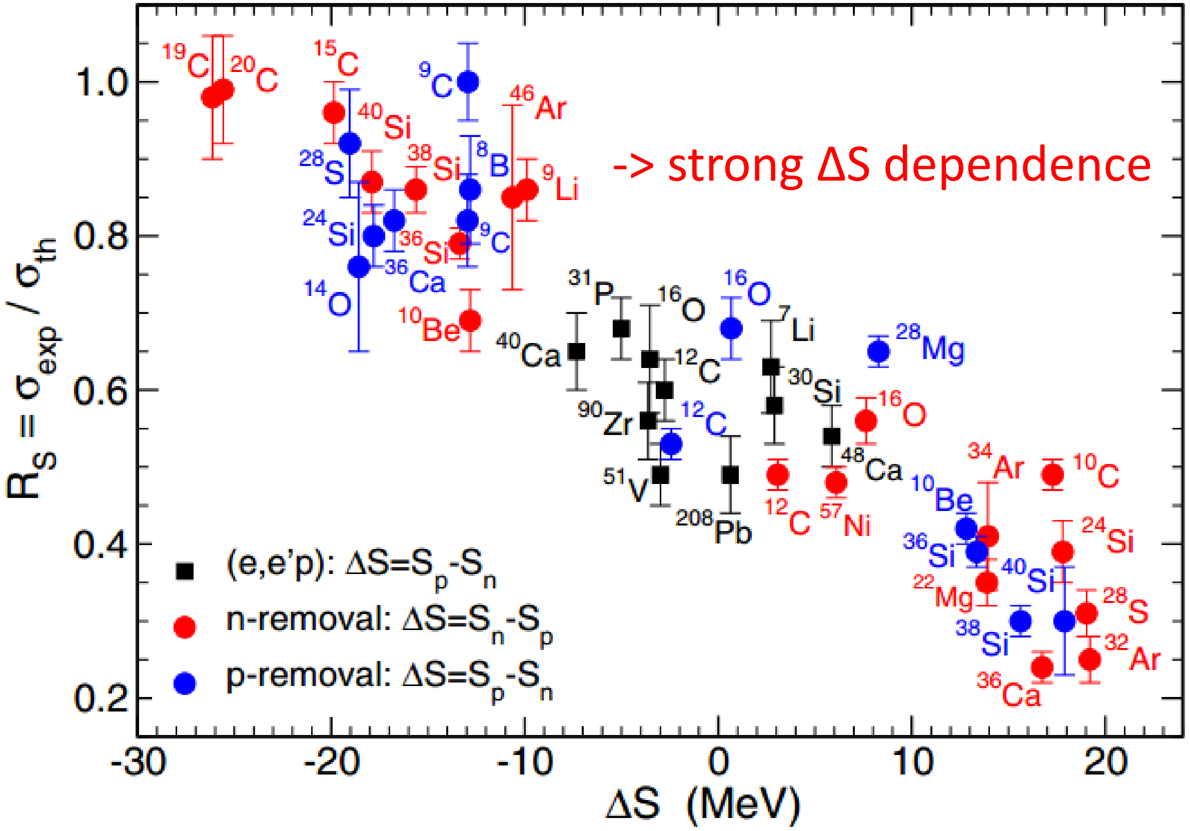
Nomenclature

Nucleon removal for ^{9}Be(^{16}O,^{15}N)X or ^{12}C(^{16}O,^{15}N)X, often referred to as heavy-ion knockout, breakup.

Knockout for (*p,pN*), (*e,e'p*), often referred to as quasifree scattering

Proton-neutron asymmetry dependence
Nucleon removal reaction

Weakly bound $\Delta S = S_{p(n)} - S_{n(p)}$ Strongly bound

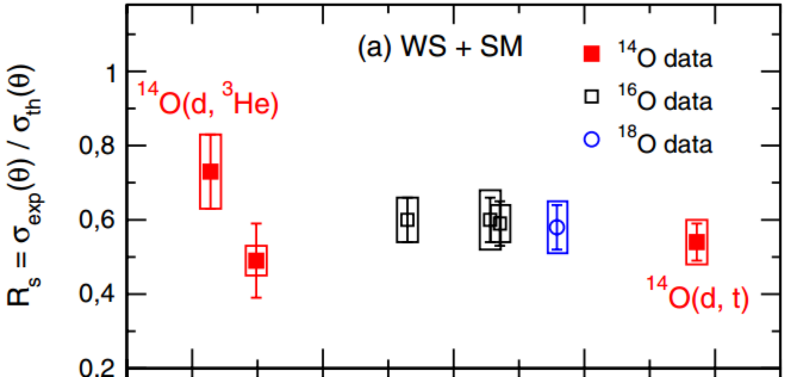


-> strong ΔS dependence

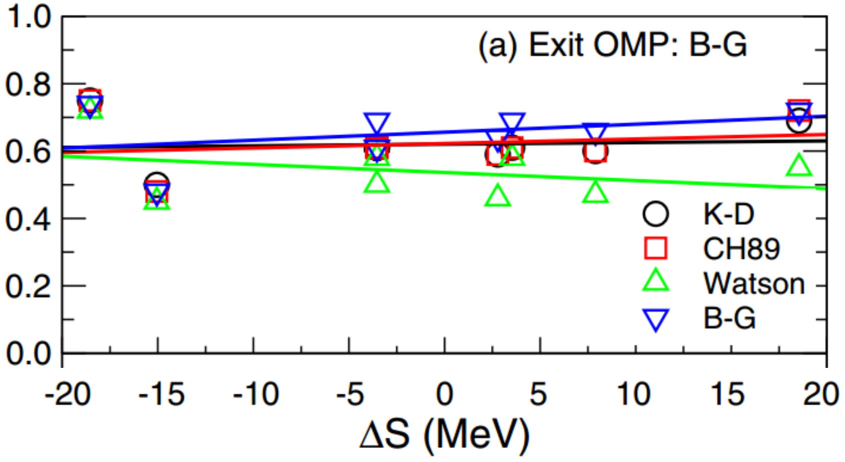
J. Lee et al., PRC **73**, 044608 (2006)
A. Gade et al., PRC **77**, 044306 (2008)
J.A. Tostevin, A. Gade, PRC **90**, 057602 (2014)

Transfer reactions 1

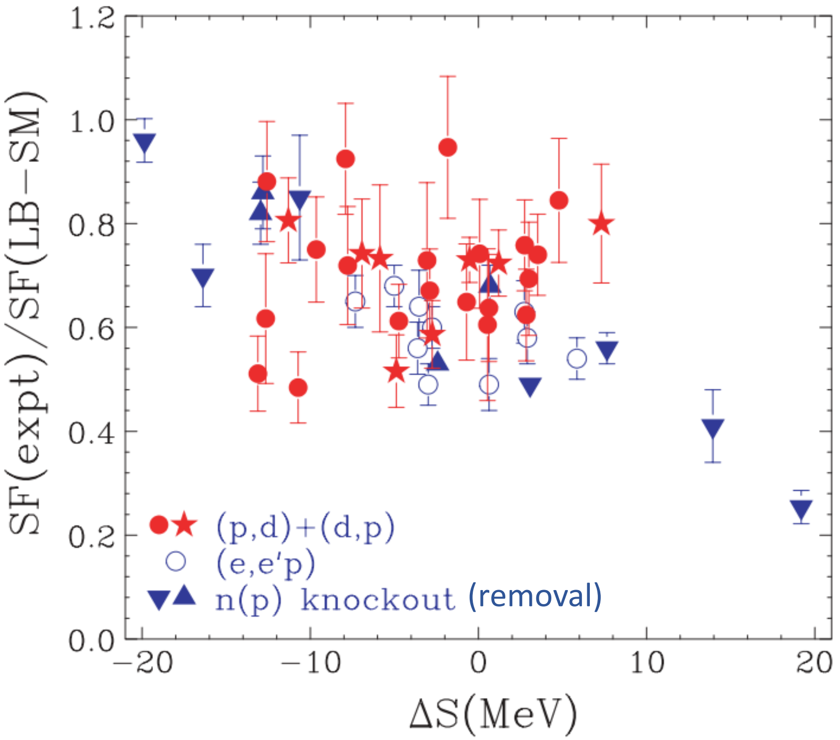
-> No strong ΔS dependence observed



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



F. Flavigny et al., PRL **97**, 034601 (2018)

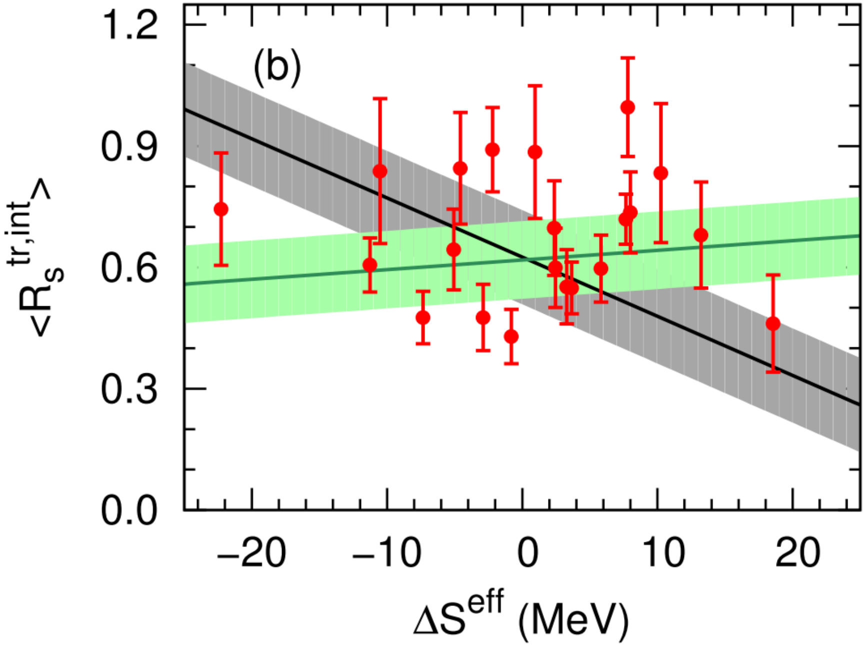


J. Lee et al., PRC **73**, 044608 (2006),
PRC **75**, 064320 (2007),
and PRL **104**, 112701 (2010)

See Juan José Manfredi's talk June 25

Transfer reactions 2

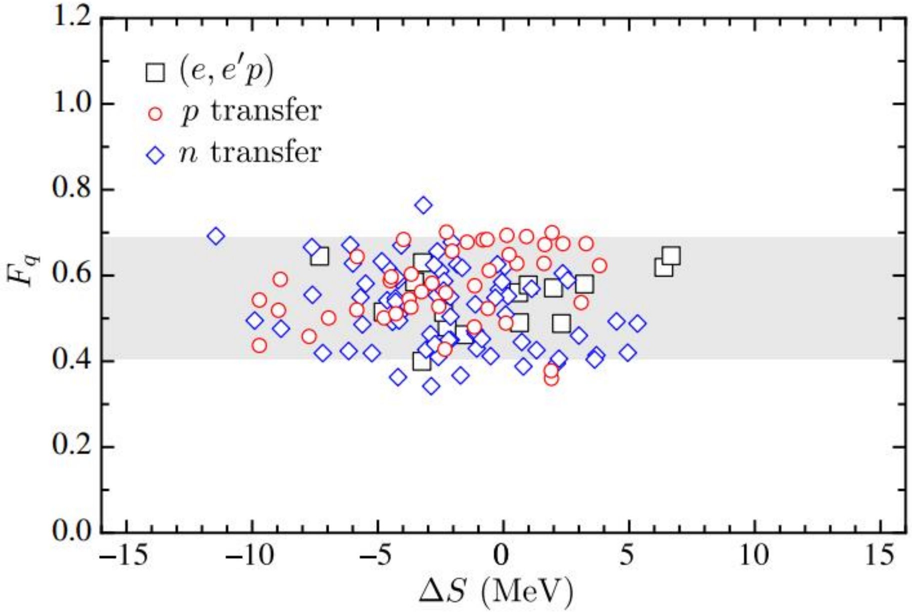
-> No strong ΔS dependence observed



X.P. Xu et al., PLB **790**, 308 (2019)

Transfer reduction factor defined in an inclusive form

$$R_s^{\text{tr,int}} = \frac{\sum_i \sigma_i^{\text{exp,int}}}{\sum_i \text{SF}_i^{\text{th}} \sigma_i^{\text{th,int}}}$$



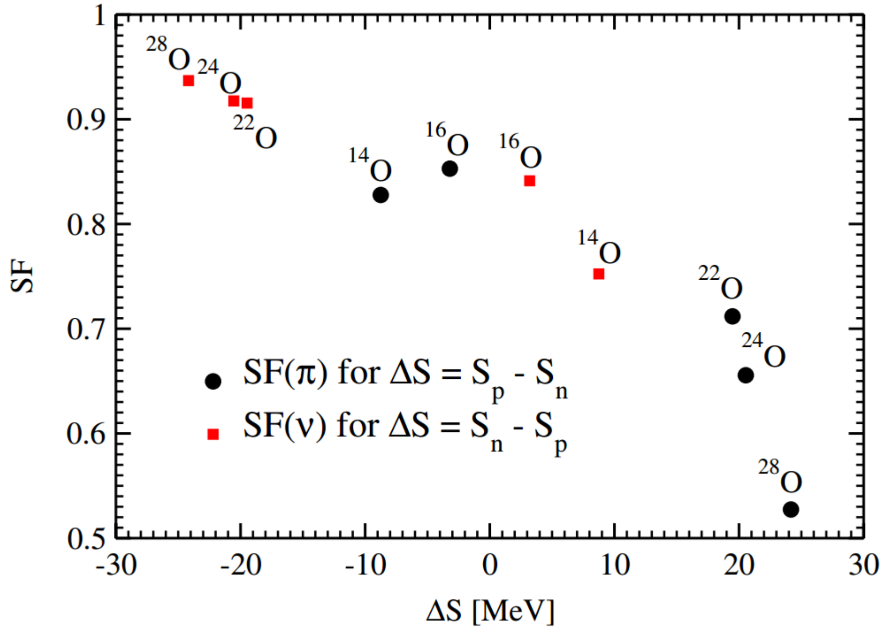
B.P. Kay et al., PRL **111**, 042502 (2013)

$$F_q \equiv \frac{1}{(2j+1)}\left[\Sigma\left(\frac{\sigma_{\text{exp}}}{\sigma_{\text{DW}}}\right)_j^{\text{add}} + \Sigma\left(\frac{\sigma_{\text{exp}}}{\sigma_{\text{DW}}}\right)_j^{\text{rem}}\right]$$

Microscopic calculation

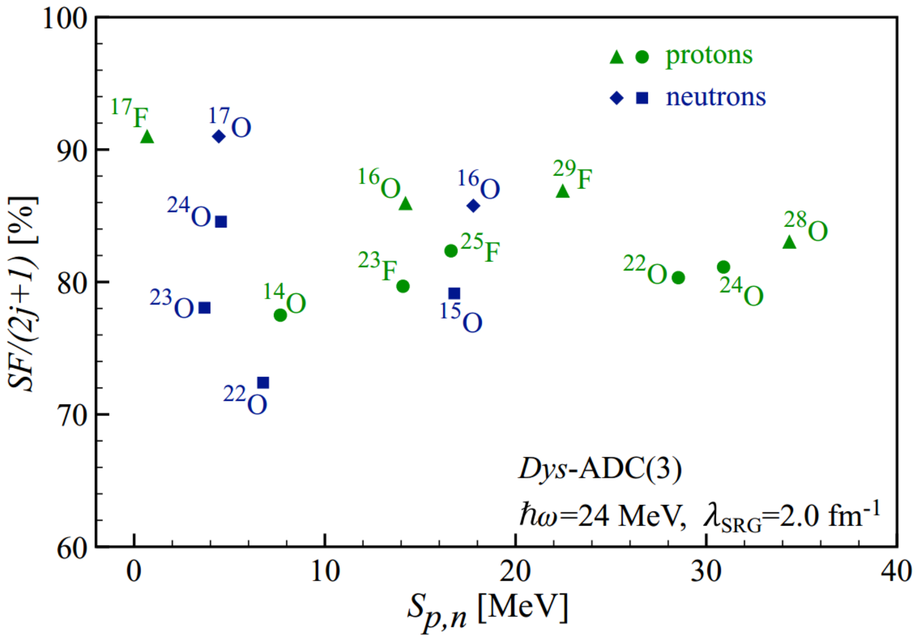
Quenching due to: SRC + LRC

-> Not conclusive



Coupled Cluster

Ø. Jensen et al., PRL **107**, 032501 (2011)



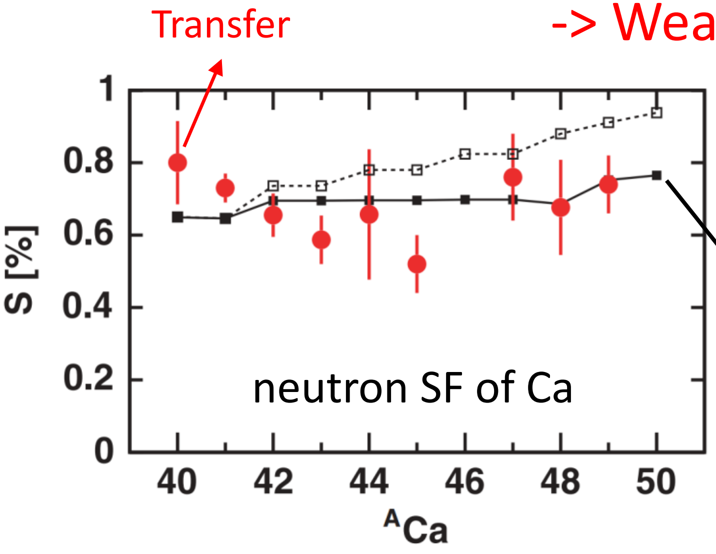
SCGF

A. Cipollone et al., PRC **92**, 014306 (2015)

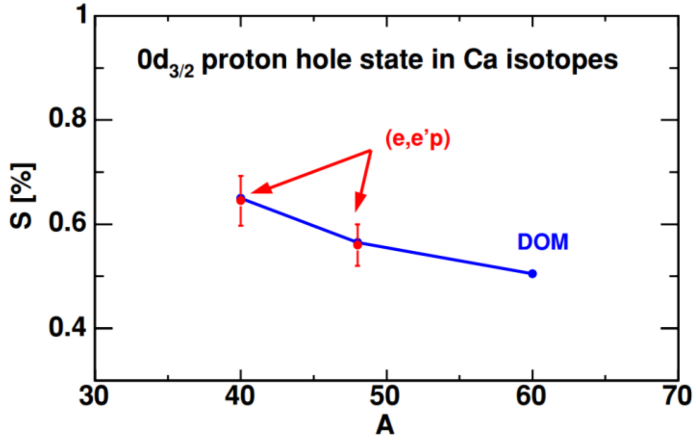
C. Barbieri, PRL **103**, 202502 (2009)

Dispersive Optical Model (DOM) analysis

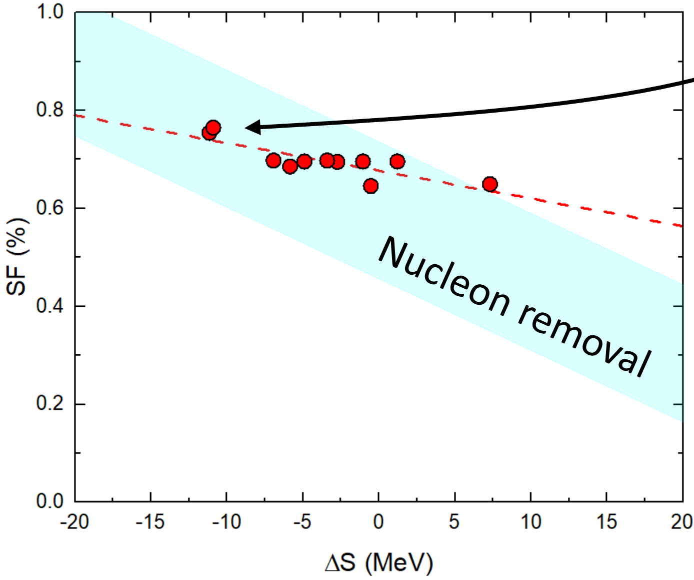
-> Weak ΔS dependence



R.J. Charity et al., PRC **76**, 044314 (2007)



W.H. Dickhoff, JPG **37**, 064007 (2010)



Replotted as function of ΔS

For recent DOM review see:
W.H. Dickhoff et al., JPG **44,** 033001 (2017)
and PPNP **105**, 252 (2019)

Why it is important ?

For nuclear structure and interaction

- Validation of single-particle picture (IPM, SM…)
- Information of nucleon-nucleon (NN) interaction: hard-core, tensor parts
- Emergent effects of exotic nuclei (very neutron/proton-rich nuclei)

For nuclear reaction

- Reliability of common reaction models used to extract SF

see A. Bonaccorso’s, N. Timofeyuk’s, and J. Manfredi’s talk for more discussion about nucleon removal and transfer mechanism

Biggest question: the slope of R_S as function of ΔS

Solution

Use a 3rd kind of reaction -> proton-induced nucleon knockout reaction (*p*,*pN*)

Proton-induced nucleon knockout (*p,pN*) (“quasifree scattering”)

Reaction models for inverse kinematics (*p,pN*) data:

(partial-wave) Distorted Wave Impulse Approximation (DWIA)
G. Jacob, Th.A.J. Maris, RMP **38**, 121 (1966); **45**, 6 (1973)
T. Wakasa, K. Ogata, T. Noro, PPNP **96**, 32 (2017)

Eikonal-DWIA
T. Aumann, C.A. Bertulani, J. Ryckebusch, PRC **88**, 064610 (2013)

Transfer-to-the-continuum in CDCC framework (TC)
A.M. Moro, PRC **92**, 044605 (2015)

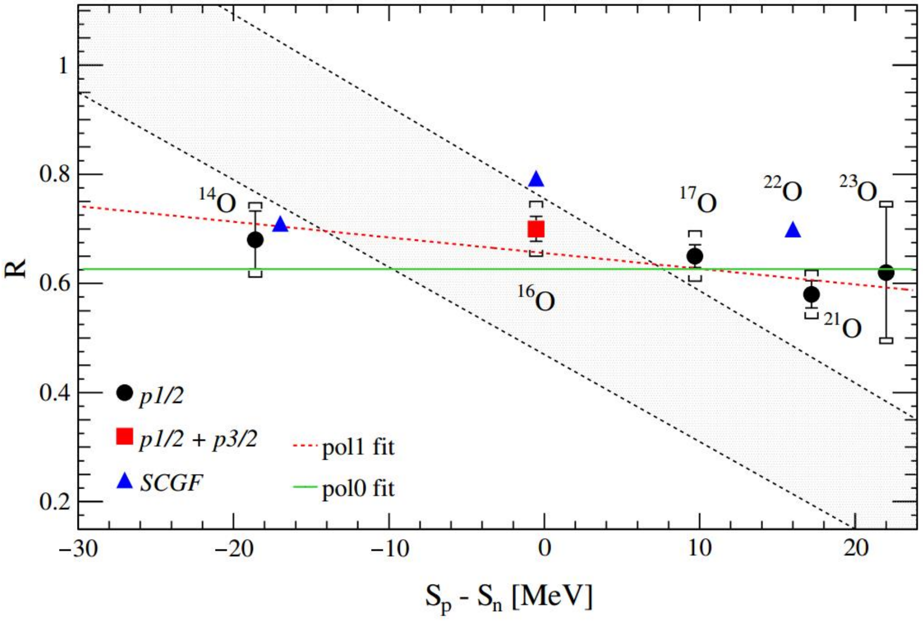
Mario Gómez-Ramos’s talk
March 26

Faddeev eqn. in Alt-Grassberger-Sandhas form (FAGS)
R. Crespo et al., PRC **77**, 024601 (2008)
R. Crespo, E. Cravo, A. Deltuva, PRC **99**, 054622 (2019)

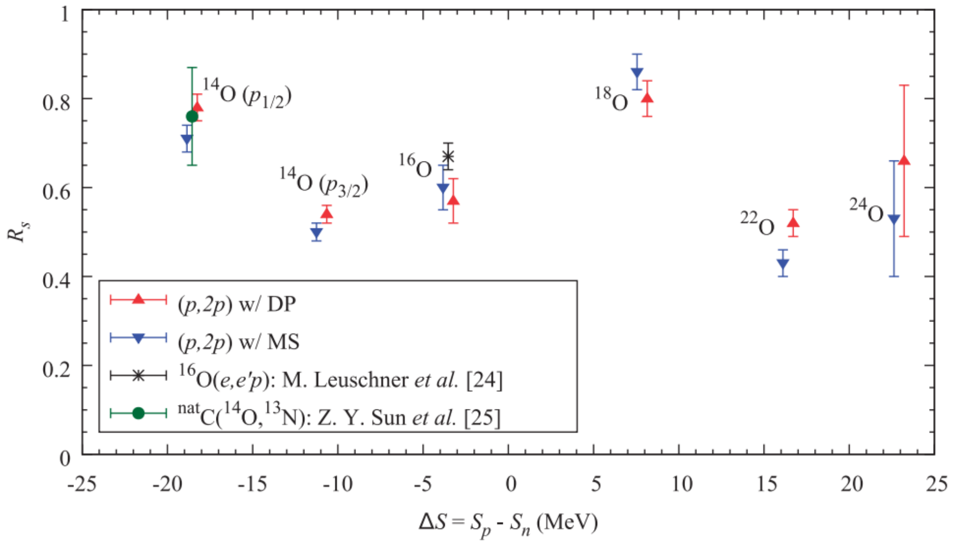
Proton-induced nucleon knockout (*p,pN*)

-> No strong ΔS dependence observed either

GSI R^3B/LAND data



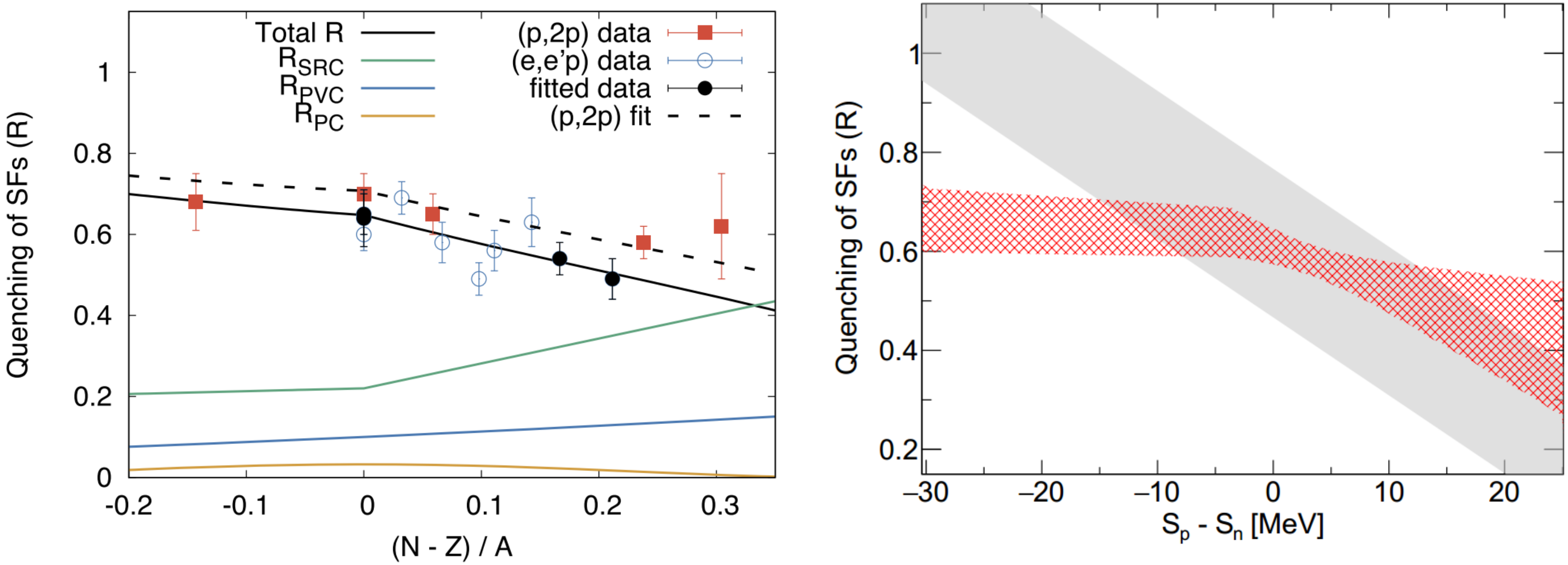
RIKEN-RCNP data



S. Kawase et al., PTEP **2018**, 021D01 (2018): DWIA

L. Atar et al., PRL **120**, 052501 (2018): eikonal-DWIA
P. Díaz Fernández et al., PRC **97**, 024311 (2018): FAGS
M. Gómez-Ramos, A.M. Moro, PLB **785**, 511 (2018): TC
M. Holl et al., PLB **795**, 682 (2019): eikonal-DWIA

Phenomenological study



S. Paschalis et al., PLB **800**, 135110 (2020)

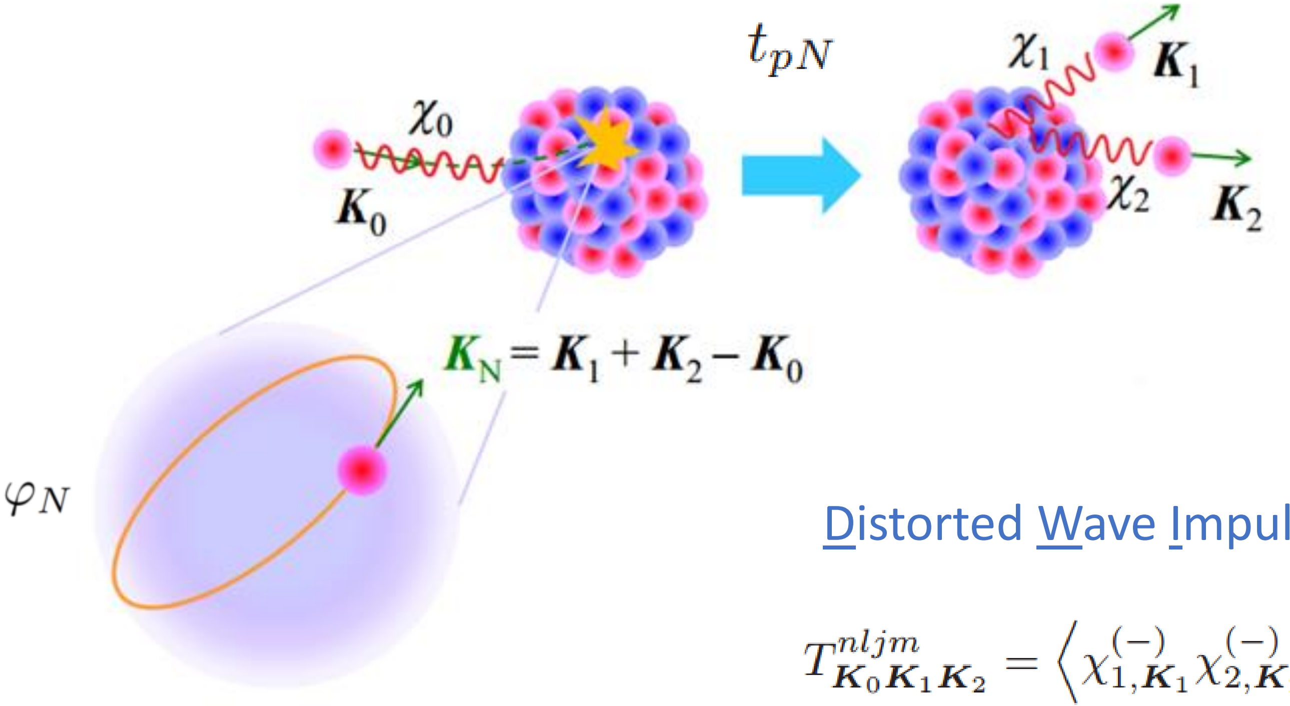
Proton-induced nucleon knockout (*p,pN*)

The extracted SF, R_S strongly depends on the reaction model.

Questions for our study:

- How much does the choices of potentials, corrections used in reaction models affect the results?
- Do current reaction models include all necessary contributions to accurately extract the absolute SF?

Proton-induced nucleon knockout reaction with DWIA



Distorted Wave Impulse Approximation

$$T^{nljm}_{\boldsymbol{K}_0\boldsymbol{K}_1\boldsymbol{K}_2} = \left\langle \chi^{(-)}_{1,\boldsymbol{K}_1}\chi^{(-)}_{2,\boldsymbol{K}_2} \middle| t_{pN} \middle| \chi^{(+)}_{0,\boldsymbol{K}_0}\varphi^{nljm} \right\rangle$$

A “snapshot” of the struck nucleon in a single-particle orbit

Courtesy of K. Ogata

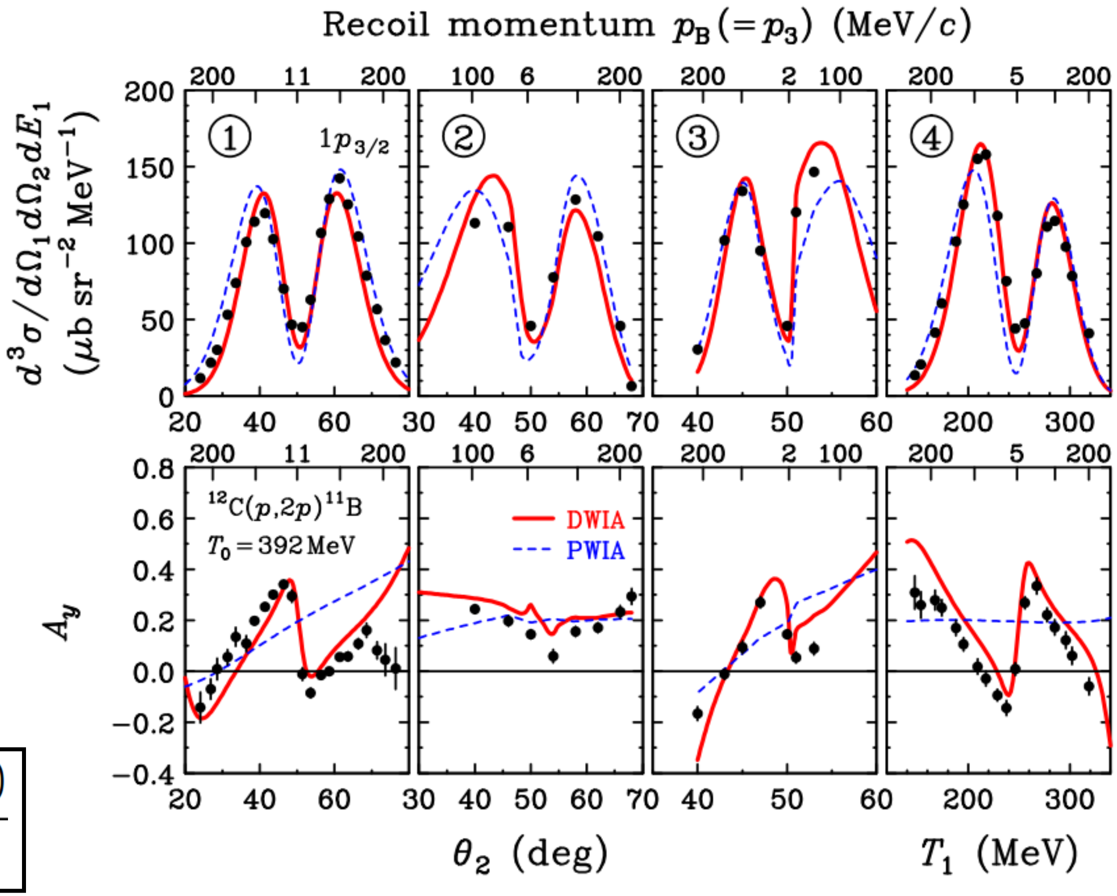
Partial-wave DWIA analysis of (*p*,*pN*) reactions in normal kinematics

In normal (forward) kinematics

Partial-wave DWIA is a well established method to extract SF from (p,pN) triple differential cross section near quasifree condition

$^{12}C(p,2p)^{11}B$

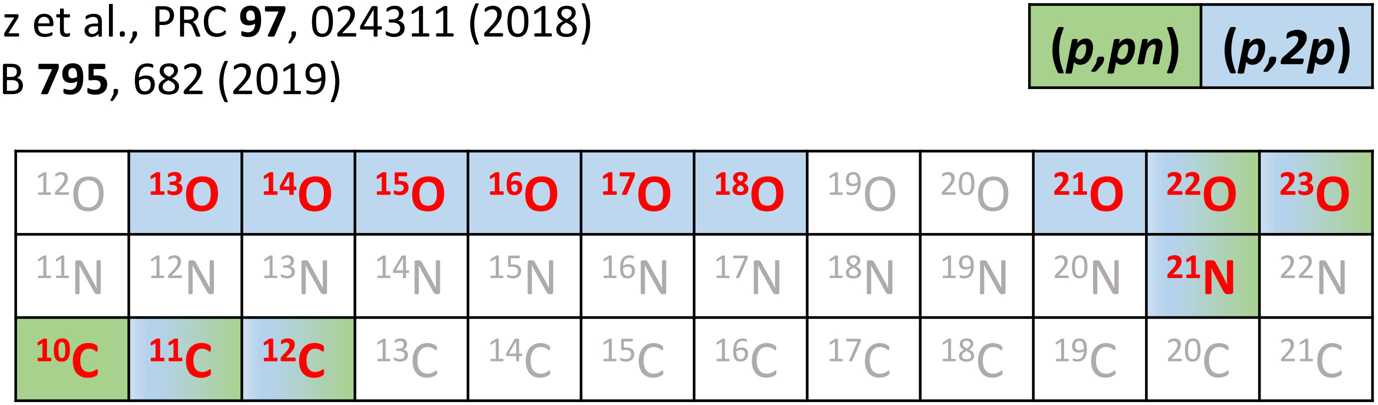
T_0 (MeV)	$S(e,e'p)$	$S(p,2p)$
392	1.72(11)	1.82(3)



T. Wakasa, K. Ogata, T. Noro, PPNP **96**, 32 (2017)
N.S. Chant, P.G. Roos, PRC **15**, 57 (1977); **27**, 1060 (1983)
G. Jacob, Th.A.J. Maris, RMP **38**, 121 (1966); **45**, 6 (1973)

Partial-wave DWIA analysis of (*p,pN*) reactions in inverse kinematics

18 (*p,pN*) reactions data, E_{beam}=300-450 MeV/u @ R^3B/LAND GSI:
V. Panin et al., PLB **753**, 204 (2016)
L. Atar et al., PRL **120**, 052501 (2018)
P. Díaz Fernández et al., PRC **97**, 024311 (2018)
M. Holl et al., PLB **795**, 682 (2019)



🟩 **(*p,pn*)** 🟦 **(*p,2p*)**

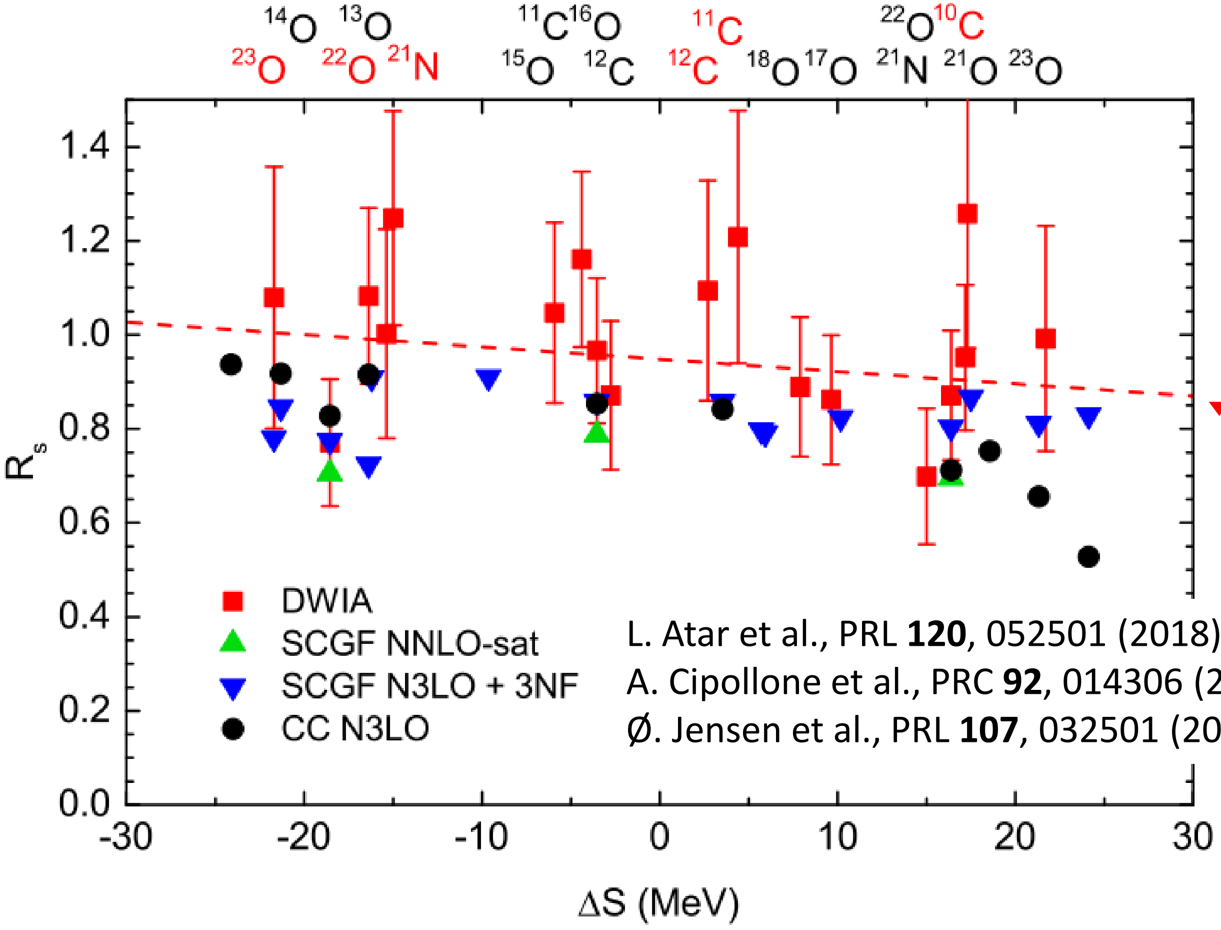
^{12}O	**^{13}O**	**^{14}O**	**^{15}O**	**^{16}O**	**^{17}O**	**^{18}O**	^{19}O	^{20}O	**^{21}O**	**^{22}O**	**^{23}O**
^{11}N	^{12}N	^{13}N	^{14}N	^{15}N	^{16}N	^{17}N	^{18}N	^{19}N	^{20}N	**^{21}N**	^{22}N
^{10}C	**^{11}C**	**^{12}C**	^{13}C	^{14}C	^{15}C	^{16}C	^{17}C	^{18}C	^{19}C	^{20}C	^{21}C

Inputs (uncertainty):
NN t-matrix of Franey-Love
Scattering wf: EDAD2 Dirac OP (10%)
Bound wf: constrained with HF-SkX (10%) following J. Lee et al., PRC **73**, 044608 (2006)
Nonlocality correction: Perey factor for bound wf, Darwin factor for scattering wf
Theoretical SF: Shell model with WBT (provided by M. Gómez-Ramos and M. Holl)

Compared with structure calculations

GSI R^3B/LAND data

$R_S = 0.947(36)-2.6(27)x10^3\Delta S$



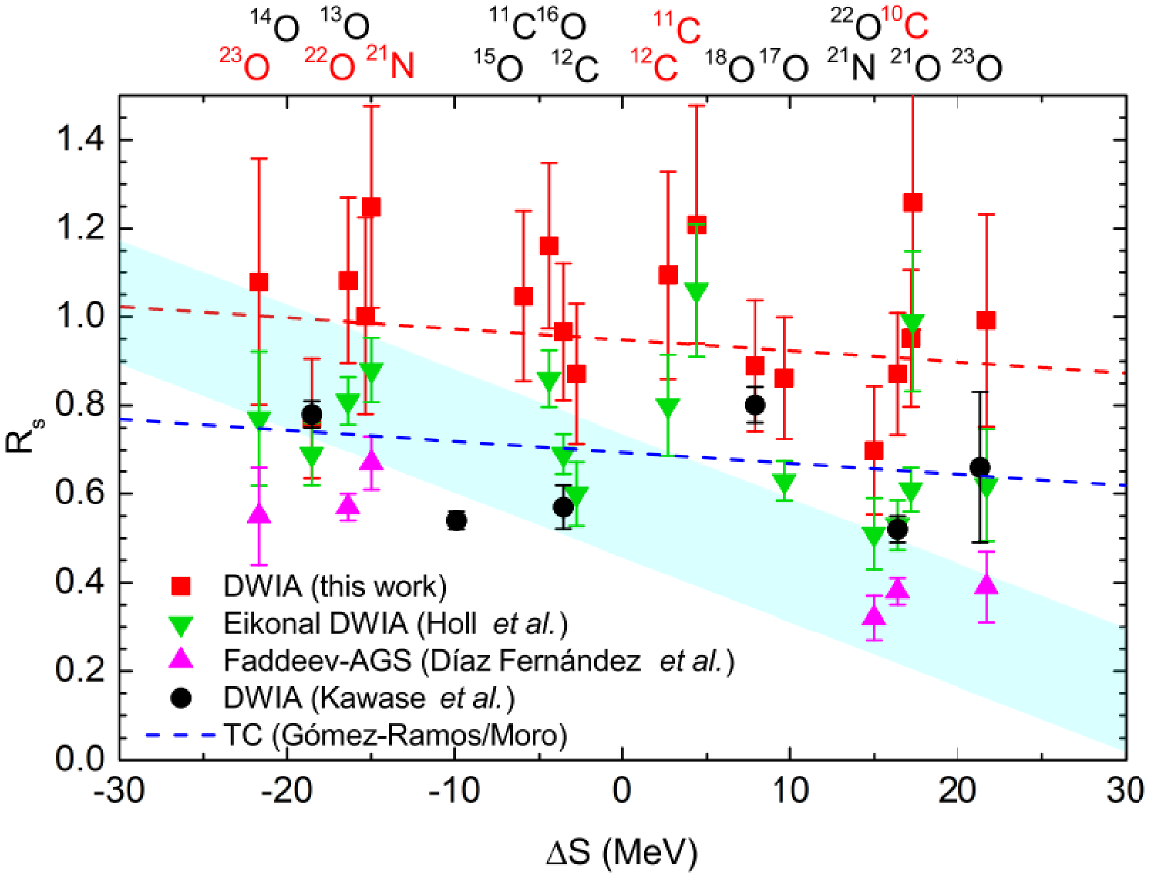
L. Atar et al., PRL **120**, 052501 (2018)
A. Cipollone et al., PRC **92**, 014306 (2015)
Ø. Jensen et al., PRL **107**, 032501 (2011)

R_S are weakly dependent on ΔS

Very large value of R_S (to be discussed later)

$$R_S = \frac{\sigma_{exp}}{SF \times \sigma_{sp}}$$

Compared with other reaction models

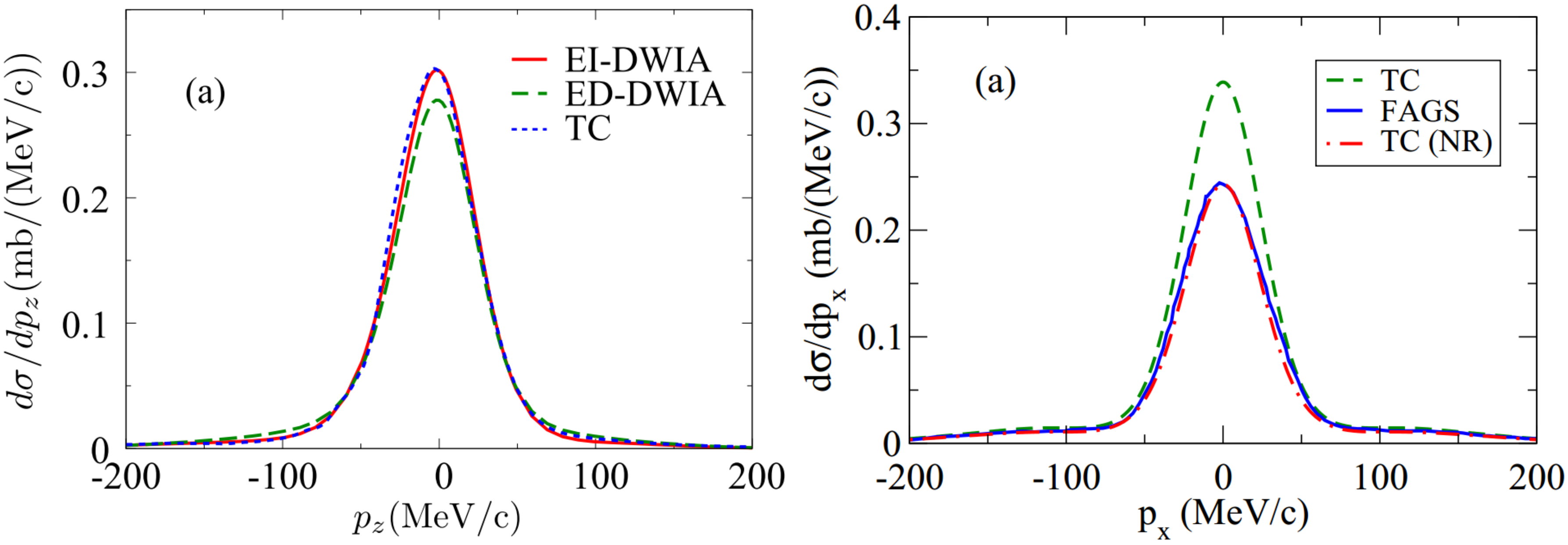


- DWIA, eikonal-DWIA and TC completely agree about the slope of the trend line (i.e the dependency of R_S on ΔS) -> weak dependency.

- The magnitudes of the trend are very different. What cause the differences?

Compared with other reaction models

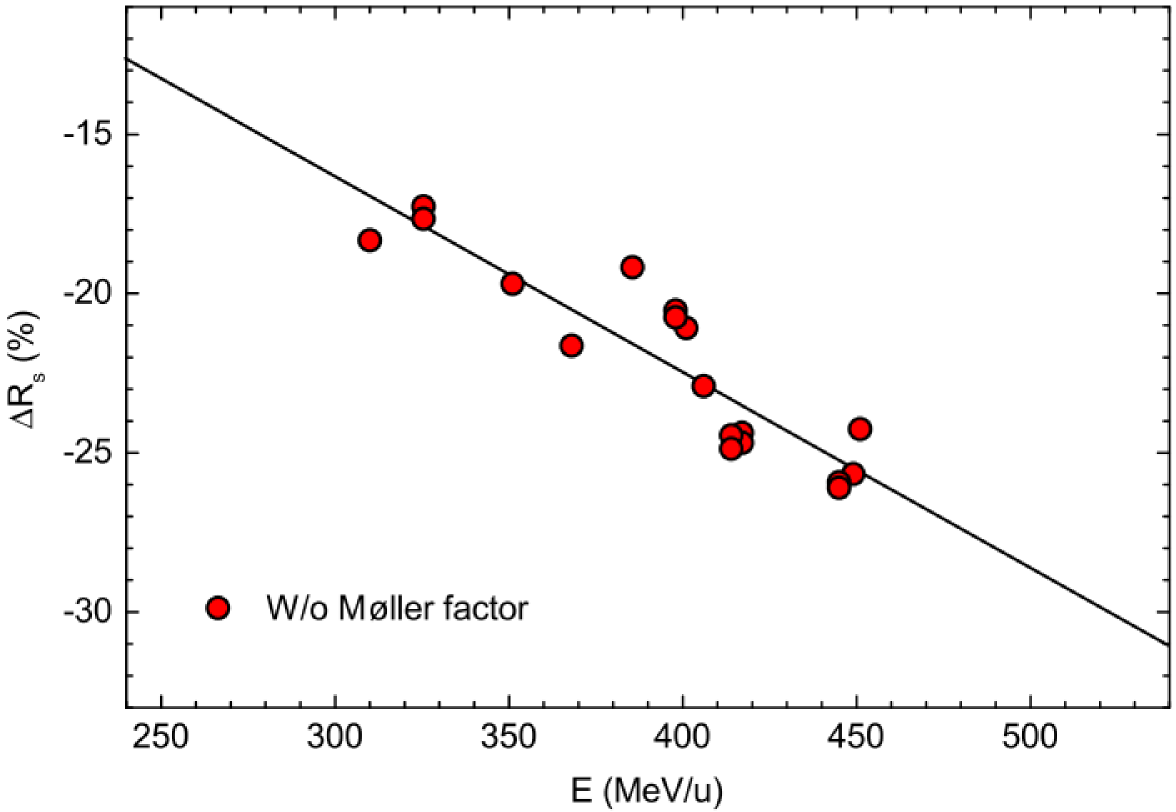
^{15}C(p,pn)^{14}C @ 420 MeV/u



K. Yoshida et al., PRC **97**, 024608 (2018).

- Using identical choice of inputs and corrections DWIA, TC, and FAGS are essentially the same.
- In practical analysis, the choice of inputs and corrections are very different.

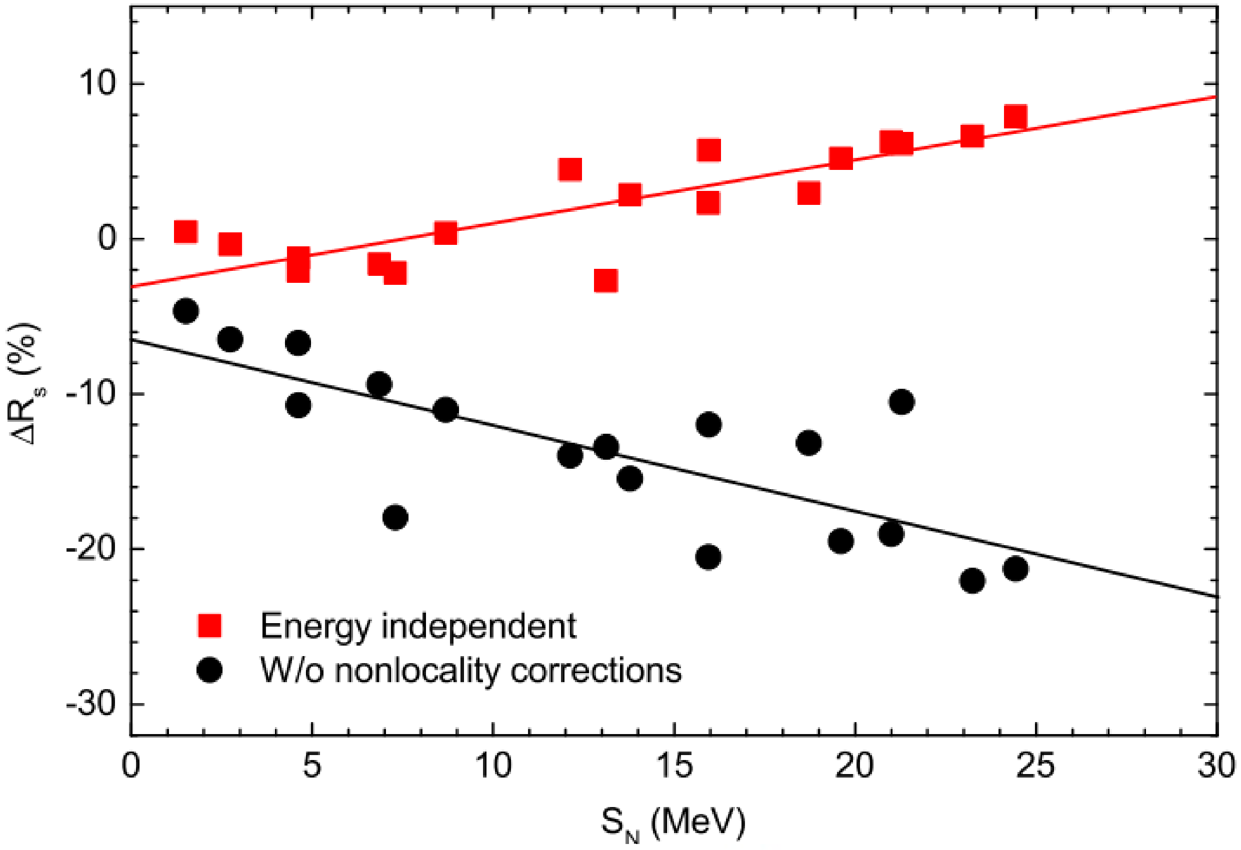
Impact of corrections on R_S of (*p,pN*)



$$f_{\text{Møl}} = \left(\frac{E_1^t E_2^t E_0^t E_N^t}{E_1 E_2 E_0 E_N} \right)^{1/2}$$

C. Møller, Kgl. Danske Videnskab. Selsbak, Mat-fys. Medd. **23**, 1 (1945).
A.K. Kerman et al., Ann. Phys. **8**, 551 (1959).

Impact of corrections on R_S of (*p,pN*)



For nonlocal effect on transfer reactions, see Natalia Timofeyuk's talk on May 12

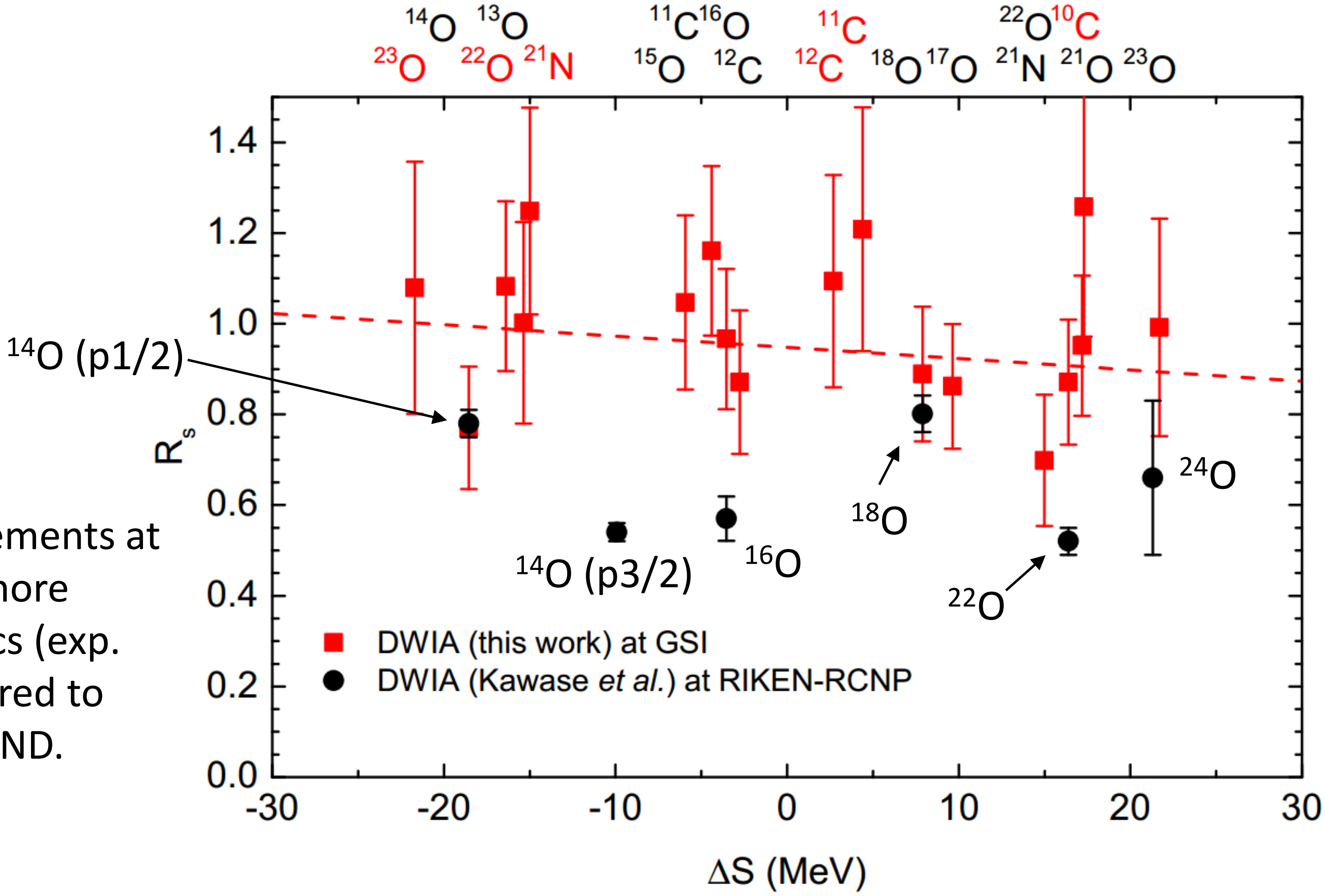
$$F_{\mathrm{PR}}(R) = C_{\mathrm{PR}}\left[1 - \frac{\mathcal{M}_{ij}}{2\hbar^2}\beta_{\mathrm{NL}}^2 U_{ij}(R)\right]^{-1/2}$$

F.G. Perey, Direct Interactions and Nuclear Reaction Mechanism

$$F_{\mathrm{DW}}(R) = C_{\mathrm{DW}}\left[\frac{E_i + U_{\mathrm{S}}(R) - U_{\mathrm{V}}(R)}{E_i}\right]^{1/2}$$

L.G. Arnold et al., PRC **23**, 1949 (1981)
S. Hama et al., PRC **41**, 2737 (1990)

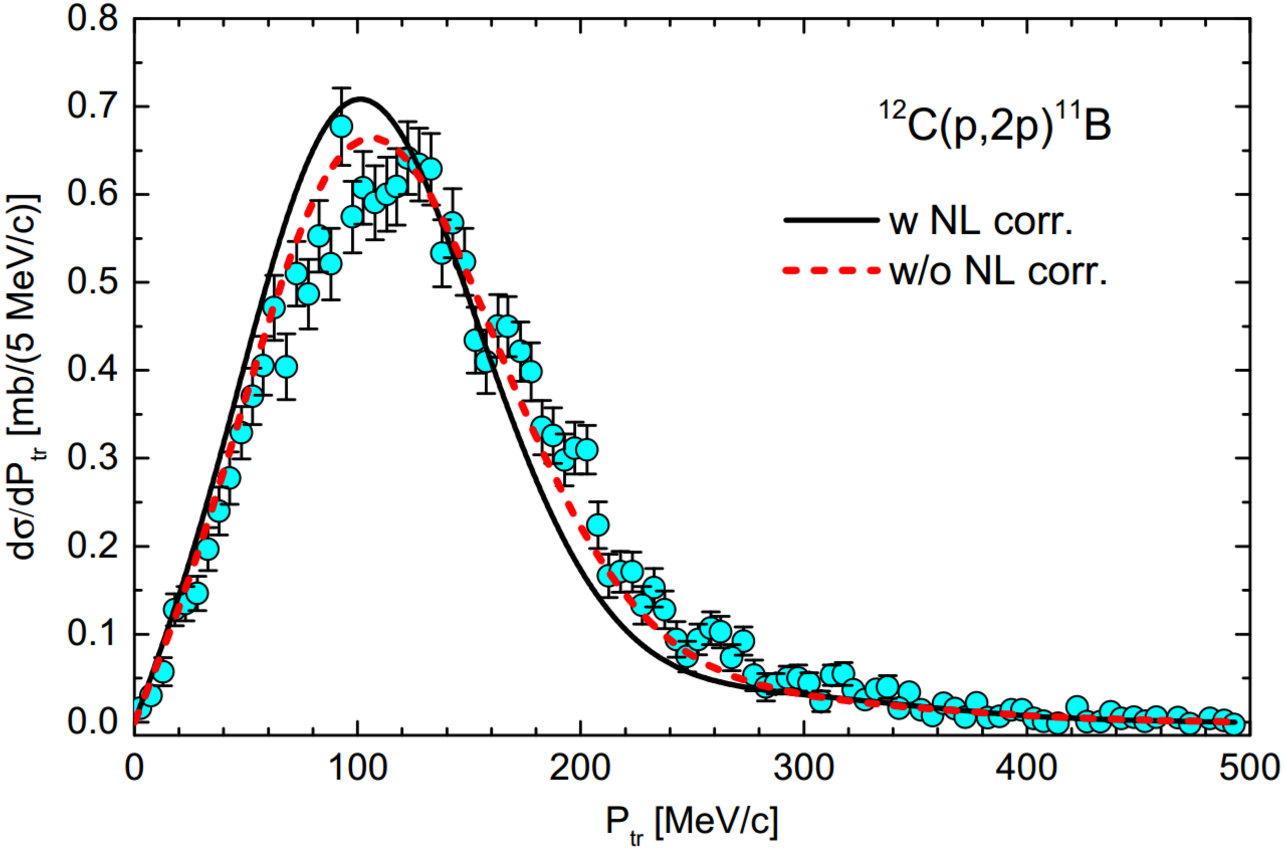
The missing contribution



The (*p,pN*) measurements at RIKEN-RCNP have more restricted kinematics (exp. acceptance) compared to those at GSI R^3B/LAND.

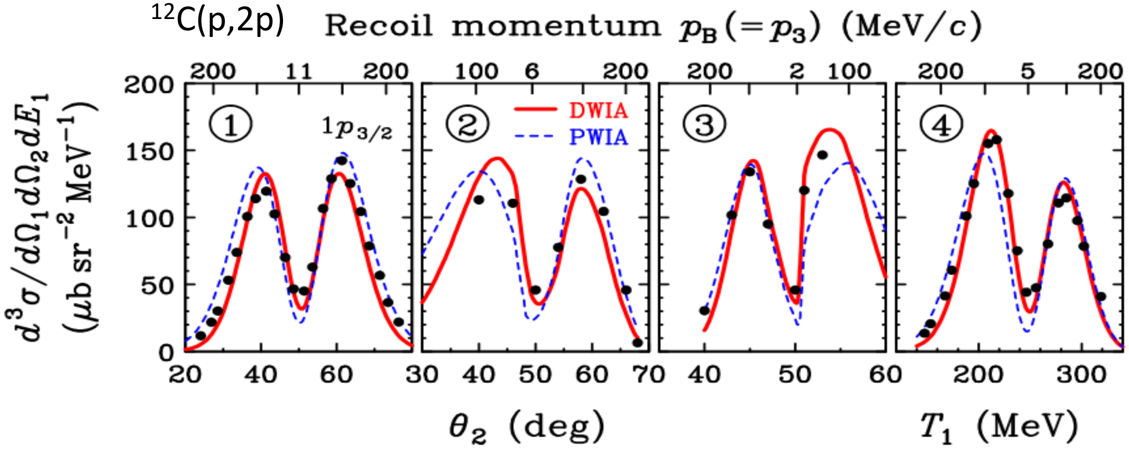
-> Some contributions (e.g. core excitation, charge exchange) are possibly missed in DWIA-type calculations.

The missing contribution

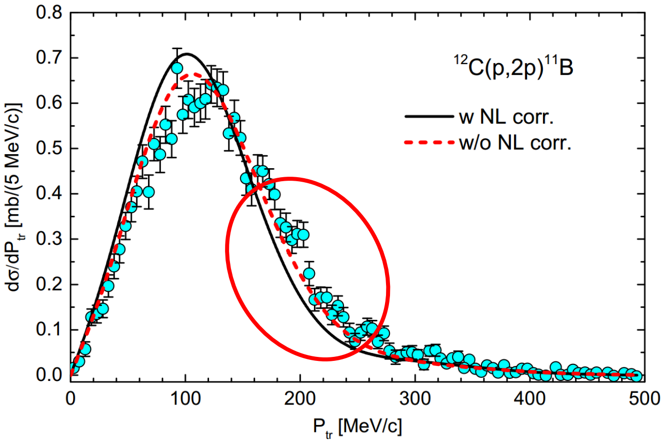


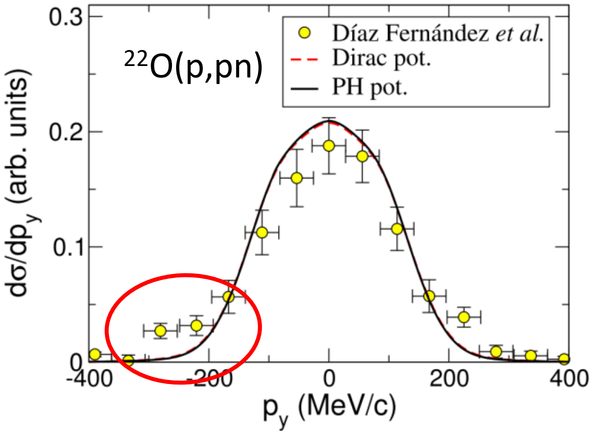
- Discrepancies in high-momentum region > 140 MeV/c
- Similar TMD shape with TC (EDAD2) and FAGS (BAU-J) calculations (R. Crespo et al., PRC **99**, 054622 (2019))
- (The lack of) nonlocality effect can affect the shape

The missing contribution



Traditionally the DWIA works well on:
Exclusive measurement in normal kinematics around quasifree condition





Semi-inclusive measurement in inverse kinematics without restriction

$$\sigma = \int \frac{d\sigma}{dK^A_{Bb}} dK^A_{Bb}$$

Gómez-Ramos, Moro, PLB **785**, 511 (2018)

Discrepancies with data from kinematics very far from quasifree condition (high recoil momentum) are accumulated

Summary of part 1

- Reduction factors R_S extracted from (*p,pN*) reactions have weak dependence on proton-neutron asymmetry ΔS.
- The nonlocality (NL) corrections and the Møller factor have nonnegligible impacts on (*p,pN*) cross sections.
- Some contributions need to explain the (*p,pN*) data in inverse kinematics seems to be missing in DWIA and possibly other reaction models, unless a considerable kinematical restriction is taken.

NTTP, K. Yoshida, K. Ogata, PRC **100**, 064604 (2019)

Part 2

Renaissance of proton-induced knockout reactions

Other studies with (*p,pX*)

- Spectroscopic info of exotic medium mass nuclei (*p,pN*) (SEASTAR collab)

- Borromean structure: (*p,pN*) with TC (M. Gómez-Ramos, J. Casal, A. Moro)
  see also Y. Kikuchi et al., PTEP **2016**, 103D03

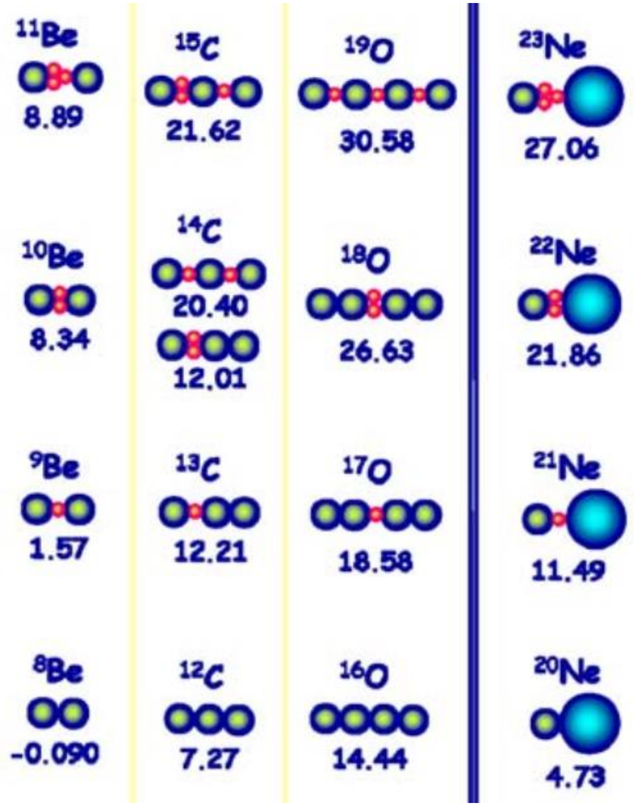
- Tensor correlation: (*p,pd*) with DWIA, S. Terashima et al., PRL **121**, 242501 (2018)

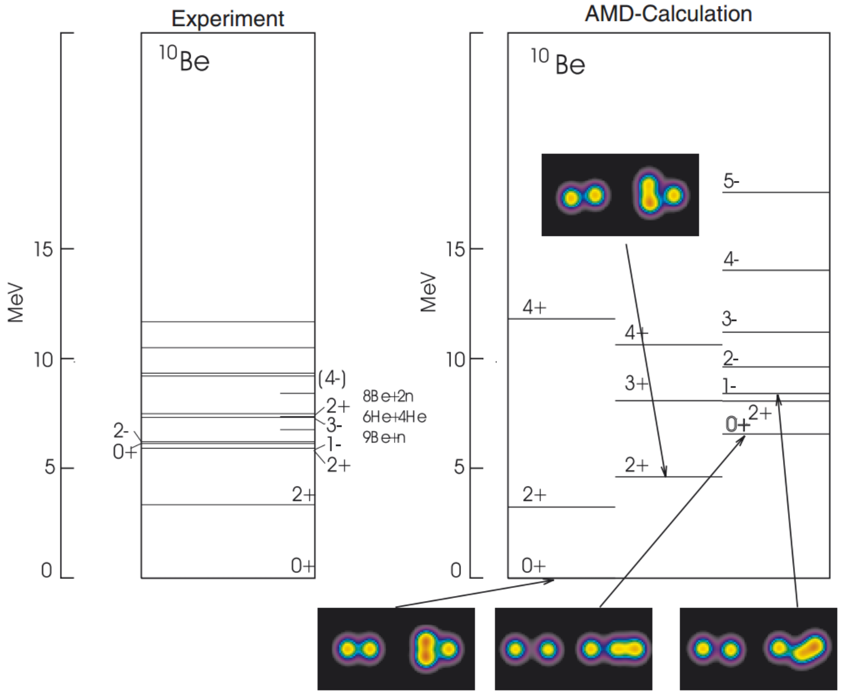
- SRC: (*p,2pn*) with SRC-driven PW model, S. Stevens et al., PLB **777**, 374 (2018)
  see also (p,3p) sequential knockout A. Frotscher et al., accepted in PRL

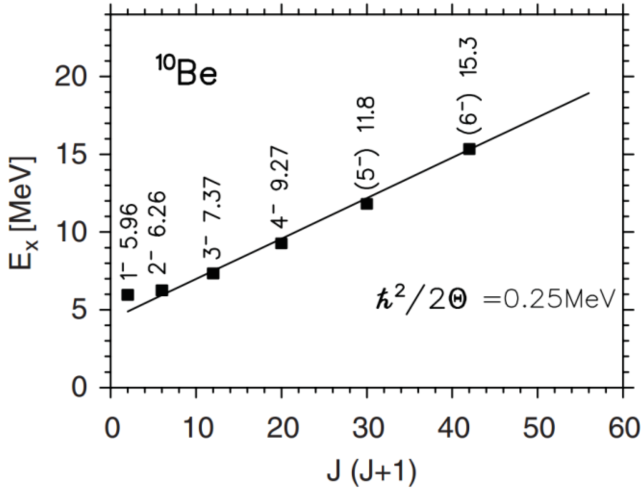
- α clustering: (*p,pα*) with DWIA + THSR/AMD
  ^{10,12}Be: Lyu et al., PRC **97**, 044612 (2018), PRC **99**, 064610 (2019)
  ^{20}Ne: K. Yoshida et al., PRC **98**, 024614 (2018), PRC **100**, 044601 (2019)
  see also Z. Yang's talk May 26 for $^{112\text{-}124}$Sn and $^{12\text{-}20}$C(*p,pα*)

➢ Neutron molecular orbital: (*p,pn*) with DWIA + THSR/AMD

Neutron molecular orbital







Extensive review: W. von Oertzen et al., Phys. Rep. **432**, 43 (2006)

No experimental probe for the radial wavefunction of the valence neutrons

Overlap function for (*p,pN*)

In DWIA

$$T^{nljm}_{\boldsymbol{K}_0\boldsymbol{K}_1\boldsymbol{K}_2} = \left\langle \chi^{(-)}_{1,\boldsymbol{K}_1}\chi^{(-)}_{2,\boldsymbol{K}_2} \middle| t_{pN} \middle| \chi^{(+)}_{0,\boldsymbol{K}_0}\boxed{\varphi^{nljm}} \right\rangle$$

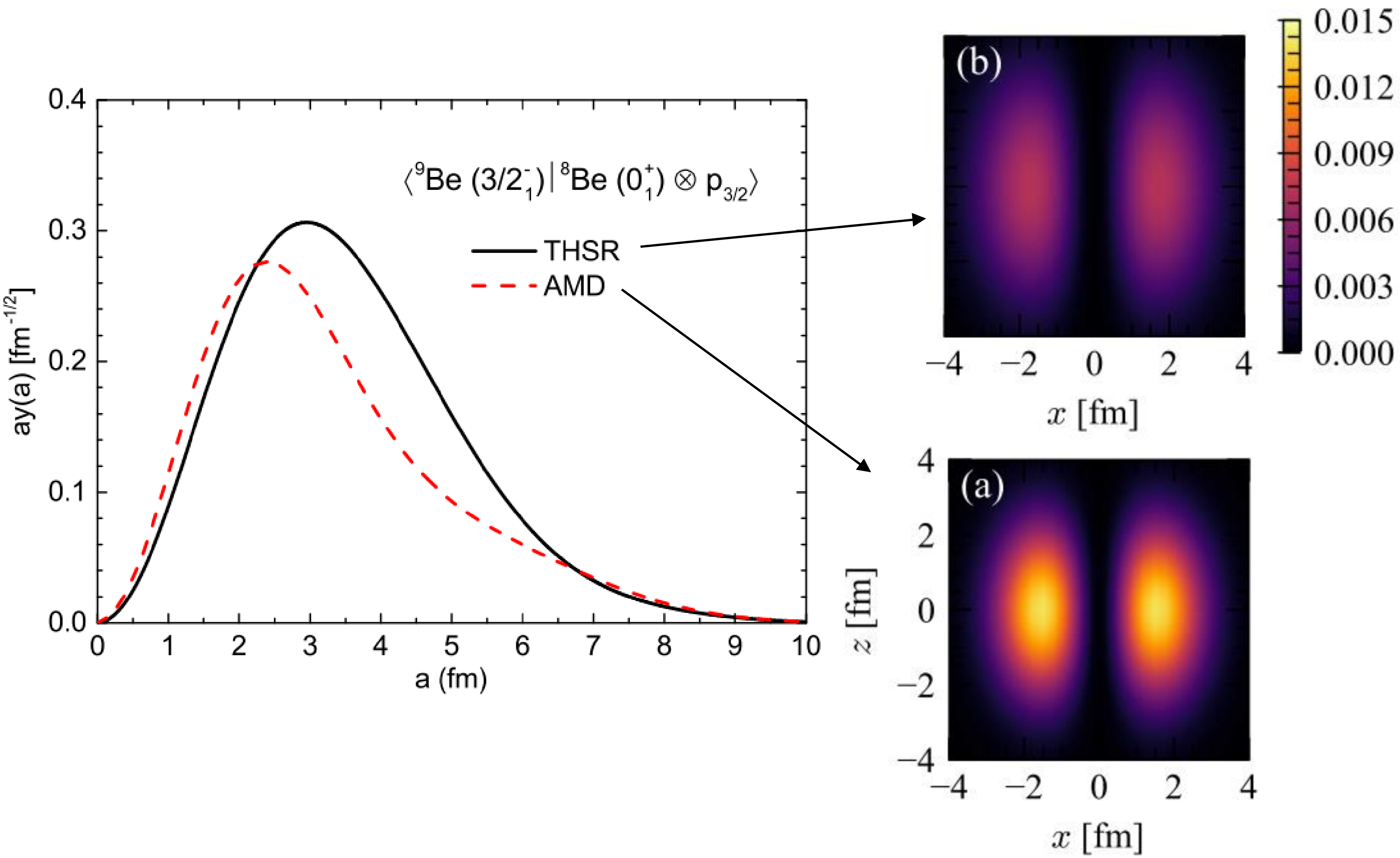
Overlap function (bound state/ single-particle wf…)

Many options

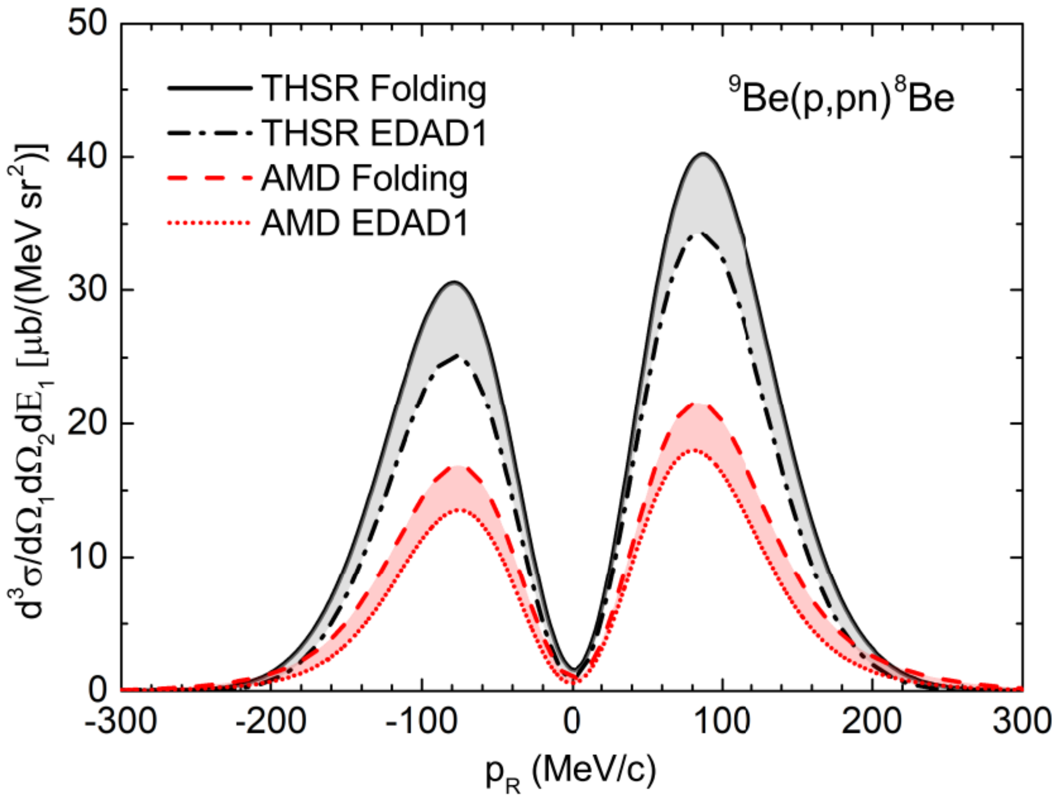
- WS pot constrained by wf rms from HF/HFB: J. Lee et al., PRC **73**, 044608 (2006)
- WS pot from (*e,e’p*) study: G.J. Kramer et al., NPA 679, 267 (2001)
- Source term approach: N.K. Timofeyuk PRC **88**, 044315 (2013)
- Nonlocal DOM: M.C. Atkinson et al., PRC **98**, 044627 (2018)
- *Ab initio* SCGF/VMC/GFMC or other correlation methods JCM/CBF/GFM: R. Crespo et al., PLB **803**, 135355 (2020)
- (This work) Reduced width amplitude (RWA) from antisymmetrized molecular dynamics (AMD) and Tohsaki-Horiuchi-Schuck-Röpke (THSR) methods

$$y(a) = \sqrt{9}\left\langle \frac{\delta(r-a)}{r^2}\phi(^{8}\mathrm{Be})[Y_1(\hat{r})\chi_n] \middle| \Phi(^{9}\mathrm{Be}) \right\rangle$$

Valence neutron amplitudes/distributions

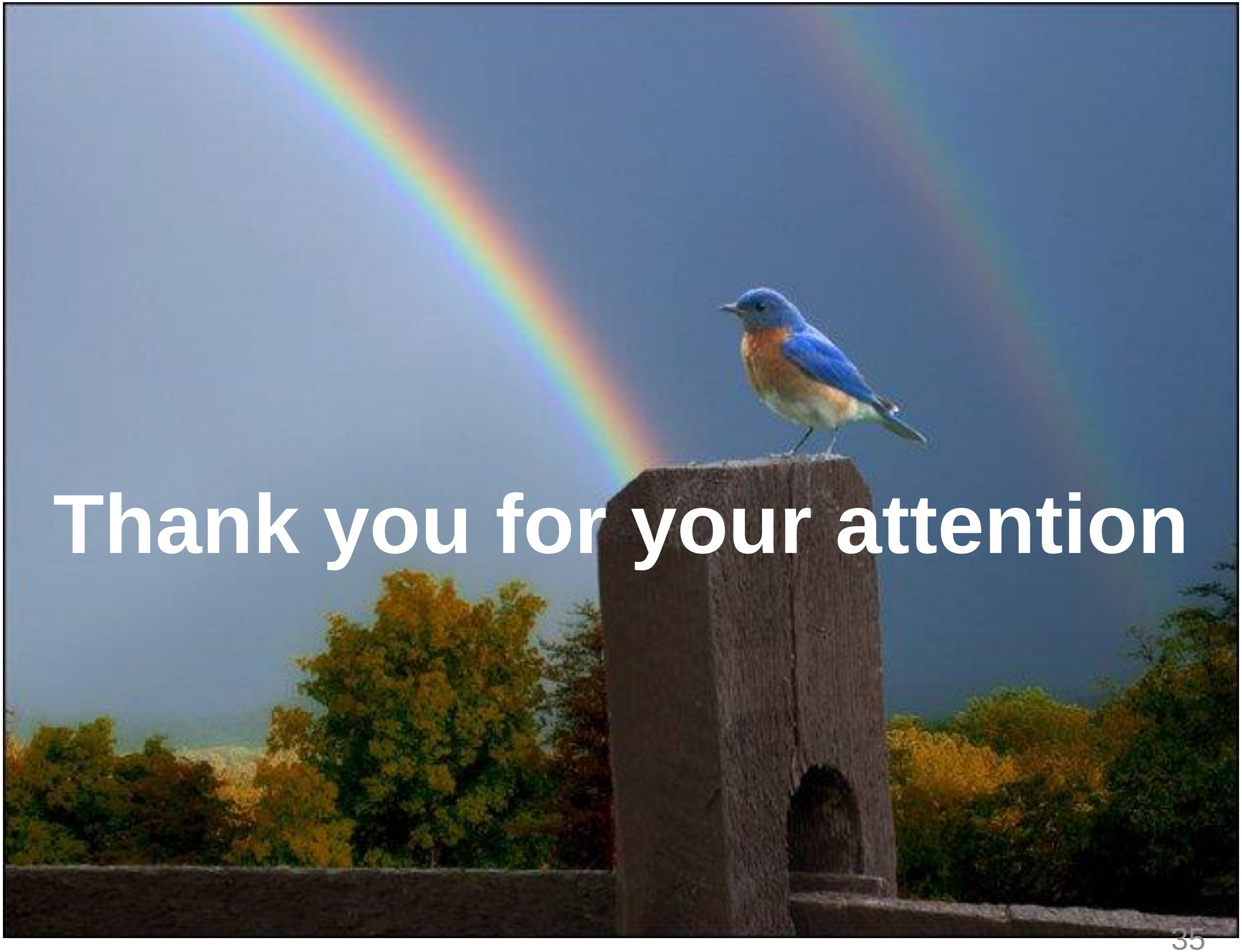


TDX of ^{9}Be(*p,pn*)^{8}Be with DWIA



- Using ^{9}Be(*p,pn*)^{8}Be cross section to determine the realistic picture of neutron molecular orbital

NTTP, M. Lyu, Y. Chiba, K. Ogata, arXiv:2005.04582



Thank you for your attention

Appendix

DWIA calculation

$$\sigma_{\mathrm{sp}} = \int \frac{d\sigma}{dK^A_{Bb}} dK^A_{Bb}. \qquad \frac{d\sigma}{dK^A_{Bb}} = 2\pi \int dK^A_{Bz} K^A_{Bb} \frac{d\sigma}{d\boldsymbol{K}^A_B}.$$

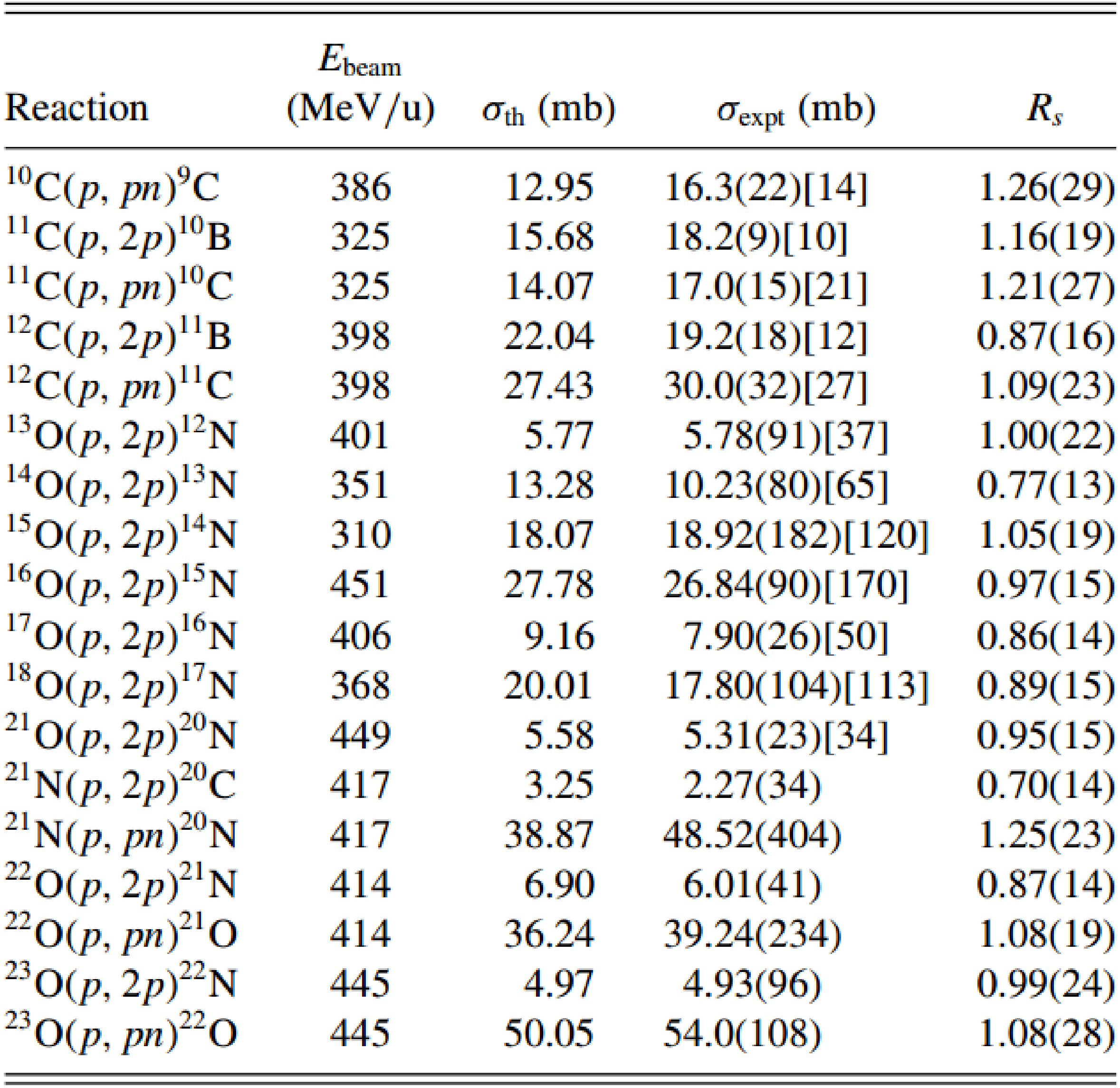
$$\frac{d\sigma}{d\boldsymbol{K}^A_B} = C_0 \int d\boldsymbol{K}^A_1 d\boldsymbol{K}^A_2 \delta(E^A_f - E^A_i)\delta(\boldsymbol{K}^A_f - \boldsymbol{K}^A_i) \times \frac{E_1 E_2 E_B}{E^A_1 E^A_2 E^A_B} \frac{d\sigma_{pN}}{d\Omega_{pN}} \sum_m (2\pi)^2 \left|\bar{T}^{nljm}_{\boldsymbol{K}_0\boldsymbol{K}_1\boldsymbol{K}_2}\right|^2,$$

where

$$C_0 \equiv \frac{E^A_0}{(\hbar c)^2 K^A_0} \frac{f_{pN}}{(2l+1)} \frac{\hbar^4}{(2\pi)^3 \mu^2_{pN}}.$$

$$\bar{T}^{nljm}_{\boldsymbol{K}_0\boldsymbol{K}_1\boldsymbol{K}_2} = \int d\boldsymbol{R}\, \chi^{*(-)}_{1,\boldsymbol{K}_1}(\boldsymbol{R})\, \chi^{*(-)}_{2,\boldsymbol{K}_2}(\boldsymbol{R})\, \chi^{(+)}_{0,\boldsymbol{K}_0}(\boldsymbol{R}) \times \varphi^{nljm}(\boldsymbol{R}) e^{-i\boldsymbol{K}_0\cdot\boldsymbol{R}/A}.$$

DWIA results



Reaction	E_{beam} (MeV/u)	σ_{th} (mb)	σ_{expt} (mb)	R_s
$^{10}\text{C}(p, pn)^{9}\text{C}$	386	12.95	16.3(22)[14]	1.26(29)
$^{11}\text{C}(p, 2p)^{10}\text{B}$	325	15.68	18.2(9)[10]	1.16(19)
$^{11}\text{C}(p, pn)^{10}\text{C}$	325	14.07	17.0(15)[21]	1.21(27)
$^{12}\text{C}(p, 2p)^{11}\text{B}$	398	22.04	19.2(18)[12]	0.87(16)
$^{12}\text{C}(p, pn)^{11}\text{C}$	398	27.43	30.0(32)[27]	1.09(23)
$^{13}\text{O}(p, 2p)^{12}\text{N}$	401	5.77	5.78(91)[37]	1.00(22)
$^{14}\text{O}(p, 2p)^{13}\text{N}$	351	13.28	10.23(80)[65]	0.77(13)
$^{15}\text{O}(p, 2p)^{14}\text{N}$	310	18.07	18.92(182)[120]	1.05(19)
$^{16}\text{O}(p, 2p)^{15}\text{N}$	451	27.78	26.84(90)[170]	0.97(15)
$^{17}\text{O}(p, 2p)^{16}\text{N}$	406	9.16	7.90(26)[50]	0.86(14)
$^{18}\text{O}(p, 2p)^{17}\text{N}$	368	20.01	17.80(104)[113]	0.89(15)
$^{21}\text{O}(p, 2p)^{20}\text{N}$	449	5.58	5.31(23)[34]	0.95(15)
$^{21}\text{N}(p, 2p)^{20}\text{C}$	417	3.25	2.27(34)	0.70(14)
$^{21}\text{N}(p, pn)^{20}\text{N}$	417	38.87	48.52(404)	1.25(23)
$^{22}\text{O}(p, 2p)^{21}\text{N}$	414	6.90	6.01(41)	0.87(14)
$^{22}\text{O}(p, pn)^{21}\text{O}$	414	36.24	39.24(234)	1.08(19)
$^{23}\text{O}(p, 2p)^{22}\text{N}$	445	4.97	4.93(96)	0.99(24)
$^{23}\text{O}(p, pn)^{22}\text{O}$	445	50.05	54.0(108)	1.08(28)