Interplay between nucleon correlations and asymmetry: Sensitivity study on oxygen isotopes

Freddy Flavigny

Outline

- **E569s in short:** Goals, results and conclusions

- **Deeper in and Beyond E569S** :
  Sensitivity study and systematic errors

  - Framework: CRC Vs DWBA

  - Overlap function and SFs

    - Woods-Saxon: r_0 dependence

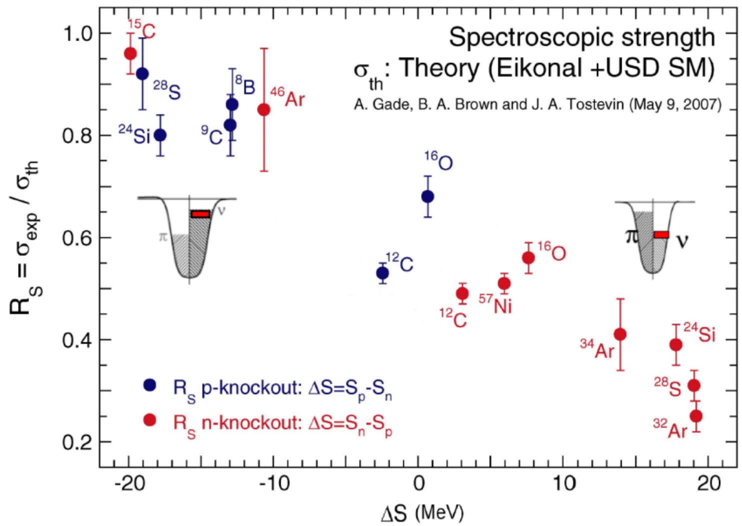
    - Ab-intio: asymptotic tails…

    - **E655s** on ^{18}Ne (M. Senoville’s talk)

Deeply-bound nucleon stripping from exotic nuclei

Knockout (-1n) et (-1p)

A. Gade *et al*, PRL. **93** 042501 (2004) ; PRC **77**, 044306 (2008)



$\Delta S = |S_n - S_p|$ (MeV)

Intermediate-energy knockout

- **Disagreement** between theory and experiment::

$$\sigma_{th} = C^2S_{th}\ \sigma_{sp}$$

2 possible sources: (structure or reaction)

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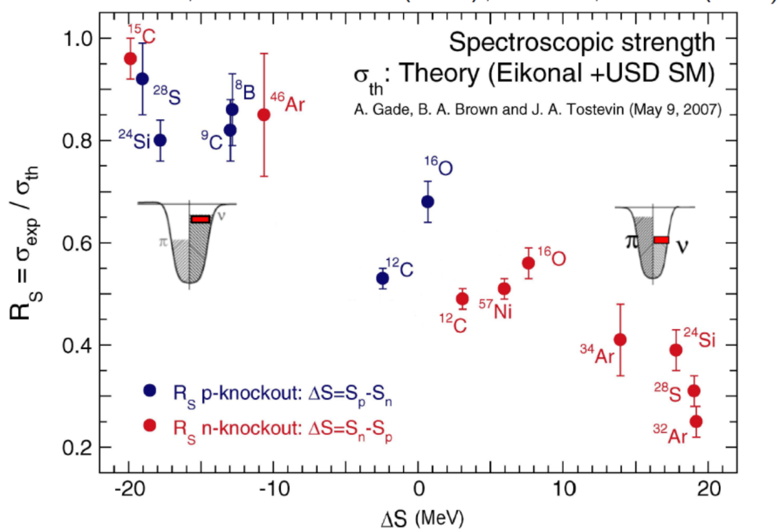

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Intermediate-energy knockout

- **Disagreement** between theory and experiment::

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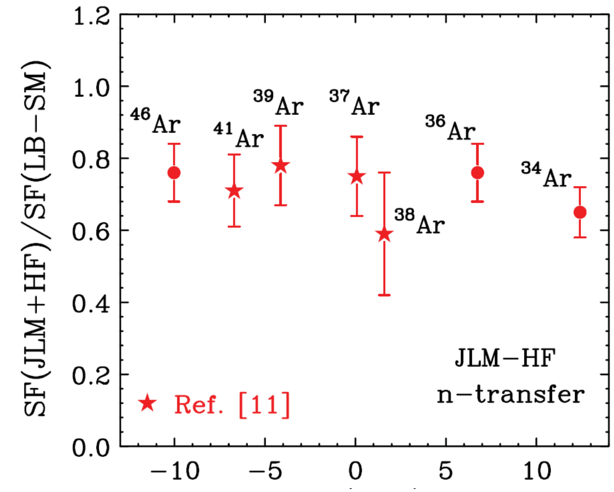
2 possible sources: (structure or reaction)

Transfer (d,p)

J. Lee et al., PRC 83, 014606 (2001)



$\Delta S = |S_n - S_p|$ (MeV)

Low-energy (p,d) transfer

- Constant reduction~30%
- Data for ΔS up to 12 MeV

Experimental program

Question : Are spectroscopic factors from knockout and transfer consistent for high ΔS ?

Experimental Program

- $^{14}O + {}^{9}Be \rightarrow {}^{13}O$ ou $^{13}N + X$
- $^{16}C + {}^{9}Be \rightarrow {}^{15}C$ ou $^{15}B + X$

53 MeV/u
75 MeV/u
@ NSCL

[F.Flavigny et al., Phys. Rev. Lett **108**, 252101 (2012)]

- $^{14}O + d \rightarrow {}^{13}O + t$
- $^{14}O + d \rightarrow {}^{13}N + {}^{3}He$
- $^{14}O + d \rightarrow {}^{14}O + d$

18 MeV/u @ SPIRAL-GANIL

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

Reaction Models

Knockout:

- *Medium effects (Pauli principle)*
  [*F. Flavigny , A. Obertelli et I. Vidana, PRC **79**, 064617 (2009)*]
- *Intra-nuclear Cascade Model*
  [C.Louchart et al., PRC **83**, 011601 (R) (2011)]
- *Transfer to the continuum model*

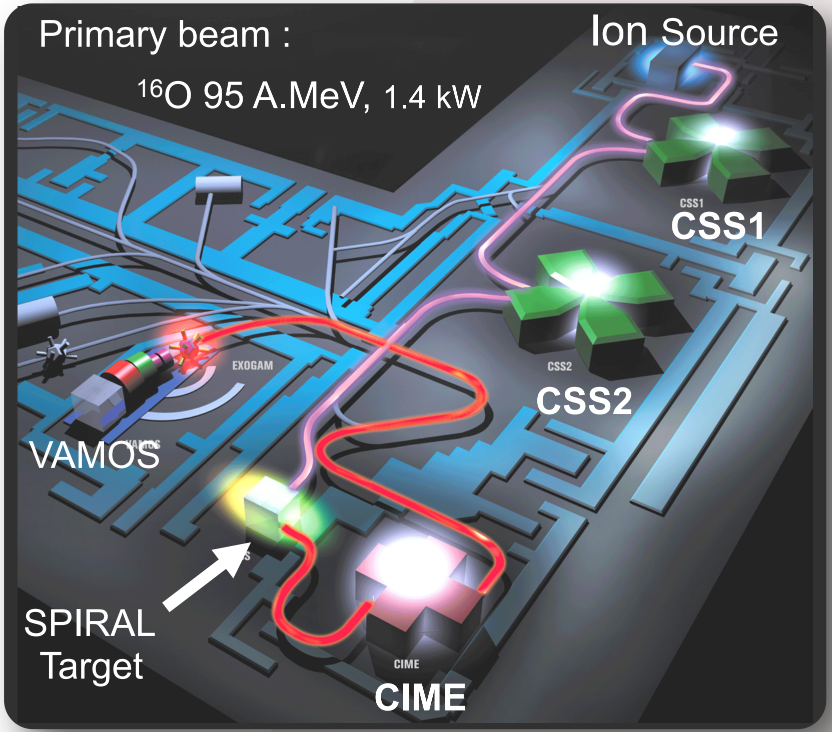
Transfer:

- *Coupled-Channel calculations (FRESCO)*
- *Use of standard and **ab-initio** overlaps*

Ideal case: ^{14}O

- ✓ Large value ΔS = 18.6 MeV
- ✓ Closed-shell nucleus, well described in SM calculations
- ✓ Beam intensity high enough for (d,^{3}H) (d,^{3}He) transfer measurements

Beam production, acceleration, detection setup



SPIRAL Beam: $^{14}O^{8+}$

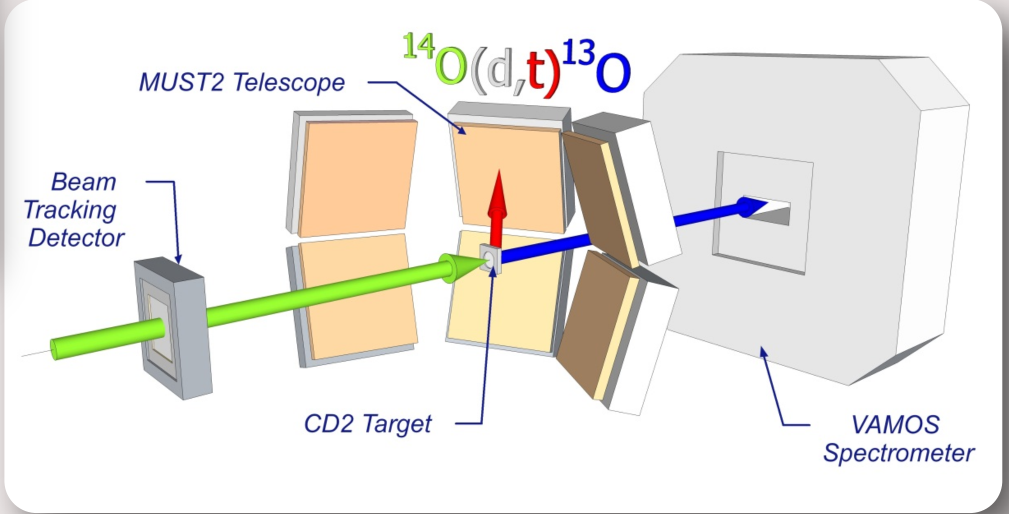
Intensity: 6.10^4 pps

Energy: 18.1 A.MeV

CD2 targets: 0.5,1.5 and 8.5 mg.cm^{-2}

Reactions: (d,d), (d,^{3}H) and (d,^{3}He)

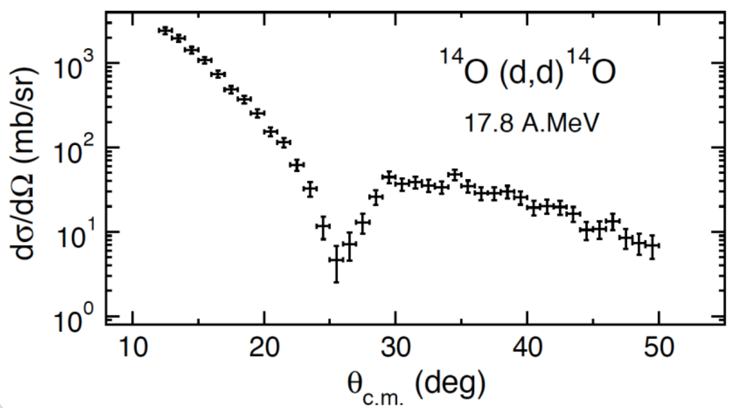
- *6 MUST2 Telescopes:*
  10x10 cm^2 300µm DSSSD + SiLi or CsI
- *VAMOS spectrometer in dispersive mode*



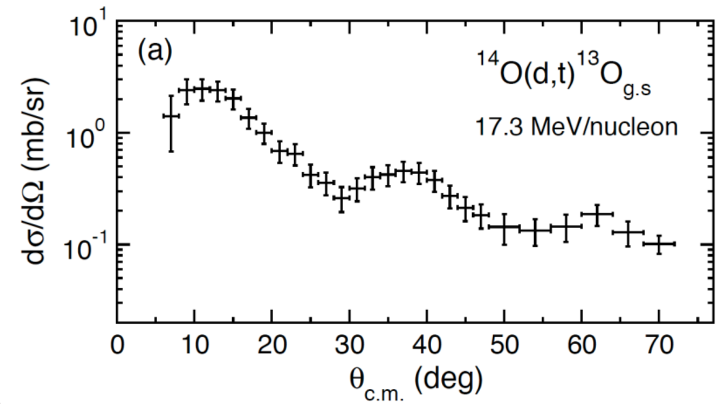
Fully exclusive measurement

Experimental Data Set

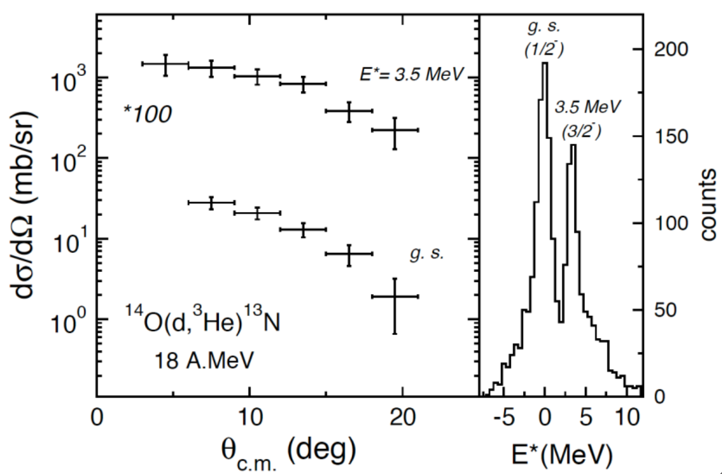
Elastic channel



One-neutron pickup channel



One-proton pickup channel



Published Data on ^{16}O and ^{18}O

[V. Bechtold et al., Phys. Lett. B **72**,169 (1977)]
[M. Gaillard et al., Nucl. Phys. A **119**, 161 (1968)]
[D. Hartwiget al., Z. Phys. **246**, 418 (1971)]

[D. Suzuki et al., Phys.Rev. Lett. **103**, 152503 (2009)]

Reaction Framework

Input Potential:

- ✓ $^{14}O + ^{2}H$
  - → A.J. Koning et J.P. Delaroche, NPA 713, 231 (2003)
  - → Validated on elastic data

Output potentials:

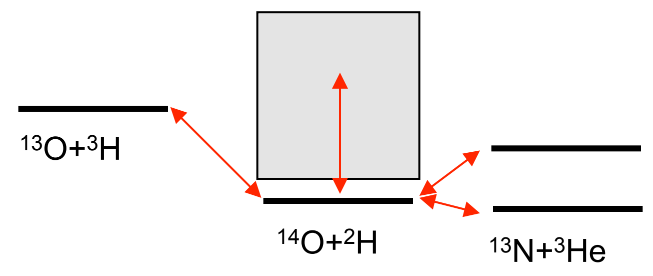
- ✓ $^{13}O + ^{3}H$ and $^{13}N + ^{3}He$
  - → D. Y. Pang et al., PRC 79, 024615 (2009)
  - → C. M. Perey and F. G. Perey, ADNDT 17,17,1 (1976)

Form factors:

- ✓ $<^{3}H|d + n>$ and $<^{3}He\ |d + p>$
  - → B. A. Watson et al., PR 182,977 (1969)

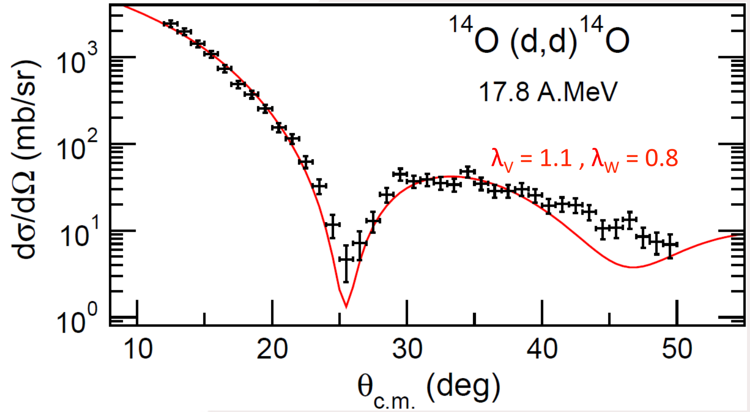
- ✓ $<^{14}O\ |\ ^{13}O + n>$ and $<^{14}O\ |\ ^{13}N + p>$
  - → Woods Saxon, **Hartree Fock constrained**

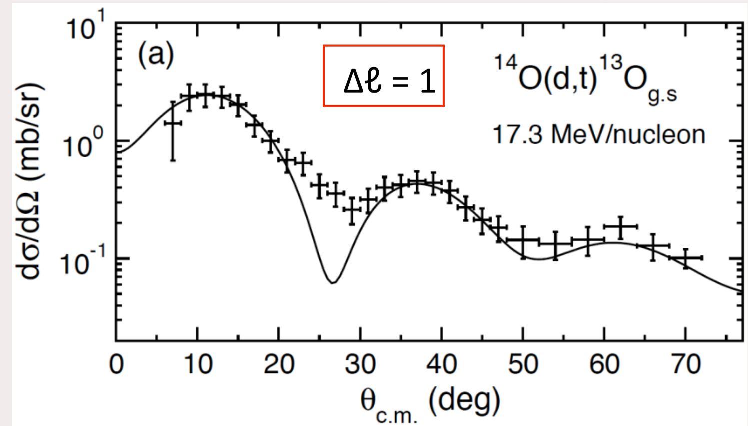
Coupling scheme

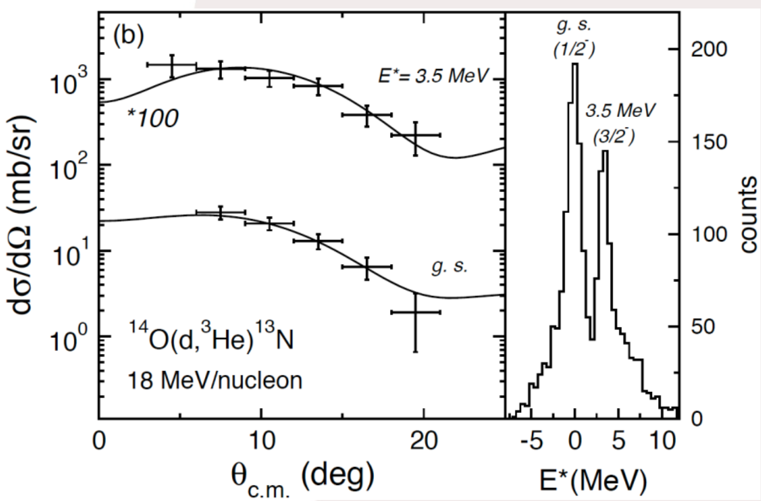


- Coupled Reaction Channel analysis (CRC)
- Coupled discretized continuum channel (CDCC) for deuteron breakup

^{14}O results

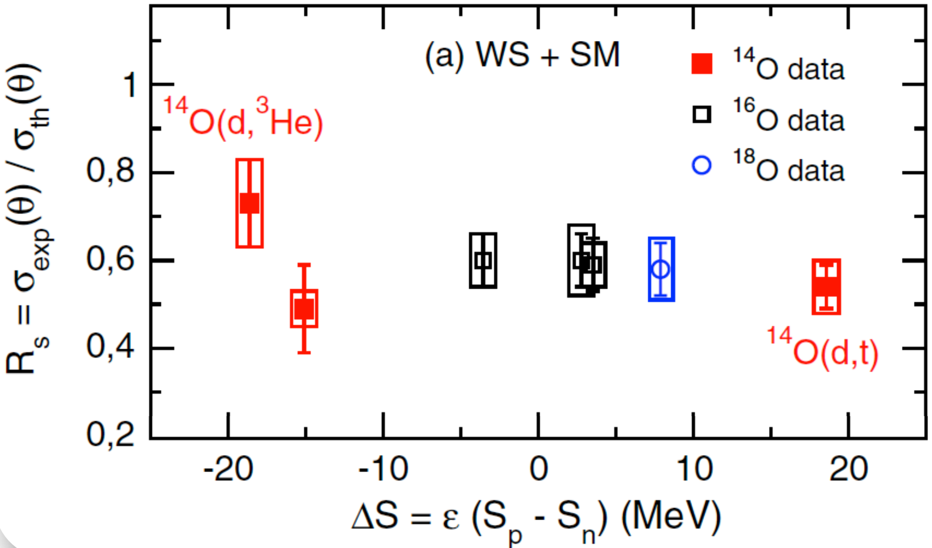






Reaction	E^* (MeV)	J^π	R^{HFB}_{rms} (fm)	r_0 (fm)	C^2S_{exp} (WS)
^{14}O (d, t) ^{13}O	0.00	$3/2^-$	2.69	1.40	1.69 (17)(20)
^{14}O $(d, {}^3$He$)$ ^{13}N	0.00	$1/2^-$	3.03	1.23	1.14(16)(15)
	3.50	$3/2^-$	2.77	1.12	0.94(19)(7)
^{16}O (d, t) ^{15}O	0.00	$1/2^-$	2.91	1.46	0.91(9)(8)
^{16}O $(d, {}^3$He$)$ ^{15}N [19,20]	0.00	$1/2^-$	2.95	1.46	0.93(9)(9)
	6.32	$3/2^-$	2.80	1.31	1.83(18)(24)
^{18}O $(d, {}^3$He$)$ ^{17}N [21]	0.00	$1/2^-$	2.91	1.46	0.92(9)(12)

Results with WS overlap functions



δ (RMS) → δr_o → box

Error bars due to exp. Uncertainties

OFs : WS (HFB constrained)
C^2S_{th}: Shell model with WBT interaction

$$\sigma_{th}(\theta) = C^2S_{th}\, \sigma_{sp}(\theta)$$

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} →

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

$\alpha = +0.0004(24)(12)\ \mathrm{MeV}^{-1}$

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

Exp. Error (1 set)

Stdrd. error from 48 data sets

Overlap functions

A crucial choice

- Overlap Function
  - Woods-Saxon geometry
    - (r_0, a_0) = (1,25; 0.65) fm
    - HF constrained r_0 + Exp. Sn
  - Ab-intio calculation

Test case : stable ^{16}O

Form factors

~~X Standard arbitrary value:~~

~~(r_0, a_0) : (1.25 fm , 0.65 fm)~~

✓ r_{rms} from $^{16}O(e,e'p)^{15}N_{gs}$:
[M. Leuschner et al., PRC 49, 955 (1994)]

r_{rms} = 2,943(30) fm

✓ WS parameters to reproduce r_{rms} and Sp:

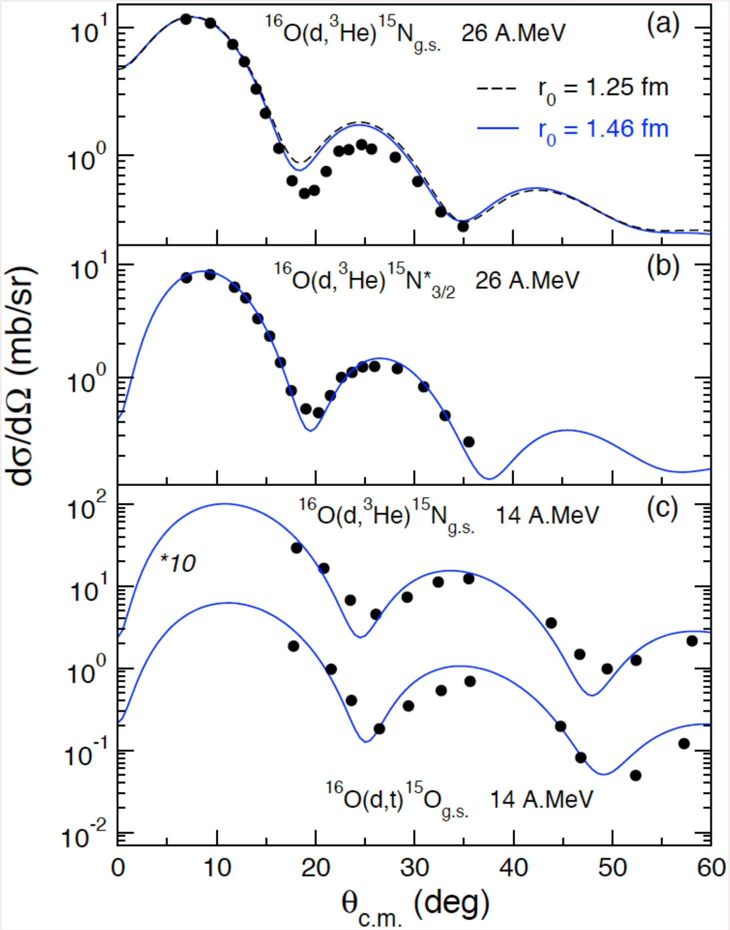
r_0 = 1,46 fm

C^2S_{exp} =0,91(9)

✓Single-particle HFB w.f. with Sly4 interaction:

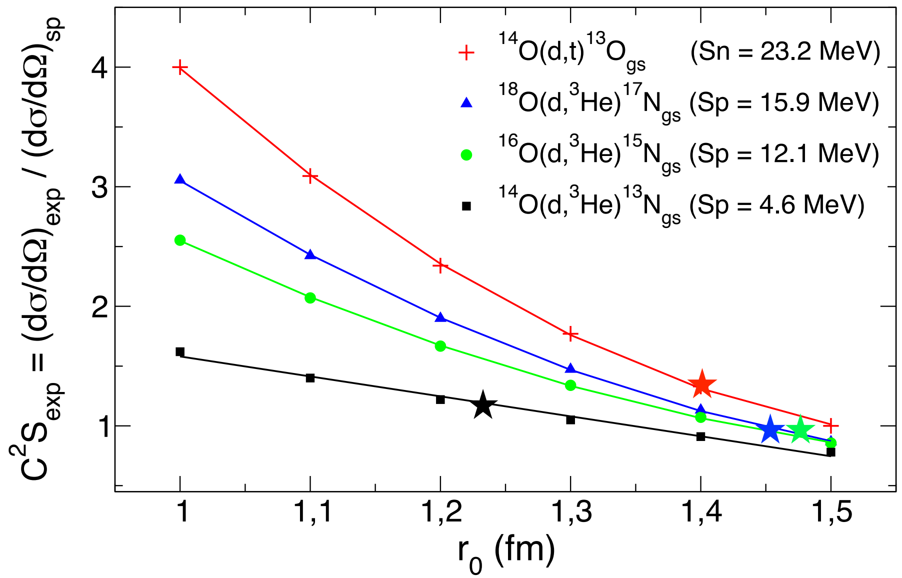
r_{rms}(HFB) = 2,95 fm

HFB RMS (fm)	$\pi 0p_{3/2}$	$\pi 0p_{1/2}$	$\nu 0p_{3/2}$	$\nu 0p_{1/2}$
^{14}O	2.77	3.03	2.69	2.72
^{16}O	2.80	2.95	2.78	2.91
^{18}O	2.81	2.91		
$^{16}O(e,e'p)^{15}N$	2.719(24)	2.943(30)		



Data points from :
[V. Bechtold et al., Phys. Lett. B **72**,169 (1977)]
[M. Gaillard et al., Nucl. Phys. A **119**, 161 (1968)]

r_0 dependence



Potentials used: (KD+GDP08)

Linear fit (a*r0+b) between 1.3 fm and 1.5:

Reaction	$S_{n,p}$ (MeV)	a (slope)
^{14}O(d,t)^{13}O	23.2	-3.85
^{18}O(d,^{3}He)^{17}N	15.9	-3.00
^{16}O(d,^{3}He)^{15}N	12.1	-2.4
^{14}O(d,^{3}He)^{13}N	4.6	-1.35

- The $C^2S_{exp}(r_0)$ dependence is enhanced if the transfer nucleon is more bound
  - For r_0 in [1; 1.25] fm, this effect becomes even larger (non linear)

Ex. for 14O(d,t): for r_0= 1.40 fm ⇒ $C^2S_{exp} \approx 1.3$
for r_0= 1.25 fm ⇒ $C^2S_{exp} \approx 2.1$

(≈ 11% change) (≈ 60% change)

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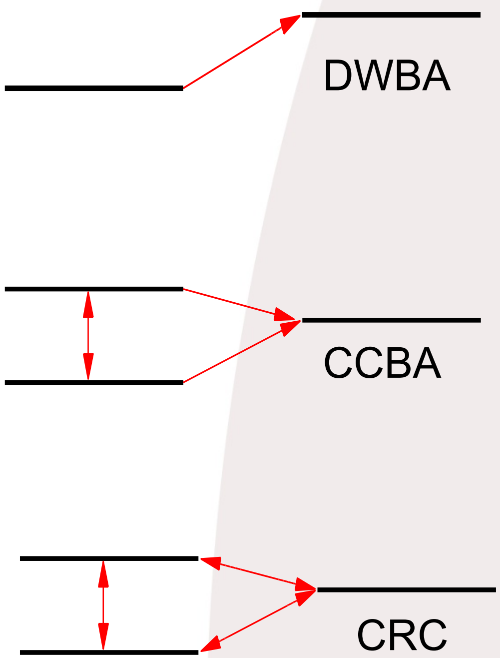
Framework

Framework

Four main reaction approaches for transfer reactions:



1) The **D**istorted **W**ave **B**orn **A**pproximation (**DWBA**)

- the simplest : assumes direct, one-step process that is weak

2) The adiabatic model:

- modification of DWBA for (d,p) and (p,d) reactions
- deuteron breakup effects included in an approximate way

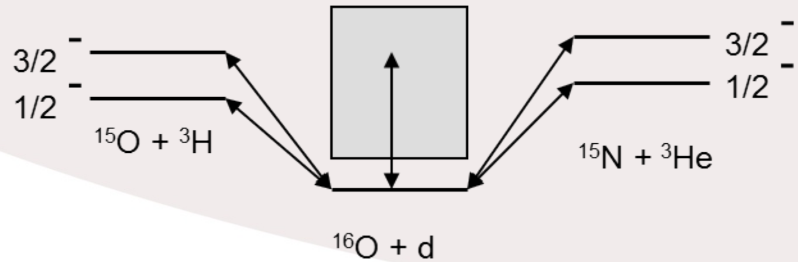
3) The **C**oupled **C**hannels **B**orn **A**pproximation (**CCBA**) :

- used when the assumption of a one-step transfer process breaks down
- strong inelastic excitations modelled with coupled channels theory
- transfers still with DWBA

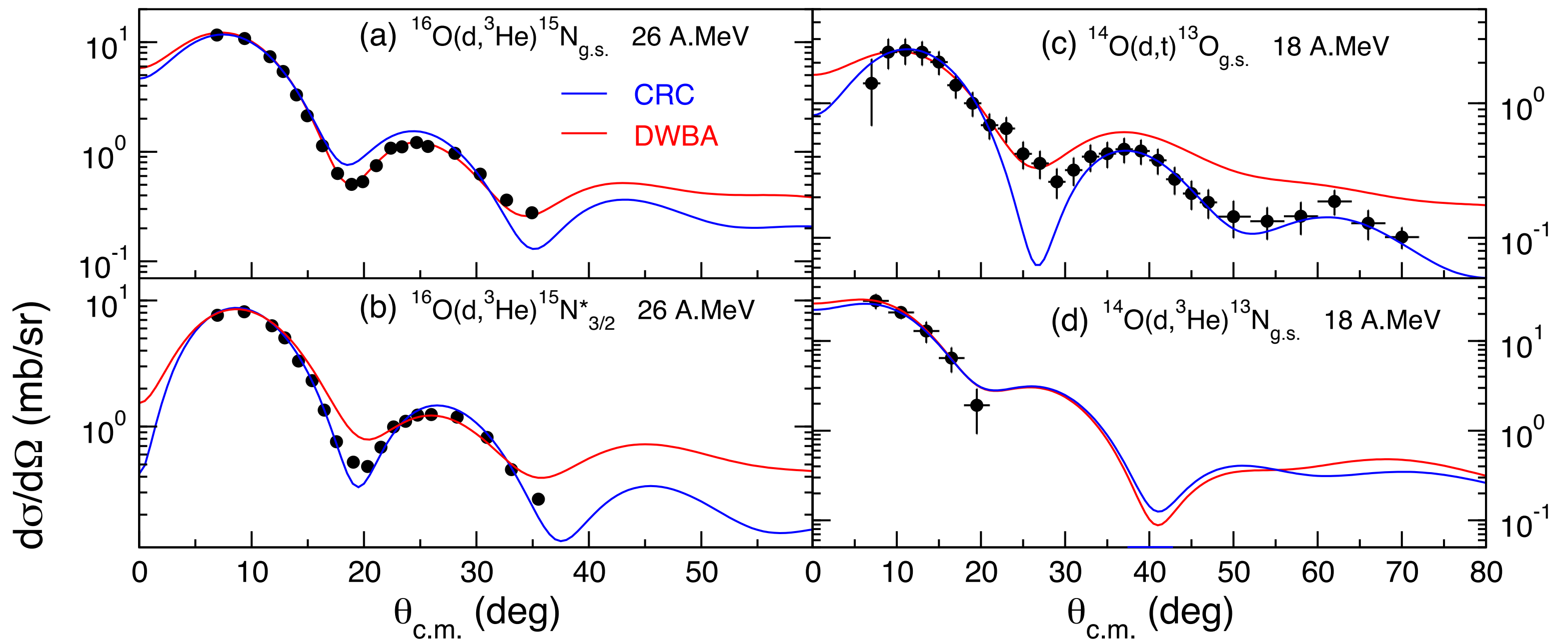
4) **C**oupled **R**eaction **C**hannels (**CRC**):

- does not assume one-step or weak transfer process.
- All processes on equal footing;
- (complex) rearrangements of flux possible

Example for ^{16}O:



Framework: CRC Vs DWBA



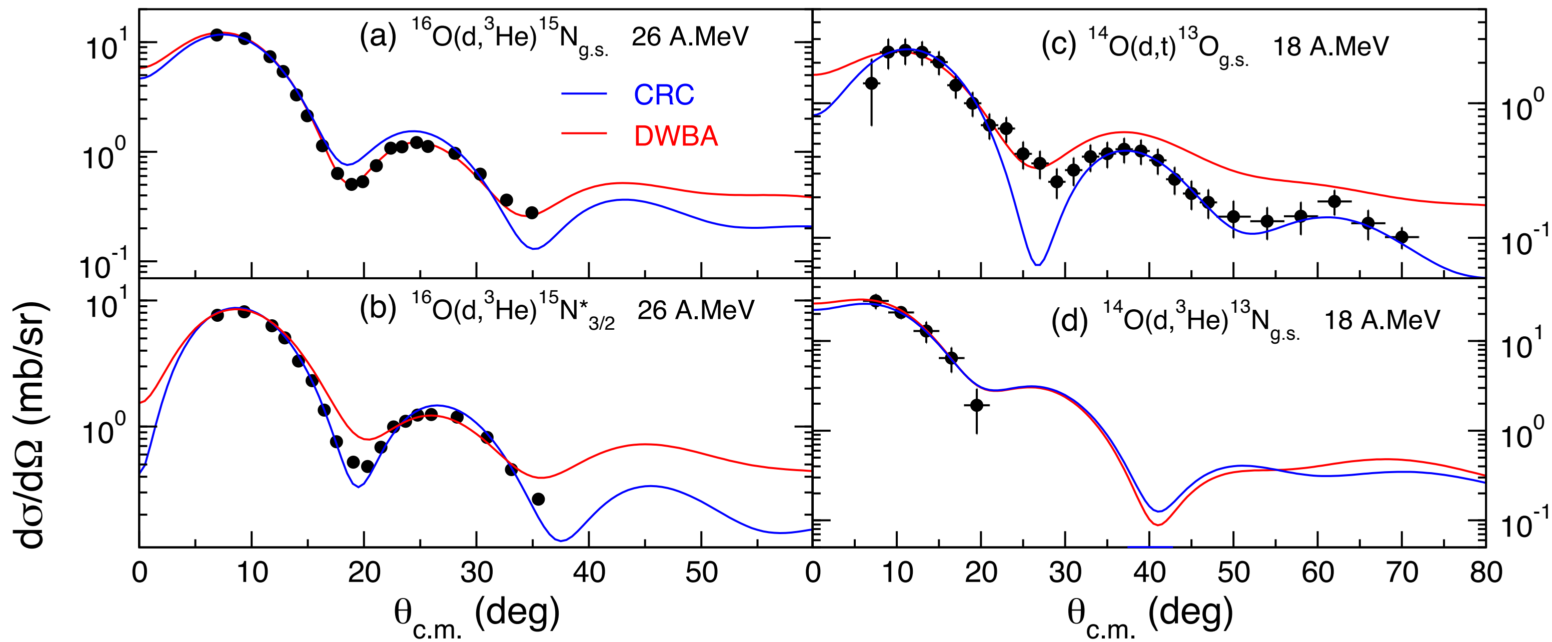
Parameters:

- One fixed set of potentials (KD+GDP08)
- Constrained Woods Saxon overlap functions

Shapes

- Better described by CRC (in general)
- But DWBA works rather well too
  (especially for small angles)

Framework: CRC Vs DWBA



Reaction	E* (MeV)	r_0 (fm)	C^2S_{exp} CRC	C^2S_{exp} DWBA	$\delta(C^2S_{exp})$ %
$^{14}O(d,^3H)^{13}O$	0	1.40	1.35	1.00	35
$^{14}O(d,^3He)^{13}N$	0	1.23	1.15	1.31	-12
	3.5	1.12	1.02	0.90	12
$^{16}O(d,^3He)^{15}N$	0	1.46	0.94	0.94	0
	6	1.31	2.00	1.70	18

$$\delta = (C^2S_{exp}^{CRC} - C^2S_{exp}^{DWBA}) / C^2S_{exp}^{DWBA}$$

Normalisation and C^2S_{exp}

- **Reaction dependant** effect
- Up to **35%** difference for $^{14}O(d,t)$

→ **Systematic error**

Ab-initio overlap functions

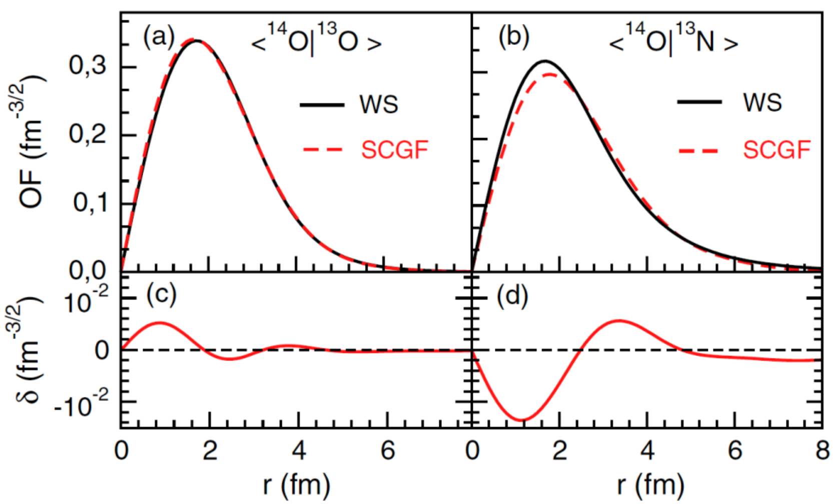
A crucial choice

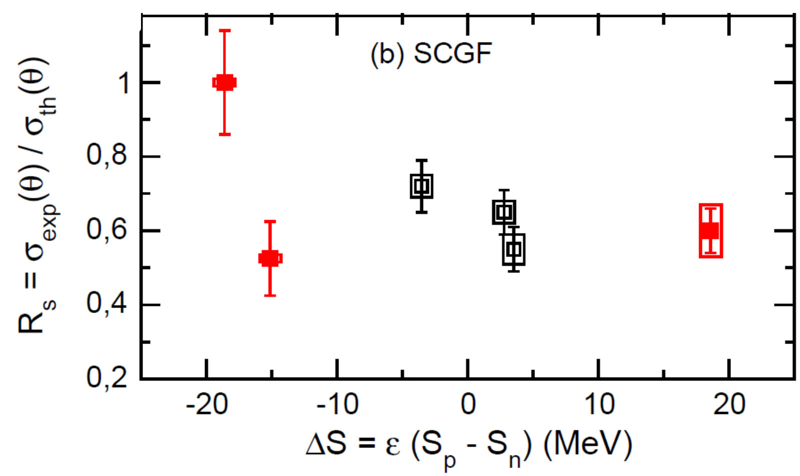
- Overlap Function
  - Woods-Saxon geometry
    - (r_0,a_0) = (1,25; 0.65) fm
    - HF constrained r_0 + Exp. Sn
  - Ab-intio calculation

Results with ab-initio overlaps

Ab-inito SF_{th} and overlaps (from C. Barbieri and A. Cipollone)

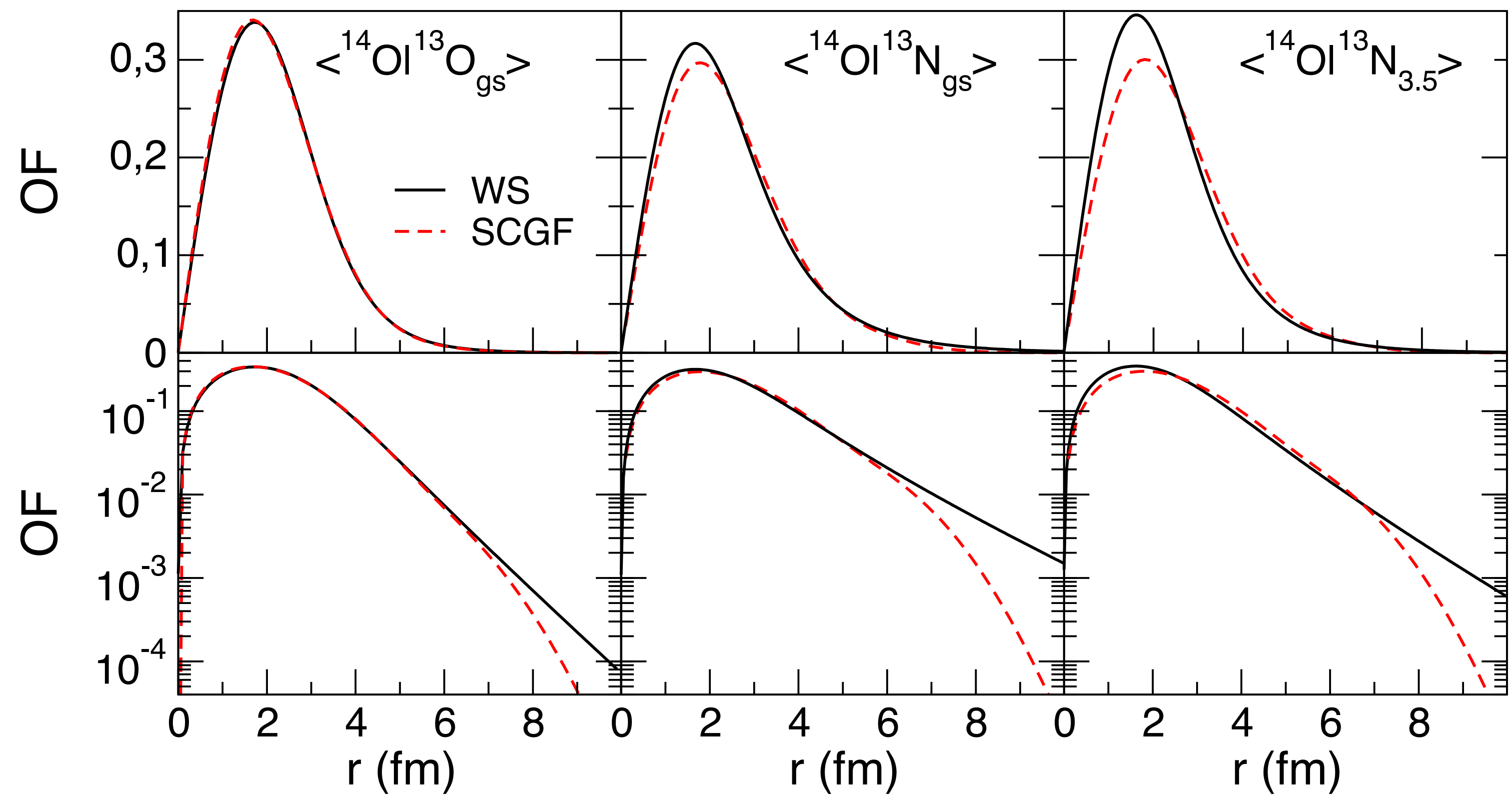
- Single-particle Green's function (third order diagrammatic construction method)
- Chiral two-body + three-body interactions (cutoff λ=1.88 fm^{-1})





$$\sigma_{th}(\theta) = C^2 S_{th}\, \sigma_{sp}(\theta)$$

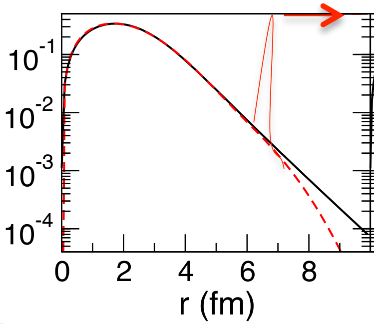
Radial sensitivity – Asymptotic tails



→ After (6-7) fm: **differences** between WS and ab-initio overlaps

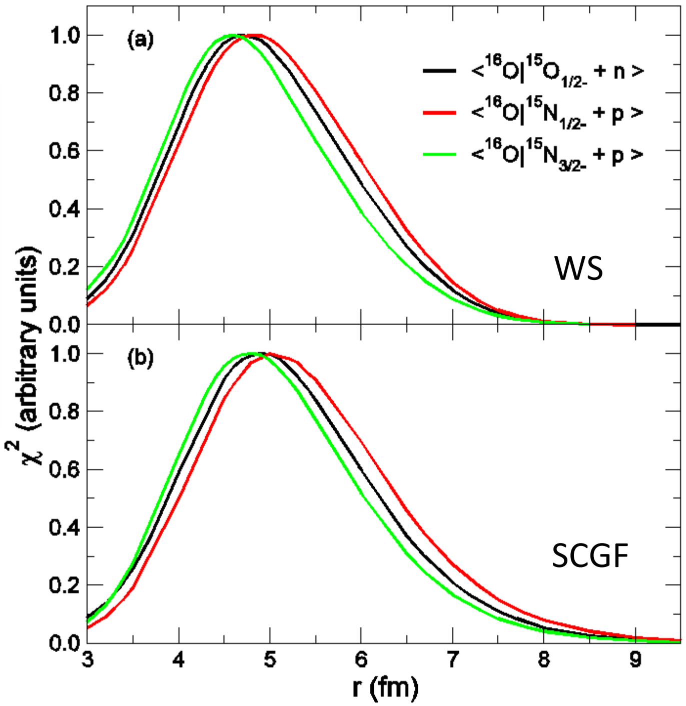
Radial sensitivity – notch test

notch

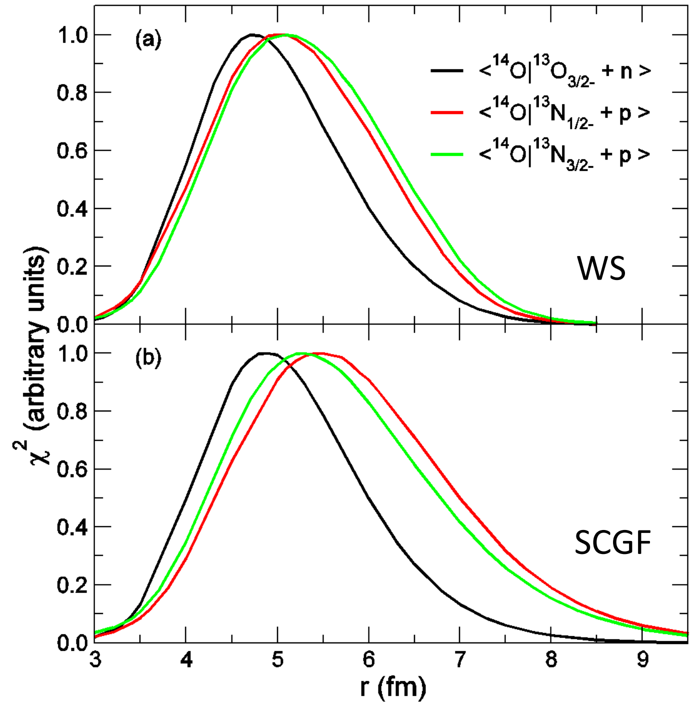


$$\chi^2 = \Sigma((d\sigma/d\Omega)_{pert} - (d\sigma/d\Omega)_{un})^2/(d\sigma/d\Omega)^2_{un}$$

For ^{16}O



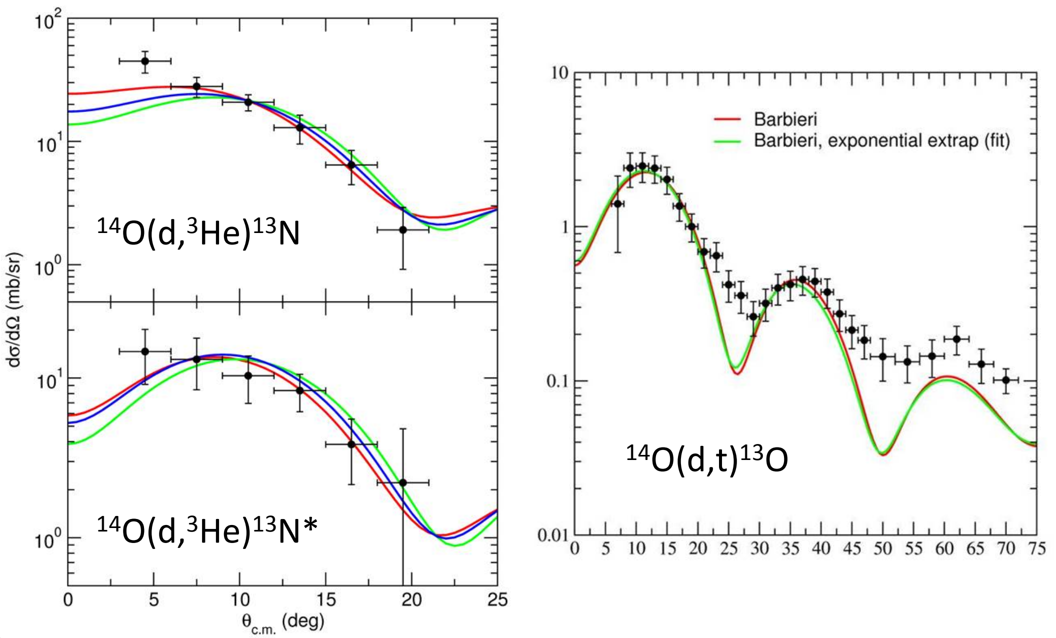
For ^{14}O



→ Effect of asymmetry visible on the region probed for ^{14}O

Radial sensitivity – Asymptotic tails

With extrapolated ab-initio OFs (after 7fm)



⇨ Small shape changes (within exp. errors)

C^2S_{exp}	1 (SCGF)	2 (SCGF ext.)	(2/1)
$^{14}O(d,t)^{13}O$	2.41	2.28	**0.95**
$^{14}O(d,^3He)^{13}N$	1,58	1.42	**0.90**
$^{14}O(d,^3He)^{13}N_{3/2-}$	1.01	0.86	**0.85**

Effect on ⇨ $Rs = C^2S_{exp}/C^2S_{th}$

Rs(1)	Rs(2)
0.60(6)(7)	0.57
1.00(14)(1)	0.90
0.53(10)(1)	0.45

Partial Conclusions

Conclusions :

- Agreement between standard presciption (WS+SM) and ab-initio
- Weak asymmetry dependence within the error bars

Sensitivity study:

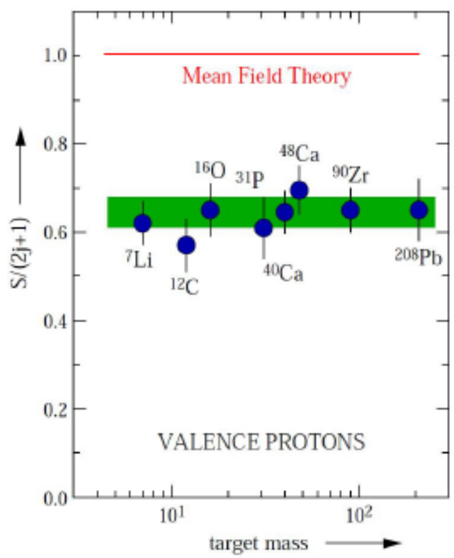
- Agreement between $^{14}O(d,t)^{13}O$ and $^{14}O(p,d)^{13}O$
- C^2S_{exp} extracted with CRC can differs significantly from DWBA
  - Even if the first maximum is well reproduced in both cases
  - Should be checked case by case…
- The dependance of C^2S_{exp} on (r_0,a_0) WS geometries is enhanced for large S_n
- Ab-intio overlap functions have pathologies regarding their asymptotic tails

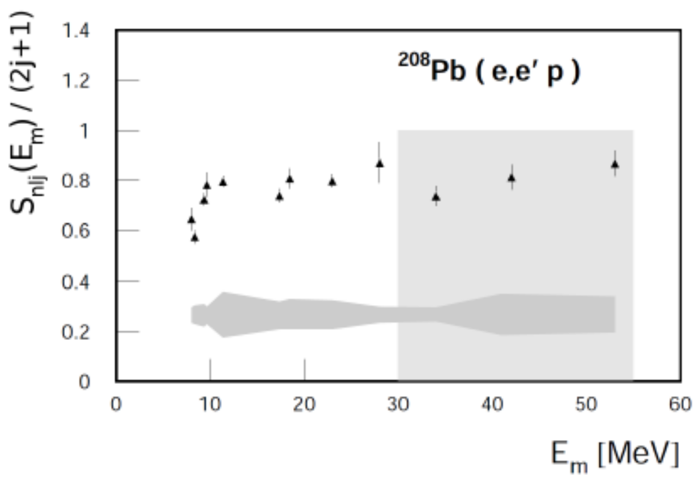
BUT:

- Reactions at stake in our study are weakly sensitive to this pathologies
- Radial sensitivity to OFs can be checked or corrected if necessary

Backup slides

Occupation des couches dans les noyaux stables





Les réactions (e,e'p) :

- interaction électromagnétique
- interaction du proton dans l'état final

⟶ Réduction entre 30 et 40% en moyenne

W. Dickhoff, Prog. Nucl. Phys. **52**, 377 (2004).

L. Lapikas, Nucl. Phys. A. **553**, 297-308 (1993).

Corrélations au delà du champ moyen :

- couplage à des excitations collectives.
- corrélations à courte portée.

C. Barbieri, Phys. Rev. Lett. **103**, 202502 (2009).

Dépendance en énergie de liaison :

- Réduction moyenne de $0.78 \pm 0.02 \pm 0.08$.

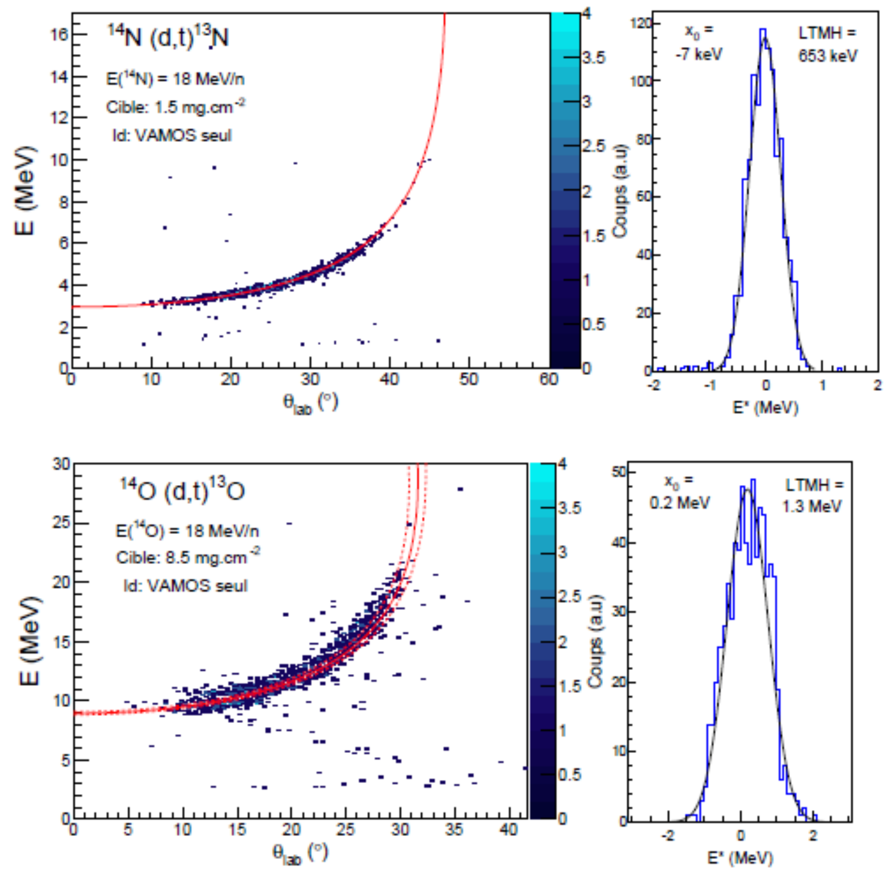
M. F. Van Batenburg, PhD thesis, University of Utrecht (2001).

Accord entre résultats (d,^{3}He) et (e,e'p).

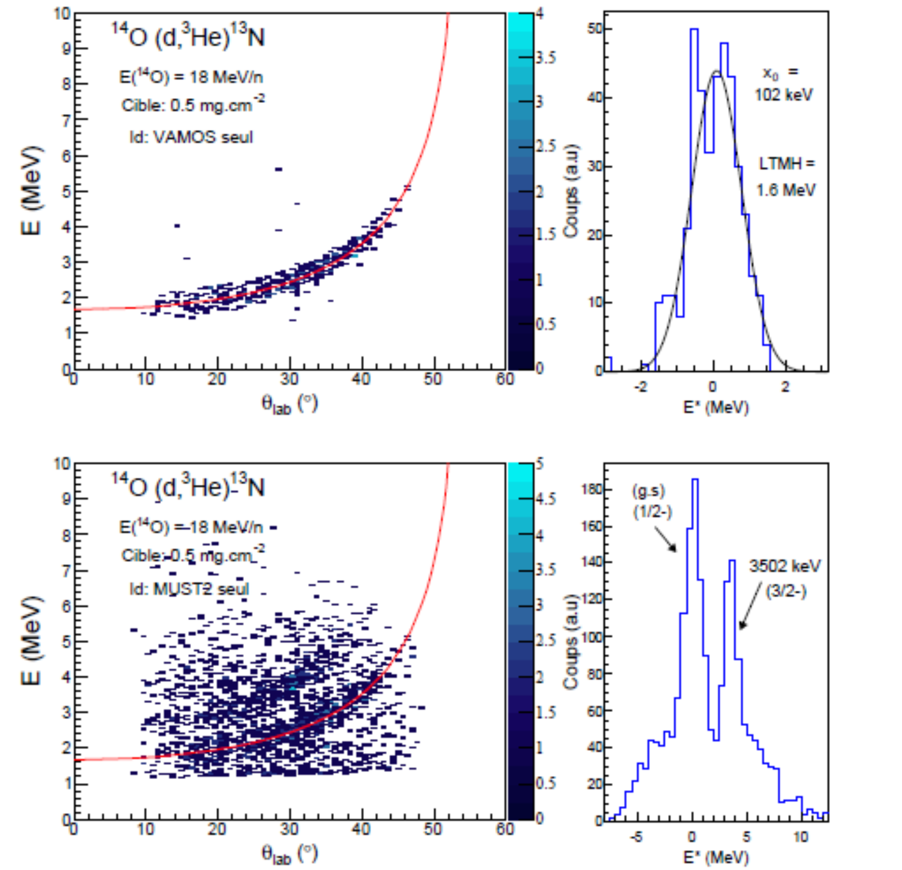
G. J. Kramer *et al.*, NPA **679** (2001) 267.

Kinematics

Transferts (d,t)



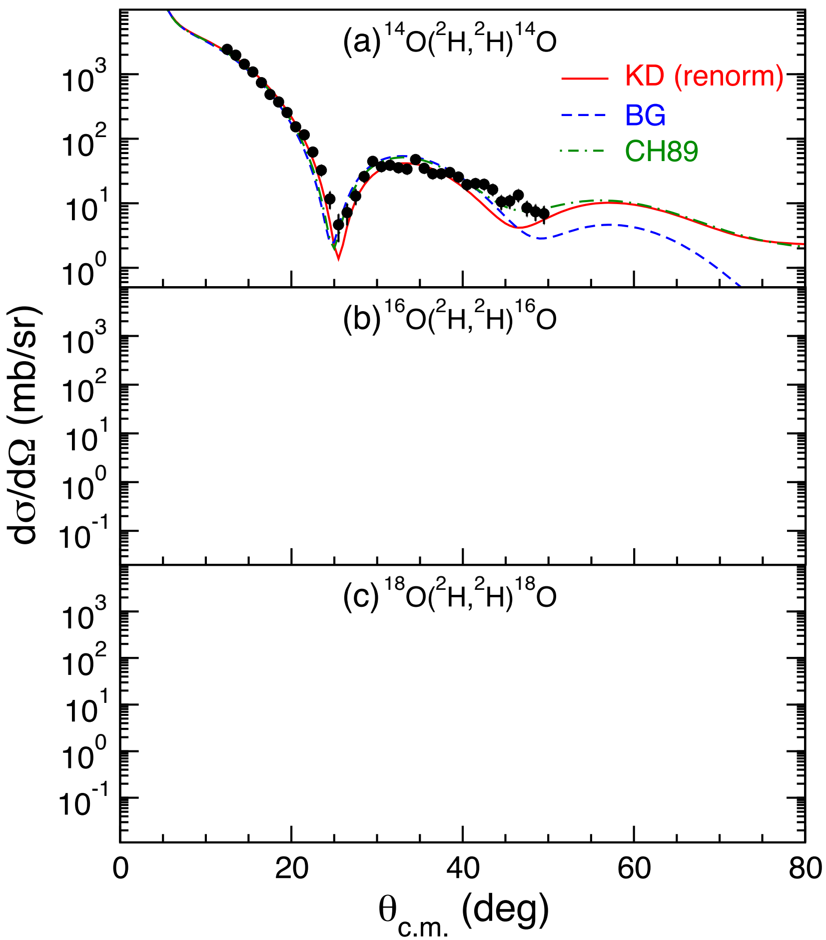
Transfert (d,^{3}He) : Sélection M2-VAMOS



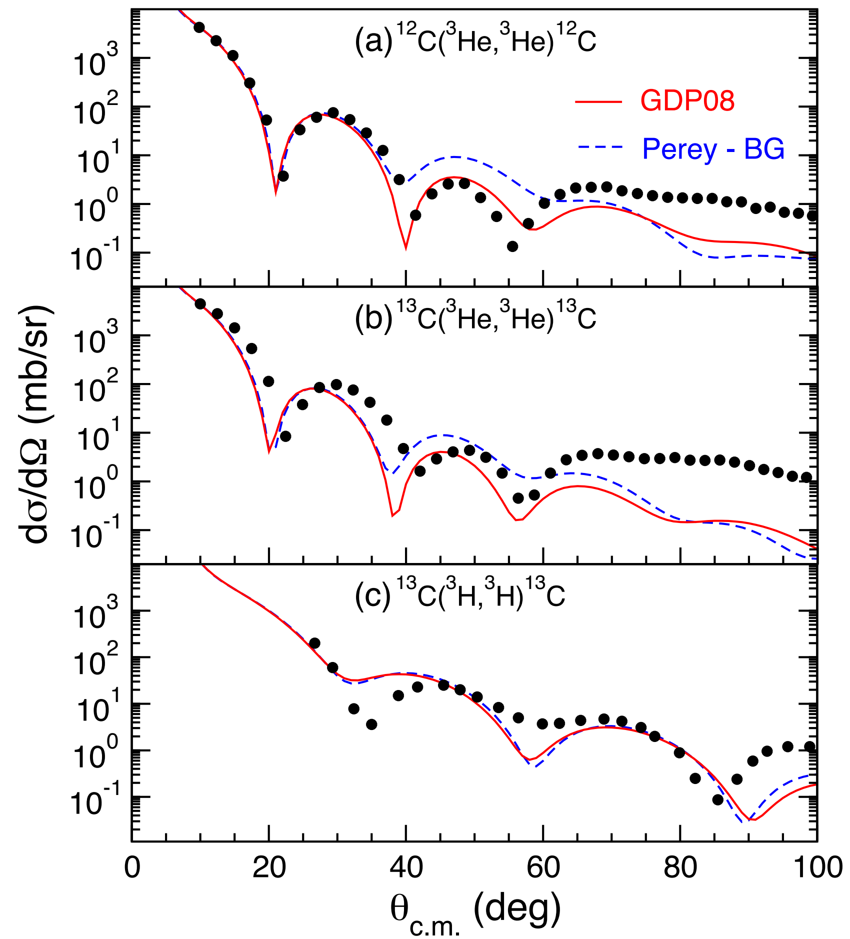
Potentials

Potentials : Elastic scattering benchmark

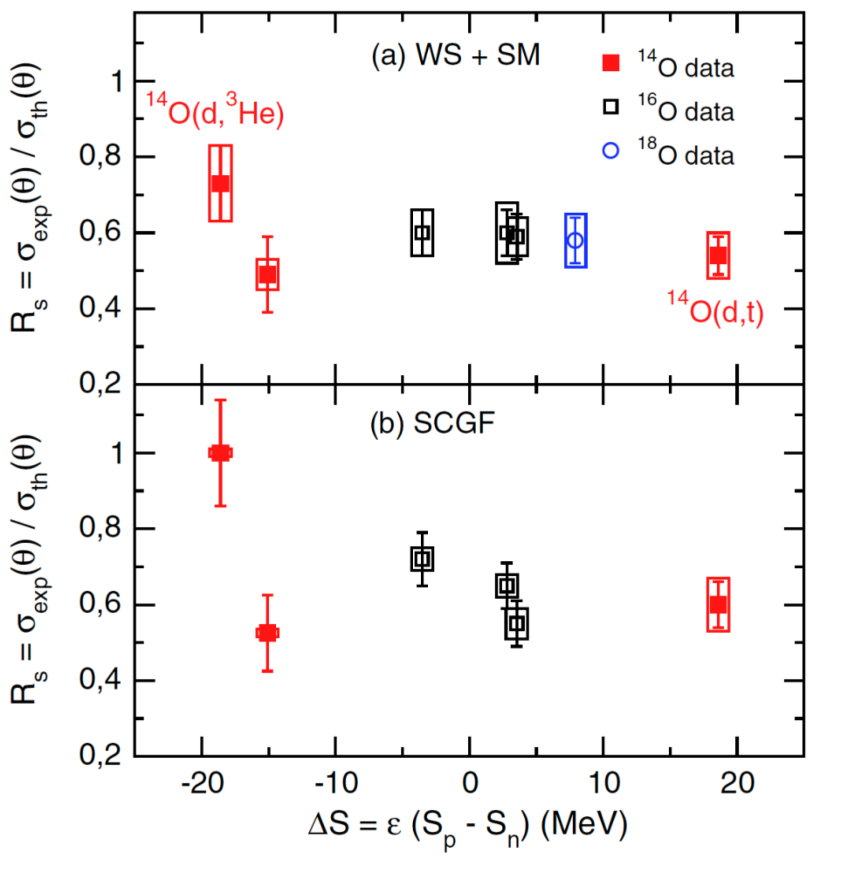
Entrance channel



Exit channel



Conclusion



α = +0.0004(24)(12) MeV^{-1}

β = Rs(0) = 0.538(28)(18)

α = -0.0042(28)(36) MeV^{-1}

β = Rs(0) = 0.538(28)(18)

Conclusion :

- **Agreement between standard presciption (WS+SM) and ab-initio**
- **Weak asymmetry dependence within the error bars**