Two-neutron pairing correlations in 112Sn, 32Mg and 68Ni, investigated through transfer reactions: new insights

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Outline:

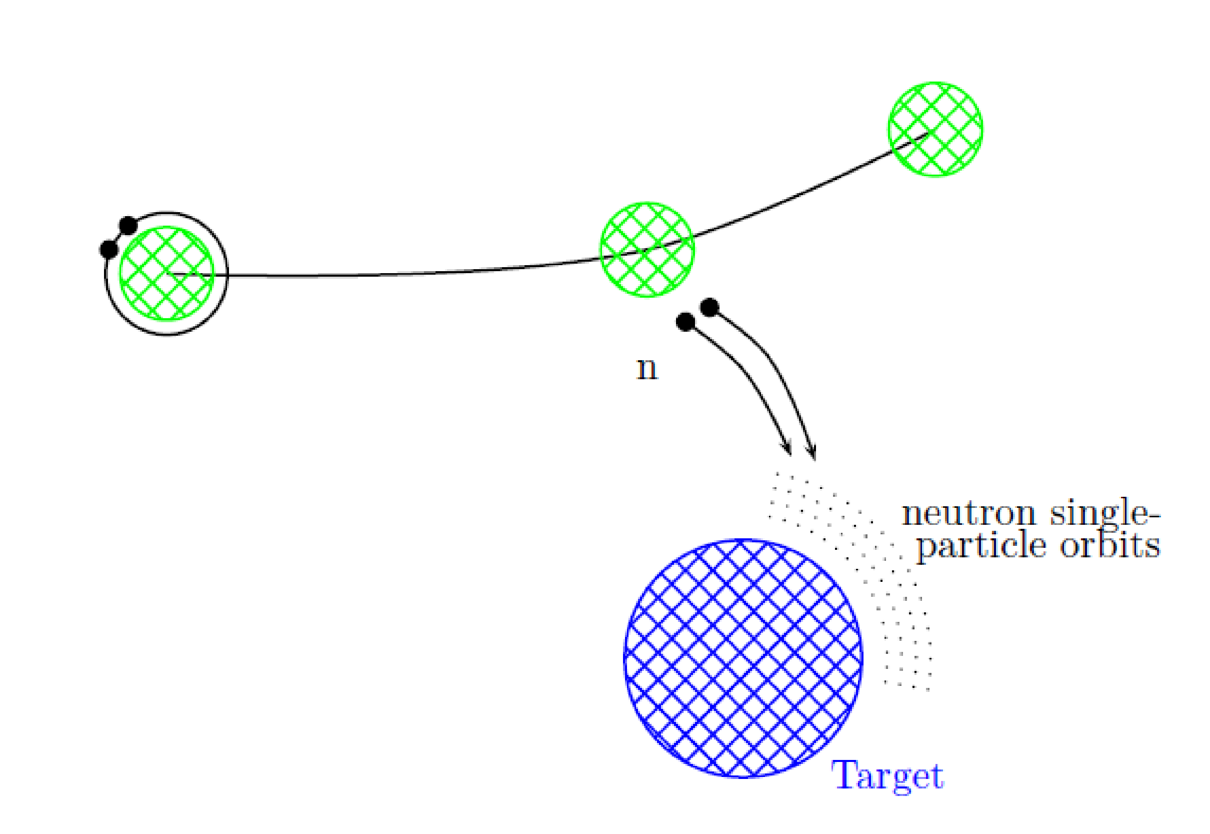
- Two- neutron transfer reactions
- (d,p) and (t,p) with DWUCK (J.A. Lay)
- 1 and 2 nucleon transfer with heavy ion reactions : (14C,12C) (16O,18O) -> **Our new code**
- Targets of special interest:
  - 112Sn : superfluid
  - 32Mg : island of inversion
  - 68Ni : issue of magicity

  we use a very simple model with a few relevant s.p. orbitals and we look for the consequences on transfer.
- Summary and conclusions

Mathematica code (notebook format) for 1 and 2 nucleon transfer reactions

$$\underbrace{a}_{\substack{b+n \\ b_2+2n}} + A \rightarrow \underbrace{b}_{b_2+n} + \underbrace{B}_{A+n} \rightarrow b_2 + \underbrace{B_2}_{\substack{A+2n \\ B+n}}$$

transfer process with $I_a = I_A = I_{b_2} = I_{B_2} = 0$



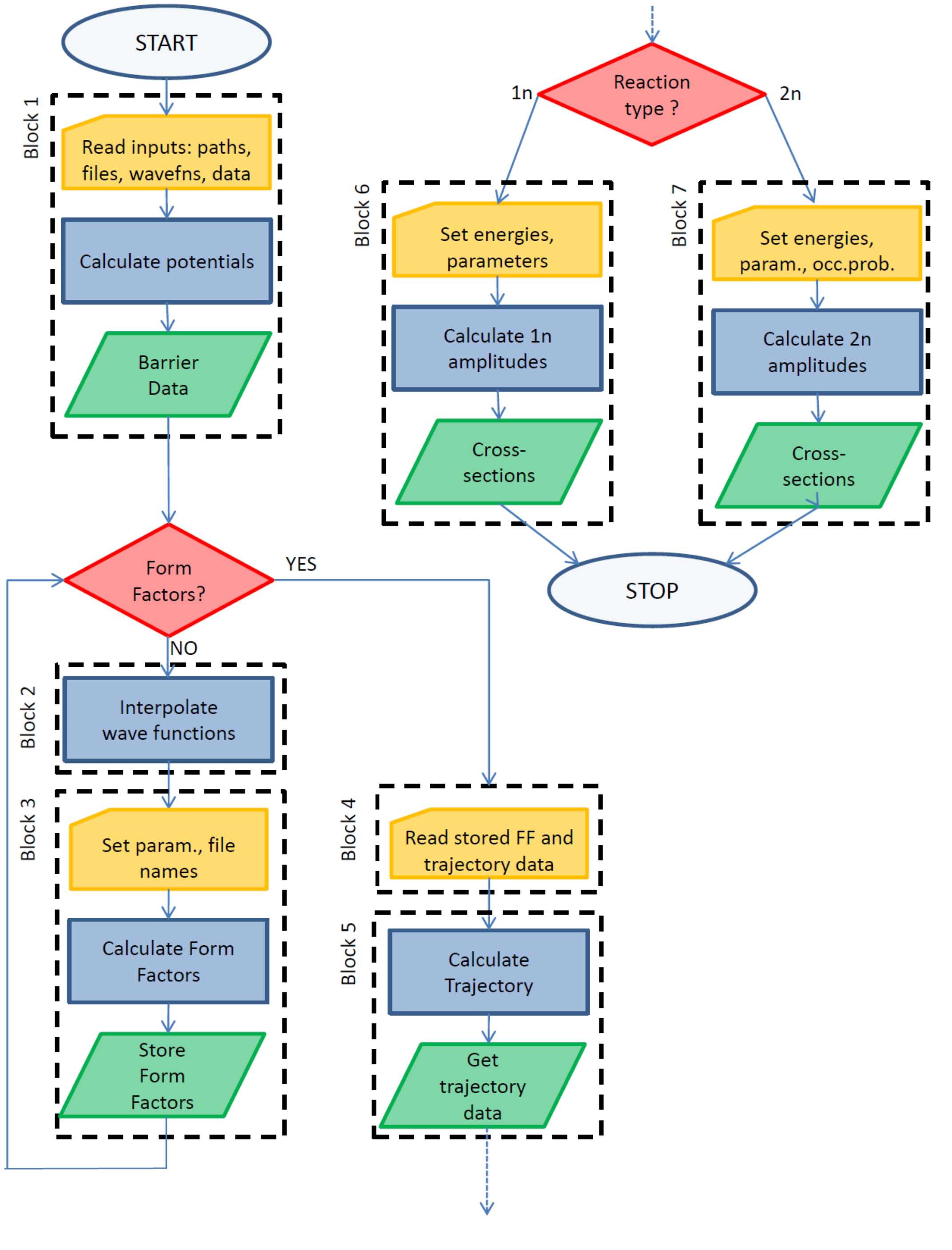
CALCULATIONS INPUTS

Structure inputs are :

- Masses and charges of colliding nuclei
- Woods-Saxon potential parameters (V_0,r_0, a_0) and spin-orbit V_{ls} adjusted to reproduce s.p. energies with correct quantum numbers and right separation energy
- Occupation numbers

Reaction inputs are :

- Bombarding energy
- Q-values (1-particle and 2-particle transfer)
- Ion-ion potential for the relative motion and absorption V(r)+ iW(r) : we take an Akyüz-Winther parameterization for simplicity, but any other optical or proximity potential can be used



T.F.F. – v.3.7
Code Flowchart:

- Reading inputs
- Calculating F.F.
- Calculate Reactions
  - Trajectory
  - 1n transfer
  - 2n transfer

Form Factor: $$f_{\beta\alpha}(\vec{r}) = \langle \psi_\beta \mid U_A \mid \psi_\alpha \rangle$$

1° step amplitudes : $$\underbrace{a}_{b+n} + A \rightarrow b + \underbrace{B}_{A+n}$$

$$a_1(b,t)_{\alpha\to\beta} = -i \sum_{JJ'MM'\lambda\mu} \langle I_A M_A J M \mid I_B M_B \rangle$$

$$\langle I_b M_b J' M' \mid I_a M_a \rangle \langle \lambda\mu J M \mid J' M' \rangle I_{\lambda\mu}(b,t)$$

where $I_{\lambda\mu}$ is the orbital integral, defined by:

$$I_{\lambda\mu} = D^{\lambda}_{\mu 0}(0,\pi/2,\pi)\frac{1}{\hbar}\int_{-\infty}^{t} f_{\beta,\alpha}(r(b,t'))e^{\frac{i}{\hbar}((E_\beta - E_\alpha)t' + \gamma_{\beta\alpha}(t')) + i\mu\phi(t')}dt'$$

2° step amplitudes :

$$a^{(2)}(b) \;=\; g\sum_{\beta} B_i(a)B_j(A)\int_{-\infty}^{\infty} dt'\, f_{\beta_2\beta}(r)\; e^{\frac{i}{\hbar}(Q_{\beta_2\beta}t' + \gamma_{\beta_2\beta}(t') + i\mu\phi(t'))}\int_{-\infty}^{t'} dt\, f_{\beta\alpha}(r)\; e^{\frac{i}{\hbar}(Q_{\beta\alpha}t + \gamma_{\beta\alpha}(t) - i\mu\phi(t))}$$

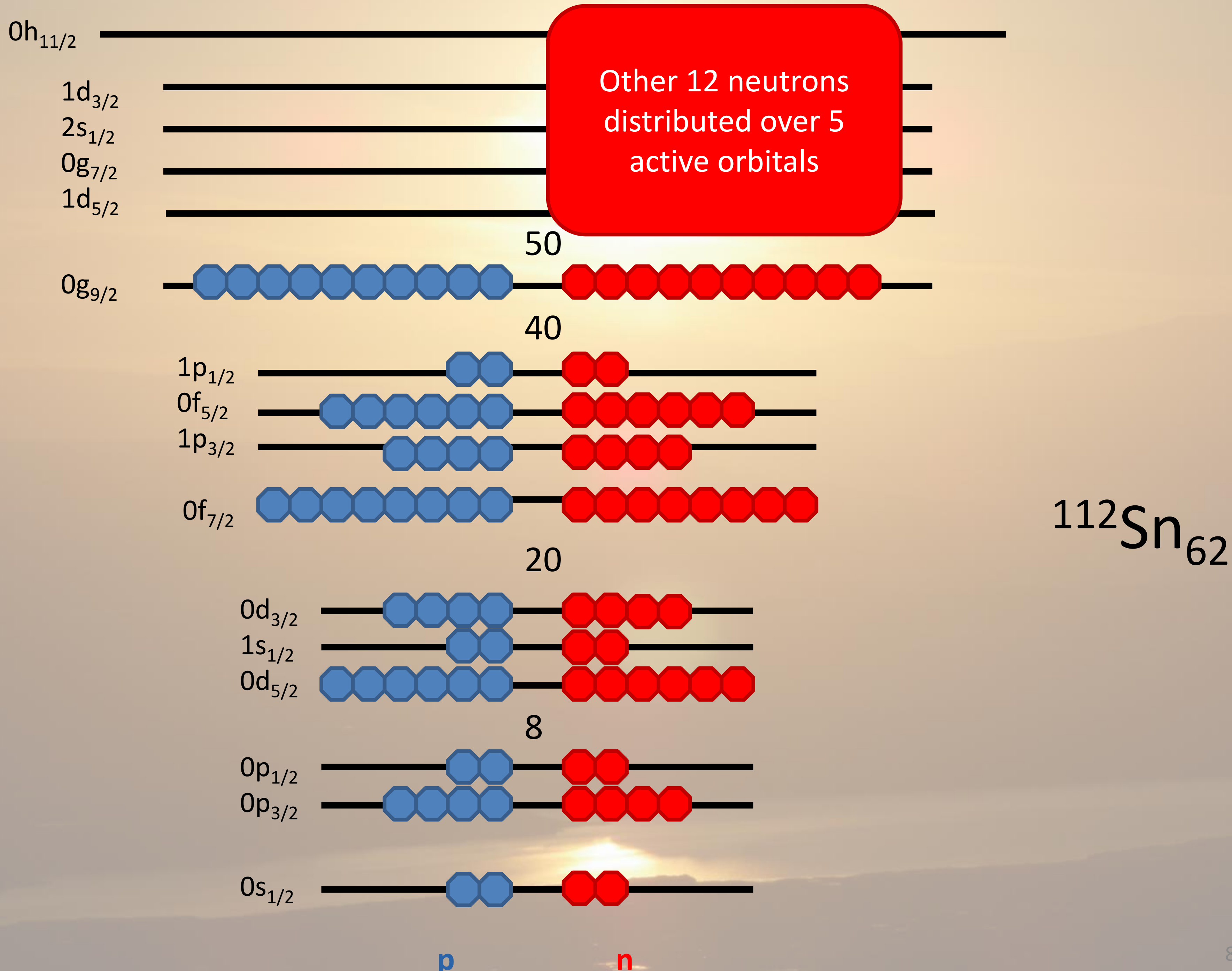
^{112}Sn

Simple BCS wavefunction with 5 active orbitals: 0g7/2, 1d5/2, 0h11/2, 2s1/2, 1d3/2

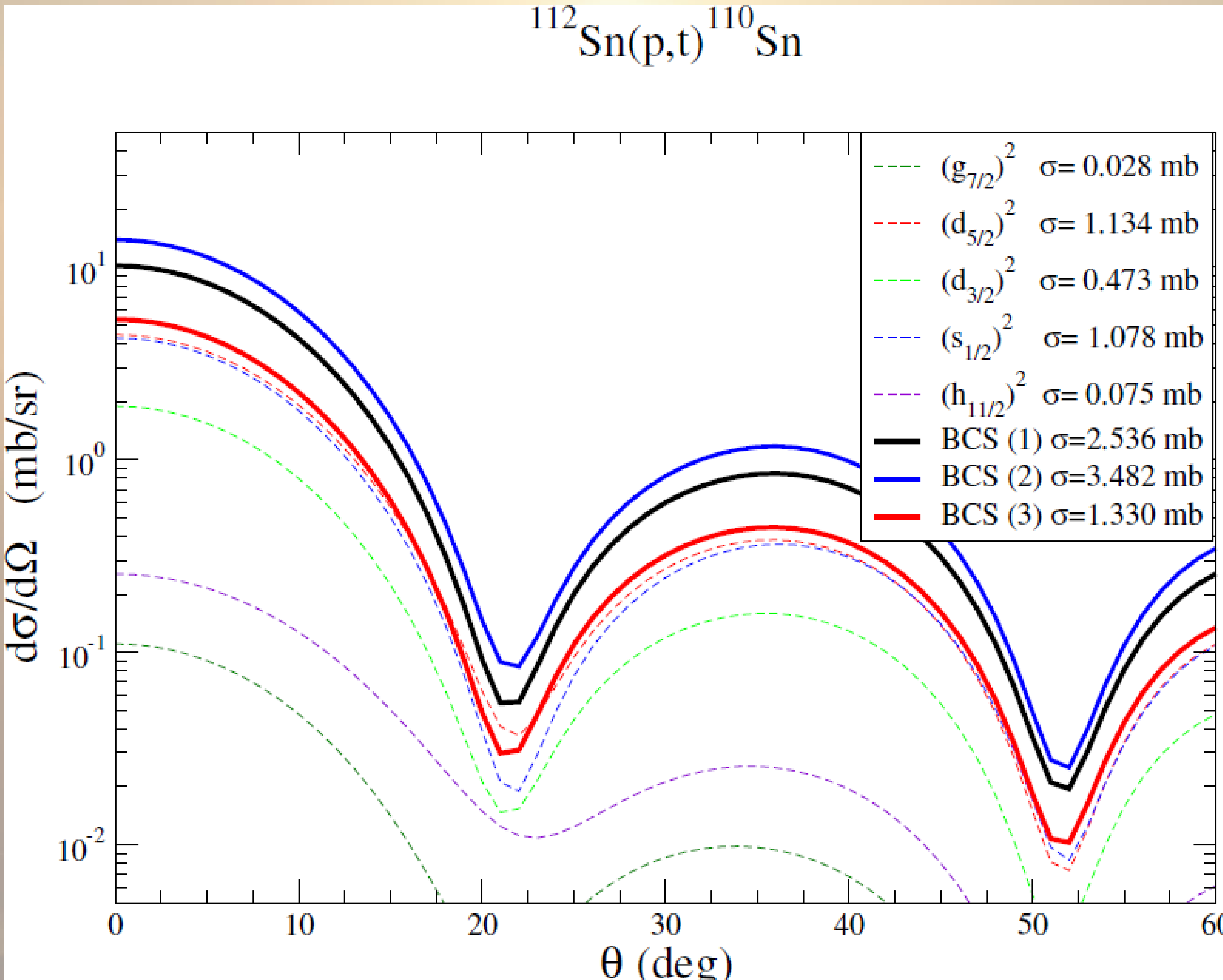
	ϵ_i(MeV)	B_i	ϵ_i(MeV)	B_i	ϵ_i(MeV)	B_i
$0g_{7/2}$	-0.027	0.75	-0.027	1.15	-2.027	0.64
$1d_{5/2}$	0.882	1.13	-0.118	0.57	0.882	1.02
$2s_{1/2}$	1.330	0.53	-0.670	0.33	1.330	0.59
$0h_{11/2}$	2.507	0.79	4.507	0.61	5.507	0.46
$2d_{3/2}$	2.905	0.39	2.905	0.26	2.905	0.27

G. Potel, F. Barranco, E. Vigezzi, and R. A. Broglia, Phys. Rev. Lett., **105**, 172502 (2010).

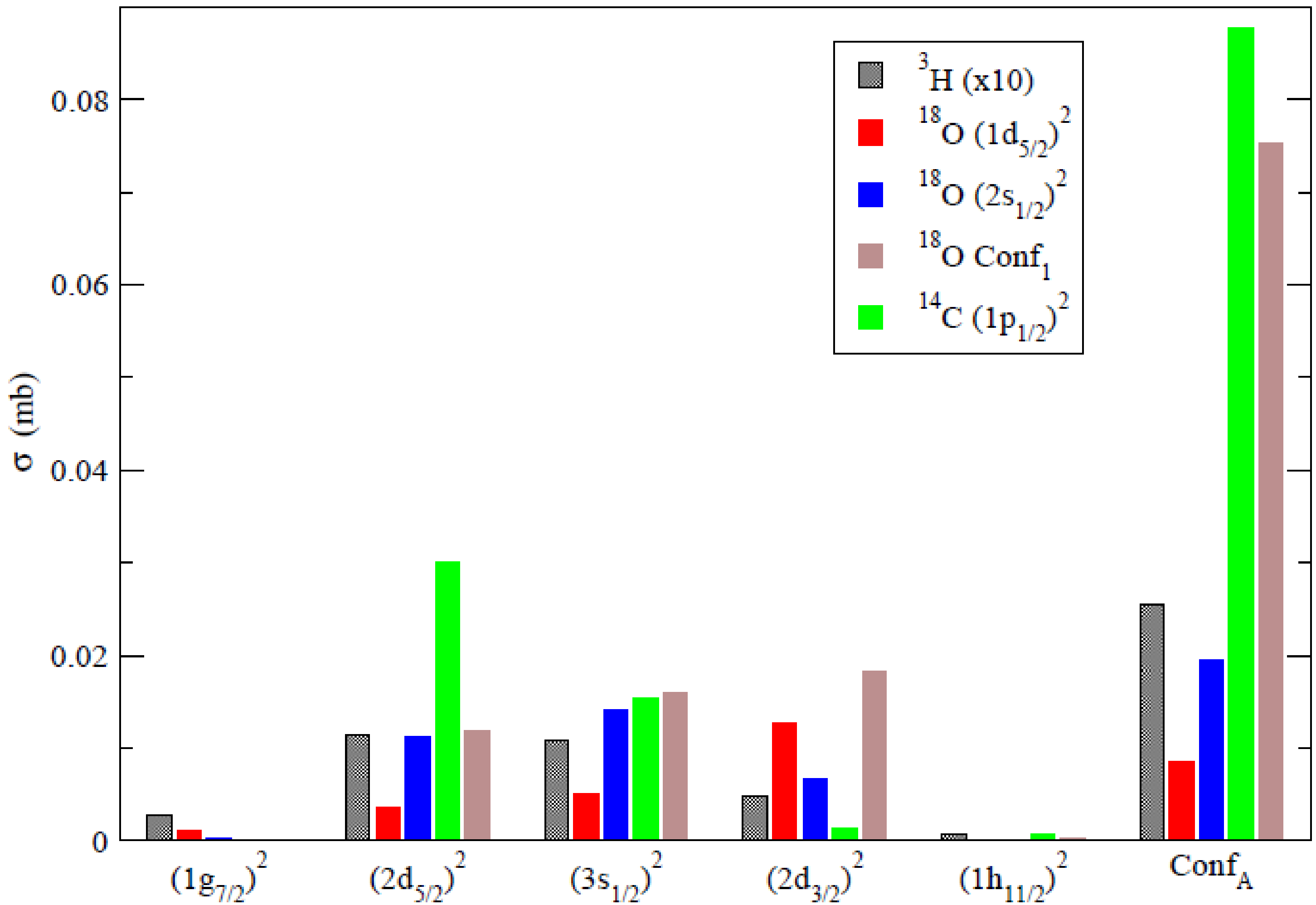
^{112}Sn	(t,p)	(^{14}C,^{12}C)				(^{18}O,^{16}O)		
		$(0p_{1/2})^2$	$(1s_{1/2})^2$	$(0p_{3/2})^2$	$(0d_{5/2})^2$	$(0d_{5/2})^2$	$(1s_{1/2})^2$	Conf_1
$(0g_{7/2})^2$	2.80E-2	1.73E-5	1.19E-4	7.09E-4	9.00E-4	1.19E-3	2.01E-4	1.24E-3
$(1d_{5/2})^2$	1.13	3.00E-2	4.71E-3	5.54E-3	1.18E-3	3.55E-3	1.13E-2	1.19E-2
$(2s_{1/2})^2$	1.08	1.53E-2	5.38E-3	7.05E-3	1.16E-3	5.02E-3	1.42E-2	1.59E-2
$(1d_{3/2})^2$	4.73E-1	1.34E-3	2.79E-3	9.87E-3	4.14E-3	1.26E-2	6.62E-3	1.83E-2
$(0h_{11/2})^2$	7.50E-2	7.77E-4	5.29E-5	1.05E-4	7.65E-5	1.10E-4	9.06E-5	1.88E-4
Conf_A	2.54	8.77E-2	2.26E-2	3.77E-2	1.21E-2	8.60E-3	1.95E-2	7.53E-2



0h11/2
1d3/2
2s1/2
0g7/2
1d5/2
Other 12 neutrons distributed over 5 active orbitals
50
0g9/2
40
1p1/2
0f5/2
1p3/2
0f7/2
112Sn62
20
0d3/2
1s1/2
0d5/2
8
0p1/2
0p3/2
0s1/2
p
n



^{112}Sn(p,t)^{110}Sn
$(g_{7/2})^2$ σ= 0.028 mb
$(d_{5/2})^2$ σ= 1.134 mb
$(d_{3/2})^2$ σ= 0.473 mb
$(s_{1/2})^2$ σ= 1.078 mb
$(h_{11/2})^2$ σ= 0.075 mb
BCS (1) σ=2.536 mb
BCS (2) σ=3.482 mb
BCS (3) σ=1.330 mb
dσ/dΩ (mb/sr)
θ (deg)
10^1
10^0
10^{-1}
10^{-2}
0
10
20
30
40
50
60



σ (mb)
0.08
0.06
0.04
0.02
0
^{3}H (x10)
^{18}O $(1d_{5/2})^2$
^{18}O $(2s_{1/2})^2$
^{18}O $Conf_1$
^{14}C $(1p_{1/2})^2$
$(1g_{7/2})^2$
$(2d_{5/2})^2$
$(3s_{1/2})^2$
$(2d_{3/2})^2$
$(1h_{11/2})^2$
$Conf_A$

^{32}Mg : island of inversion

we can assume in a simple model for the addition and removal pairs the following configurations:

$$\Downarrow = (0d_{3/2})^{-2} \tag{3.1}$$

$$\Uparrow = a(0f_{7/2})^2 + b(1p_{3/2})^2 \tag{3.2}$$

and for the ground and excited state in ^{32}Mg the form

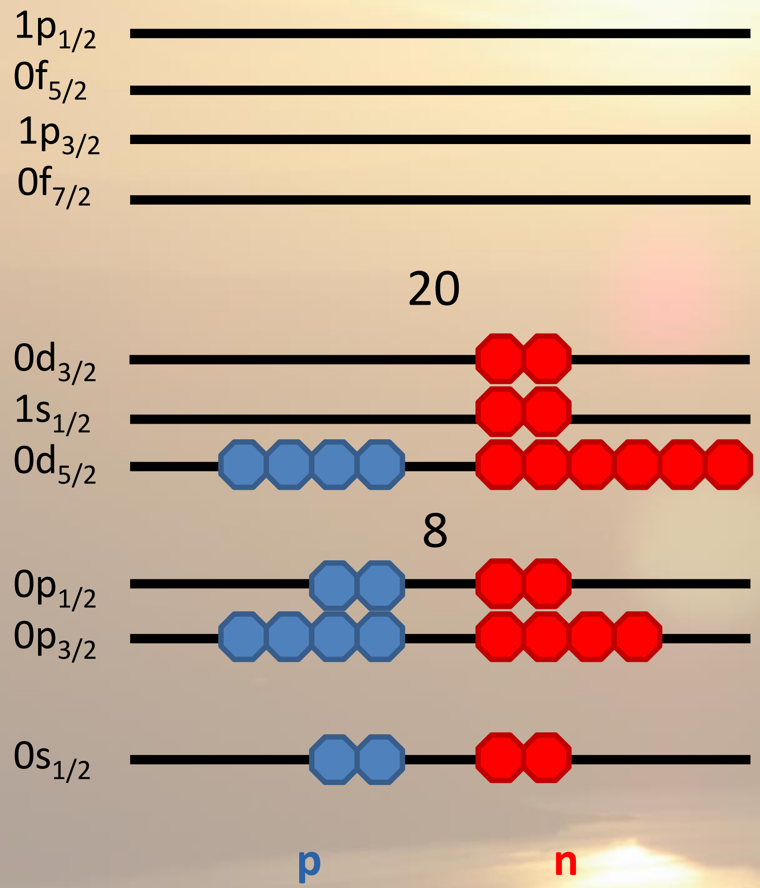
$$|\,0^+_{gs}\rangle \;=\; \alpha\,|\,0\rangle + \beta\,|\Downarrow\Uparrow\rangle \tag{3.3}$$

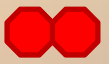
$$|\,0^+_{exc}\rangle \;=\; -\beta\,|\,0\rangle + \alpha\,|\Downarrow\Uparrow\rangle \tag{3.4}$$

where the coefficient a (and $b^2 = 1 - a^2$) determines the microscopic content of the pair addition state.

H. T. Fortune, Phys. Rev. C, **85**, 064615 (2012)
H. T. Fortune, Phys. Rev. C, **85**, 014315 (2012)
K. Wimmer *et al.*, Phys. Rev. Lett., **105**, 252501 (2010)

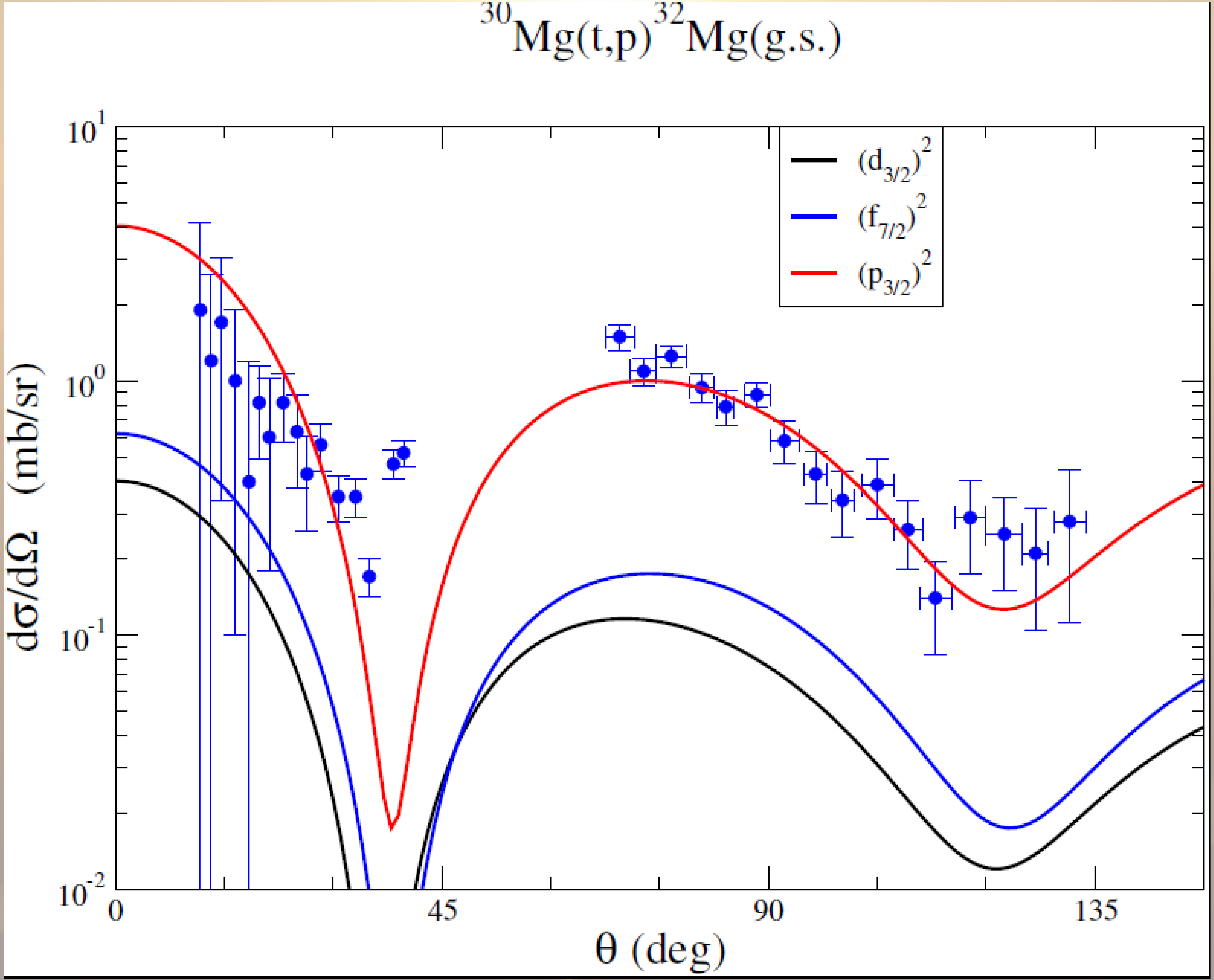
$^{30}Mg_{18}$ plus 2n : $^{32}Mg_{20}$

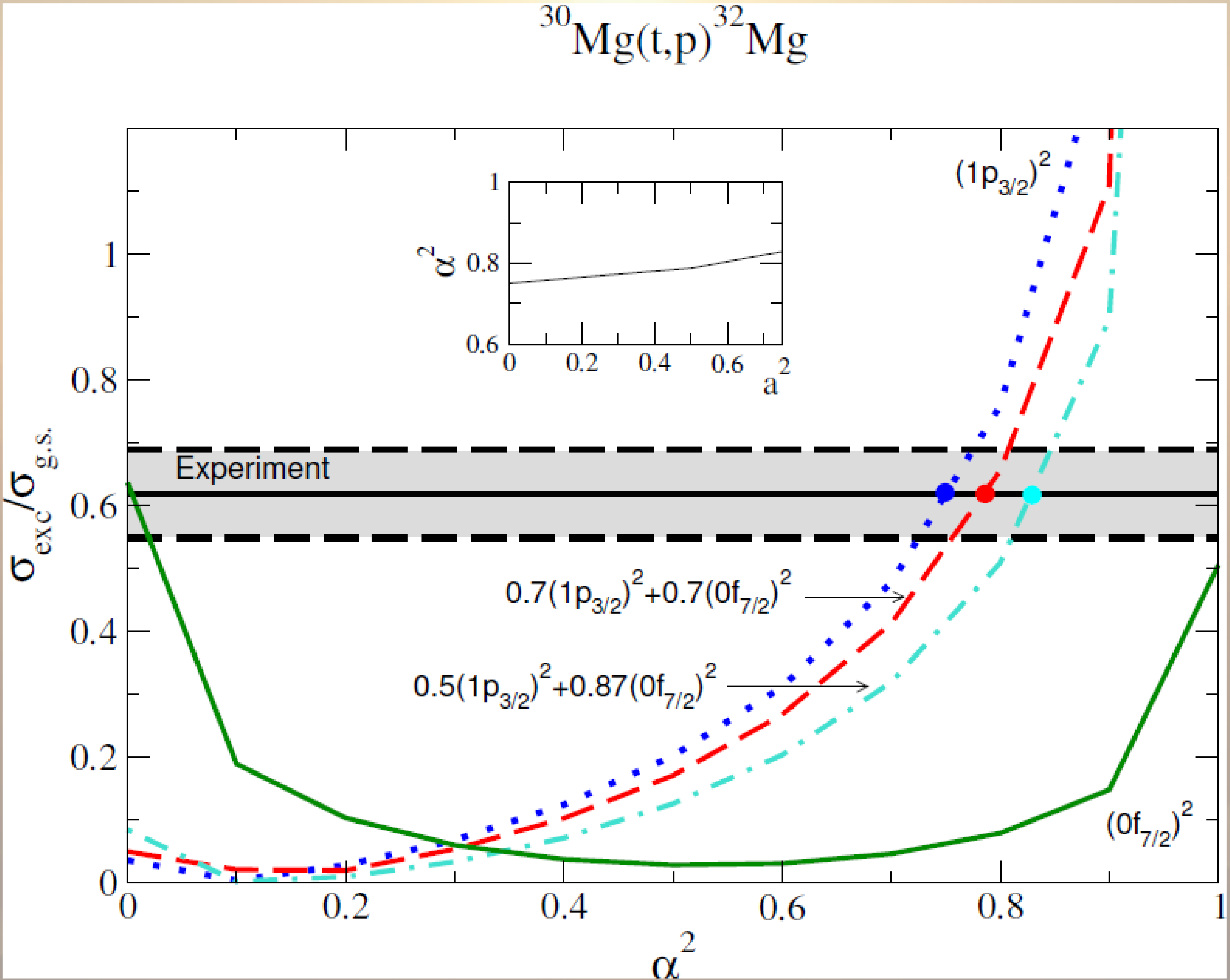




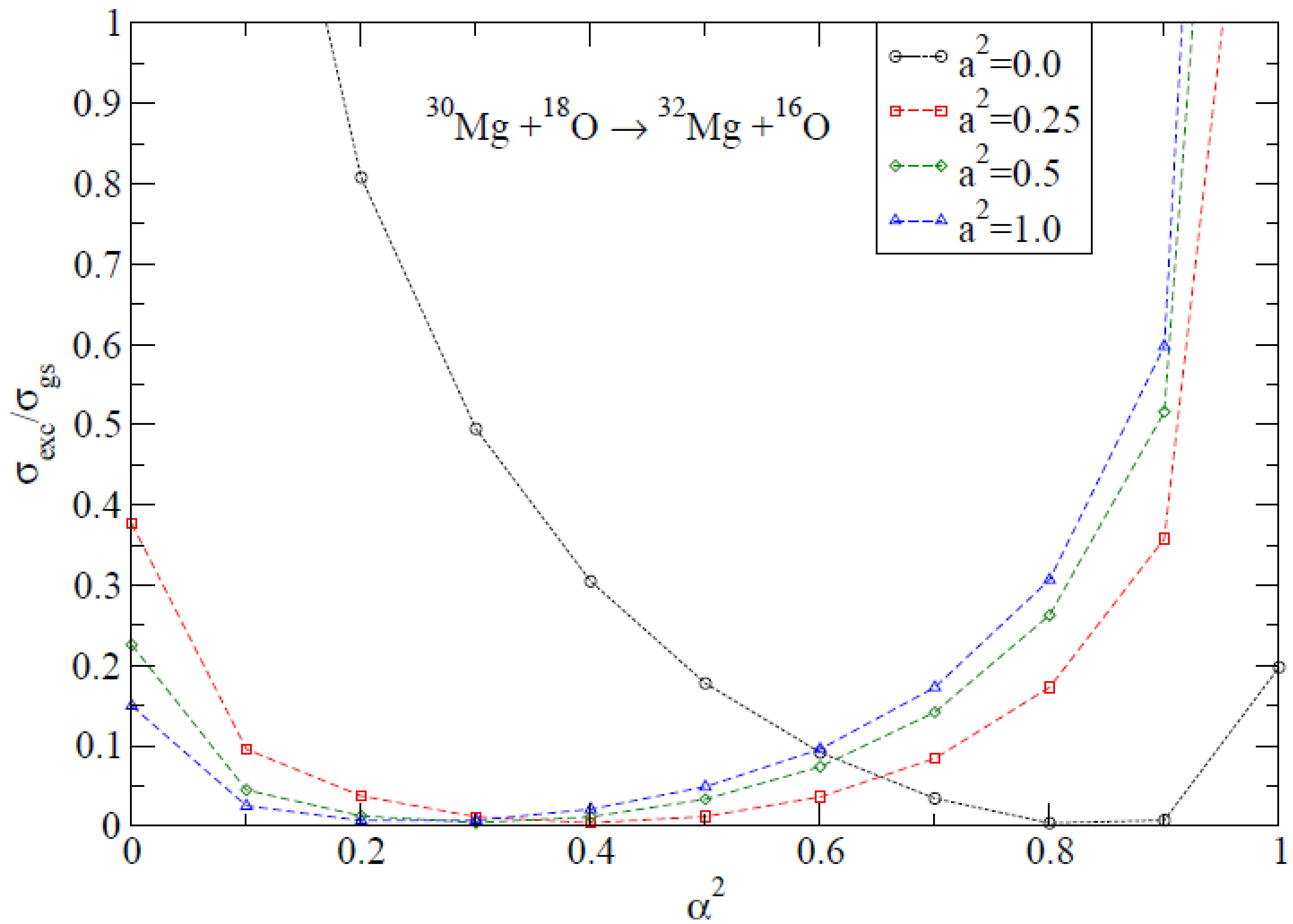
$|\Downarrow\Uparrow\rangle$

$^{30}Mg(t,p)^{32}Mg$ reaction at E=5.4 MeV





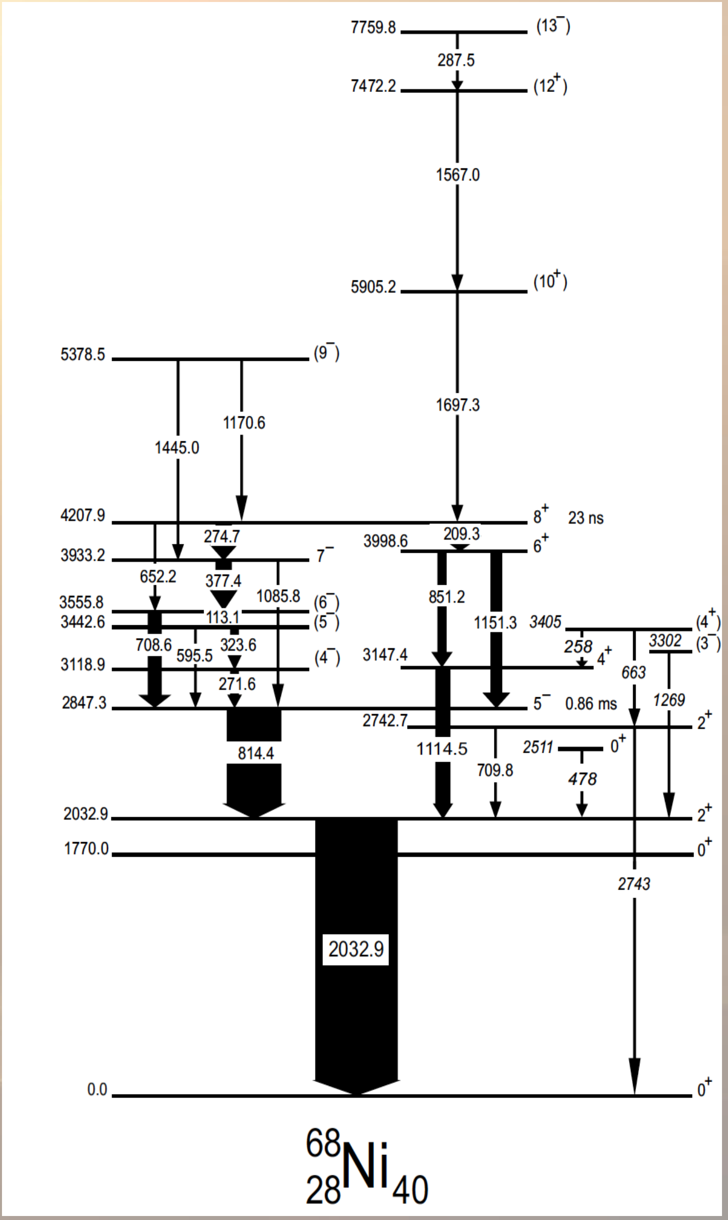
^{30}Mg(t,p)^{32}Mg
Experiment
$(1p_{3/2})^2$
$0.7(1p_{3/2})^2+0.7(0f_{7/2})^2$
$0.5(1p_{3/2})^2+0.87(0f_{7/2})^2$
$(0f_{7/2})^2$
$\sigma_{exc}/\sigma_{g.s.}$
α^2
a^2



$^{30}Mg + ^{18}O \rightarrow ^{32}Mg + ^{16}O$
$a^2=0.0$
$a^2=0.25$
$a^2=0.5$
$a^2=1.0$
σ_{exc}/σ_{gs}
α^2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

^{68}Ni : issue of magicity Z=28 N=40

Our interest in this case was spurred by discussions with R.Raabe (K.U. Leuven) and the presentation of J.Elseviers at the INPC conference (Florence 2013). We acknowledge the sharing of data on the (t,p) reaction.
See previous talk by F.Flavigny



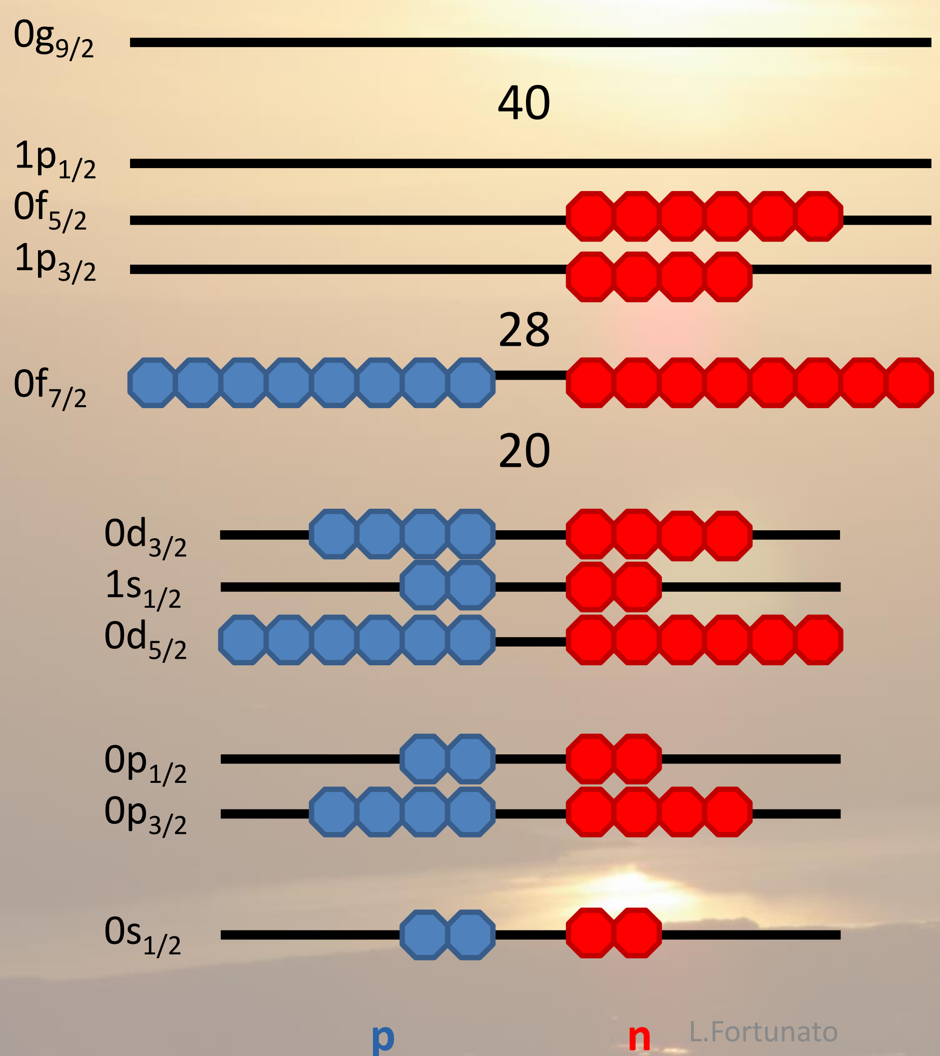
we suggest a mixing of 0p-0h and 2p-2h configurations, of the form

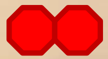
$$| 0^+_{gs} \rangle = \alpha \,| 0 \rangle + \beta \;\; | (g_{9/2})^2 (p_{1/2})^{-2} \rangle \qquad (3.5)$$

$$| 0^+_{exc} \rangle = -\beta \,| 0 \rangle + \alpha \;\; | (g_{9/2})^2 (p_{1/2})^{-2} \rangle \qquad (3.6)$$

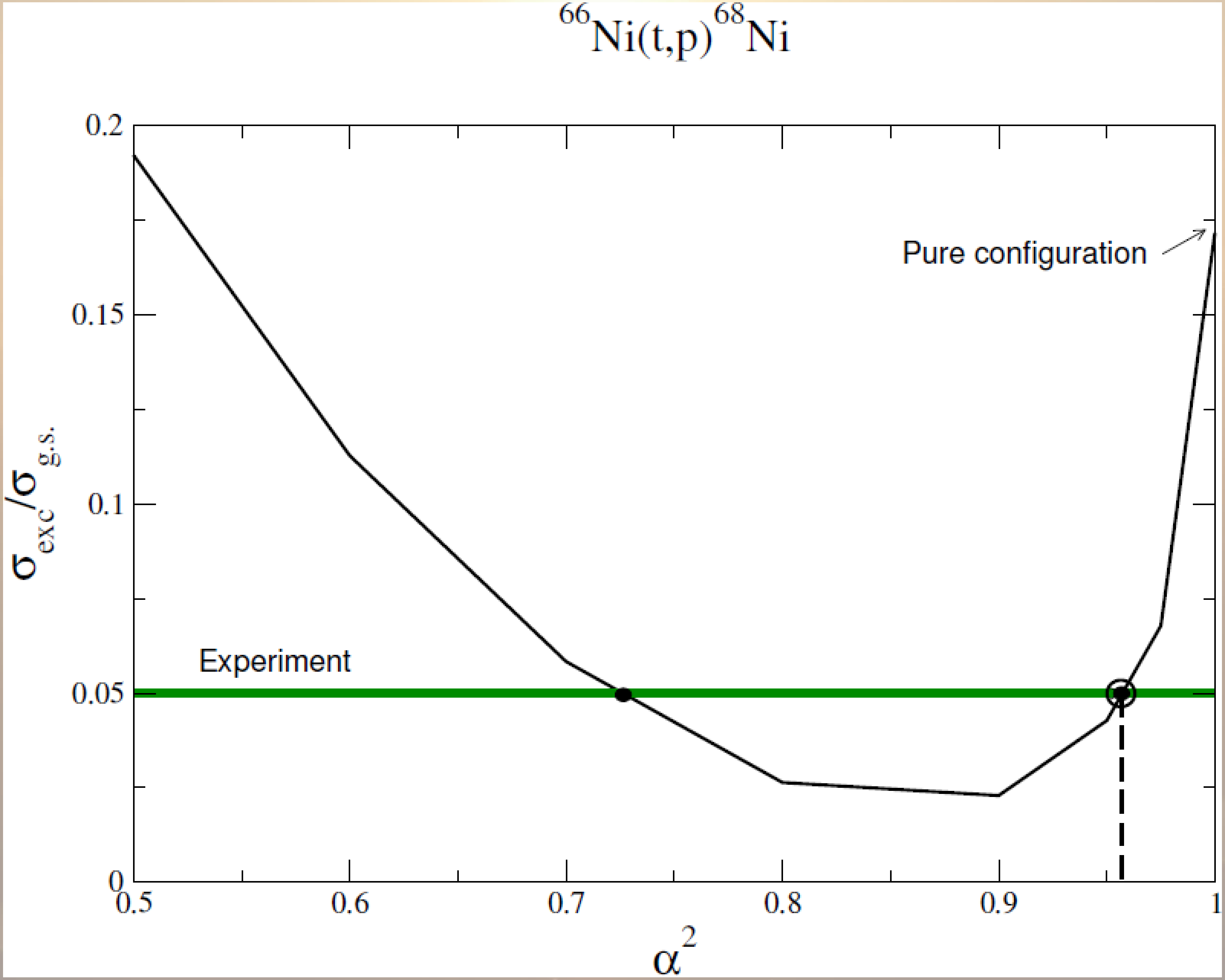
Here, $| 0 \rangle$ corresponds to the filling of the four lowest major neutron shells.

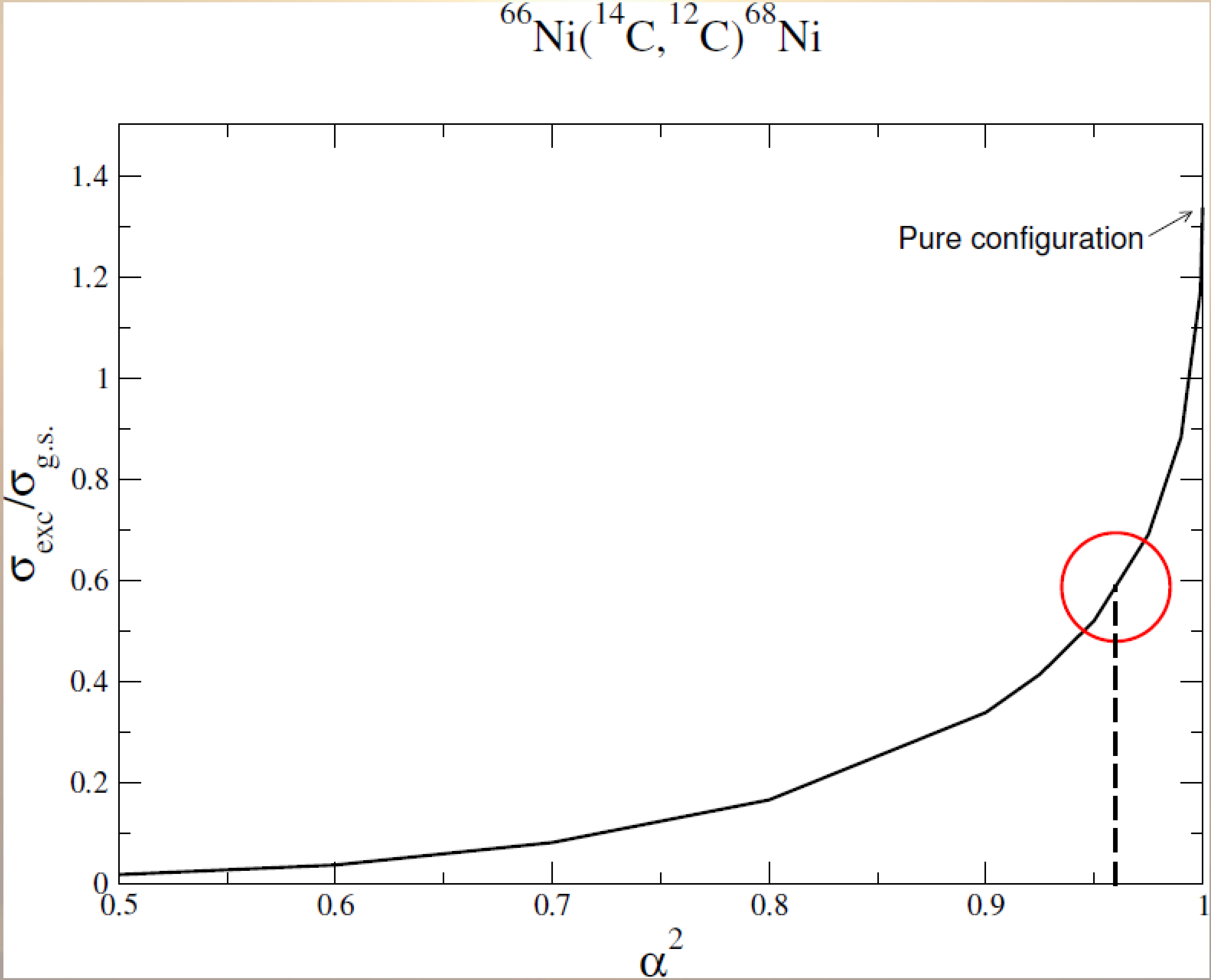
$^{66}Ni_{38}$ plus 2 n : $^{68}Ni_{40}$





$$| \, (g_{9/2})^2 (p_{1/2})^{-2} \rangle$$


$^{66}Ni(t,p)^{68}Ni$
$\sigma_{exc}/\sigma_{g.s.}$
α^2
Pure configuration
Experiment
0.2
0.15
0.1
0.05
0
0.5
0.6
0.7
0.8
0.9
1


$^{66}Ni(^{14}C, ^{12}C)^{68}Ni$
Pure configuration
$\sigma_{exc}/\sigma_{g.s.}$
α^2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
0.5
0.6
0.7
0.8
0.9
1

- Conclusions:
- 2 neutron transfer reactions are the ideal tool to probe certain detailed features of nuclear structure that might be revealing.
- 112Sn has a complicated BCS wavefunction where the role and relative importance of each orbital might be probed with different reactions → need compilation of different reactions
- 32Mg can be understood in terms of a simple (but not simplistic!) model and the comparison of 2n trasnfer reactions might help elucidating its structure → (t,p) reaction best
- The interesting case of 68Ni can also be modelized in terms of a few important configurations. Again, 2n transfer with heavier reactions partners might help determining its structure → H.I. reactions best