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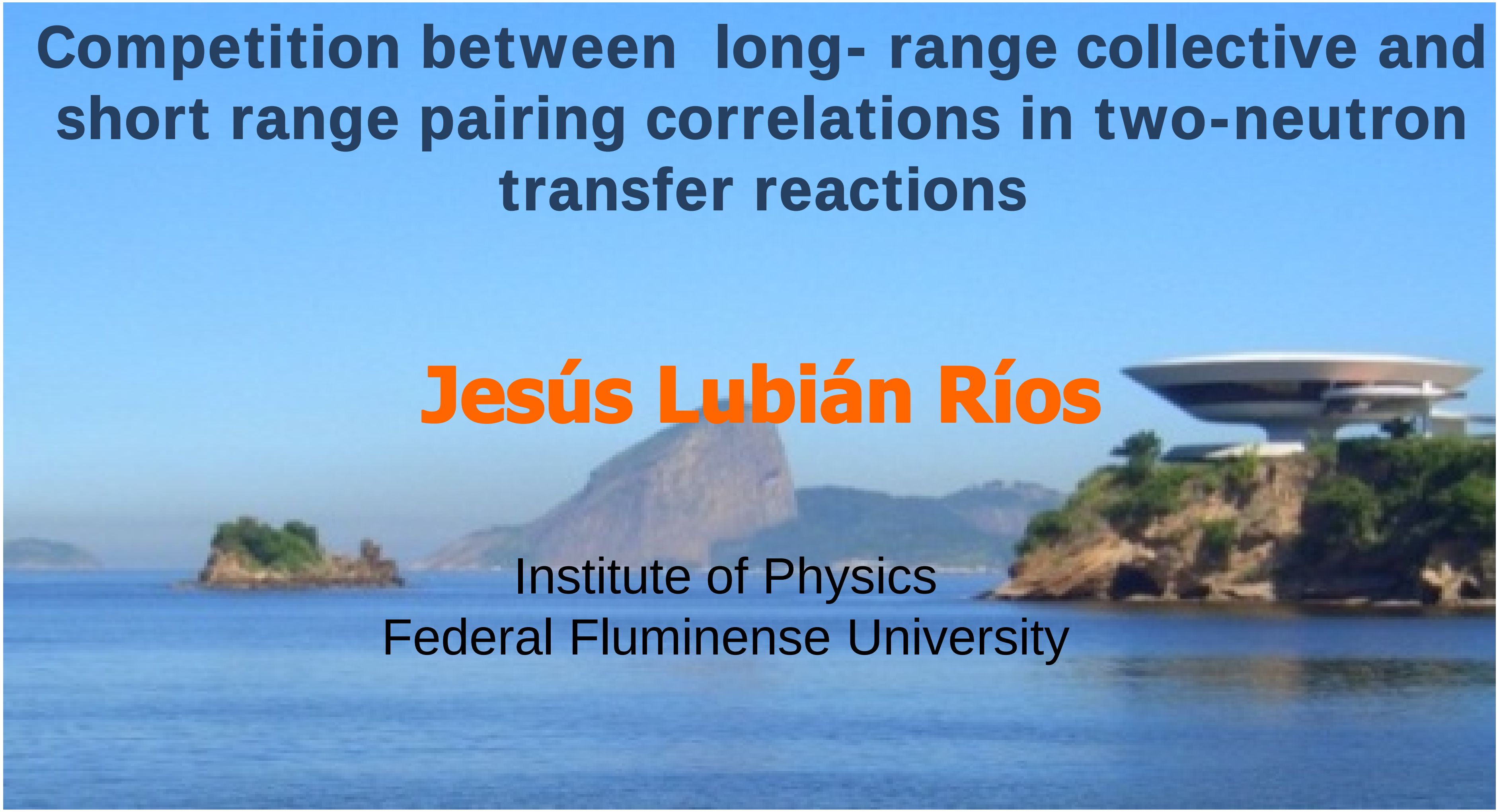

# Competition between long- range collective and short range pairing correlations in two-neutron transfer reactions

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# Outline

Nuclear spectroscopy via transfer reactions between heavy ions

- The ($^{18}O$,$^{16}O$) reaction

- Experimental results about $^{12,13}C(^{18}O,^{16}O)^{14,15}C$, $^{16}O(^{18}O,^{16}O)^{18}O$, $^{64}Ni(^{18}O,^{16}O)^{66}Ni$ and $^{28}Si(^{18}O,^{16}O)^{30}Si$reaction @ 84 MeV incident energy

- CRC and two-step DWBA calculations
- Microscopic cluster calculations

# Nuclear spectroscopy via ($^{18}$O,$^{16}$O) reaction

The **($^{18}$O,$^{16}$O)** reactions are good candidates to show the role of **pairing interaction** thanks to

- The presence of a **correlated pair** of neutrons in the $^{18}O_{g.s.}$ wave function
- The very low polarizability of the **$^{16}$O core**

**$^{14}$C** is a good benchmark for considerations on the reaction mechanism, **$^{64}$Ni and $^{28}$Si** are good benchmark for studying long-range vs short-range correlations

Studies on both
$^{13}$C($^{18}$O,$^{17}$O)$^{14}$C **1n transfer** and $^{12}$C($^{18}$O,$^{16}$O)$^{14}$C **2n transfer**

- Presence of 2n correlations in the $^{14}C_{g.s.}$ wave function
- Strong selectivity in the populated states
- Absolute cross sections reproduced without any scaling factor

M. Cavallaro et al., PRC 88 (2013) 054601

# Theoretical models and main ingredients

## Exact finite range CRC
## and
## two-step CCBA calculations

- Sao Paulo Potential (**SPP**) used in the optical model

  *L.C. Chamon, et al., PRL 79 (1997) 5218*

- **Wood-Saxon form factors** were used to generate single particle and cluster wave functions. Depth were adjusted to fit the exp. separation energies

- **Deformation parameters** for collective excitations

- **Spectroscopic Amplitudes** by shell-model in the $1p_{1/2}$, $1d_{5/2}$, $2s_{1/2}$ model space (zbm interaction)

  *A.P. Zuker, et al., PRL 17 (1969) 983*

# Theoretical models and main ingredients

The CRC equations are in many cases of the form

$$\begin{aligned}
\left[E_{\kappa pt} - T_{\kappa L}(R_\kappa) - U_\kappa(R_\kappa)\right] f_\alpha(R_\kappa) &= \sum_{\alpha',\Gamma>0} i^{L'-L}\, V^{\Gamma}_{\alpha:\alpha'}(R_{\kappa'}) f_{\alpha'}(R_{\kappa'}) \\
&+ \sum_{\alpha',\kappa'\neq\kappa} i^{L'-L} \int_0^{R_m} V_{\alpha:\alpha'}((R_\kappa), R_{\kappa'}) f_{\alpha'}(R_{\kappa'}) dR_{\kappa'}
\end{aligned}$$

**Single nucleon states are given by**

$$\phi_{JM}(\xi_c, \mathbf{r}) = \sum_{\ell j I} A^{jIJ}_{\ell s j}\ \left[\phi_I(\xi_c)\varphi_{\ell s j}(\mathbf{r})\right]_{JM}$$

$$= \sum_{\ell j I, m\mu m_s m_\ell} A^{jIJ}_{\ell s j}\, \langle j m I \mu | J M\rangle\, \phi_{I\mu}(\xi_c)\, \langle \ell m_\ell s m_s | j m\rangle\, Y^{m_\ell}_\ell(\hat{\mathbf{r}}) \phi^{m_s}_s \frac{1}{r} u_{\ell s j I}(r)$$

**and are the solution of**

$$\left[T_\ell(r) + V(r) + \epsilon_I - E\right] u_{\ell s j I}(r) + \sum_{\ell' j' I',\ \Gamma>0} V^{\Gamma}_{\ell s j I:\ell' s j' I'}(r) u_{\ell' s j' I'}(r) = 0$$

# Theoretical models and main ingredients

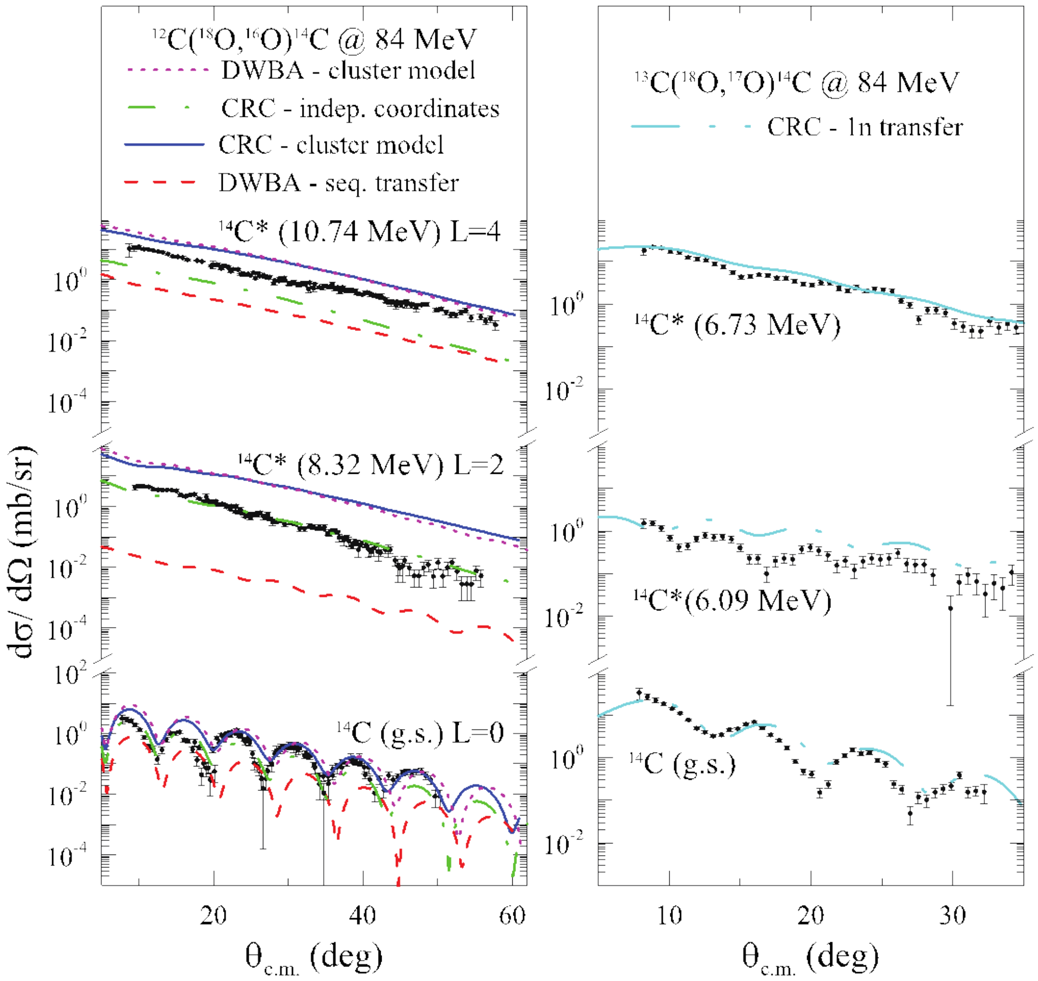
Independent coordinate model

$$\begin{aligned}
\varphi_{12}(\mathbf{r}_1,\mathbf{r}_2) &= \sum_i c_i \;|(\ell_1(i),s_1)j_1(i),(\ell_2(i),s_2)j_2(i);\;\; J_{12}T\rangle \\
&\to \sum_u c_i \sum_{L\ell S j} |L,(\ell,(s_1 s_2)S)j;J_{12}T\rangle\, \phi^{J_{12}T,i}_{L(\ell S)j}(r,\rho)
\end{aligned}$$

$$\begin{aligned}
\phi^{J_{12}T,i}_{L(\ell S)j}(r,\rho) &= \langle L,(\ell,(s_1 s_2)S)j;J_{12}T|\,(\ell_1(i),s_1)j_1(i),(\ell_2(i),s_2)j_2(i);\;\; J_{12}T\rangle \\
&\times\langle[Y_L(\hat{\mathbf{r}})Y_\ell(\hat{\rho})]_\lambda\,|\,[\varphi_{\ell_1 s_1 j_1}(\mathbf{r}_1)\varphi_{\ell_2 s_2 j_2}(\mathbf{r}_2)]_{J_{12}T}\rangle
\end{aligned}$$

**and the radial integral overlaps are derived from using Moshinsky harmonic oscillator expansion**

# Theoretical results for other channels



**Presence of two-neutron pairing correlations in other $^{14}C$ states**

M. Cavallaro et al., PRC 88 (2013) 054601

**Extreme Cluster Model**

(CRC)

- ❖ Relative motion of the 2n system frozen and separated by the c.m.
- ❖ Only the term with the 2n coupled to S = 0 participates to the transfer

**Sequential transfer**

(DWBA)

Introducing the $^{17}O + ^{13}C$ intermediate partition

**Independent coord.**

(CRC)

CRC **-1n transfer**

**No arbitrary scaling**

# New works published in 2016-2017

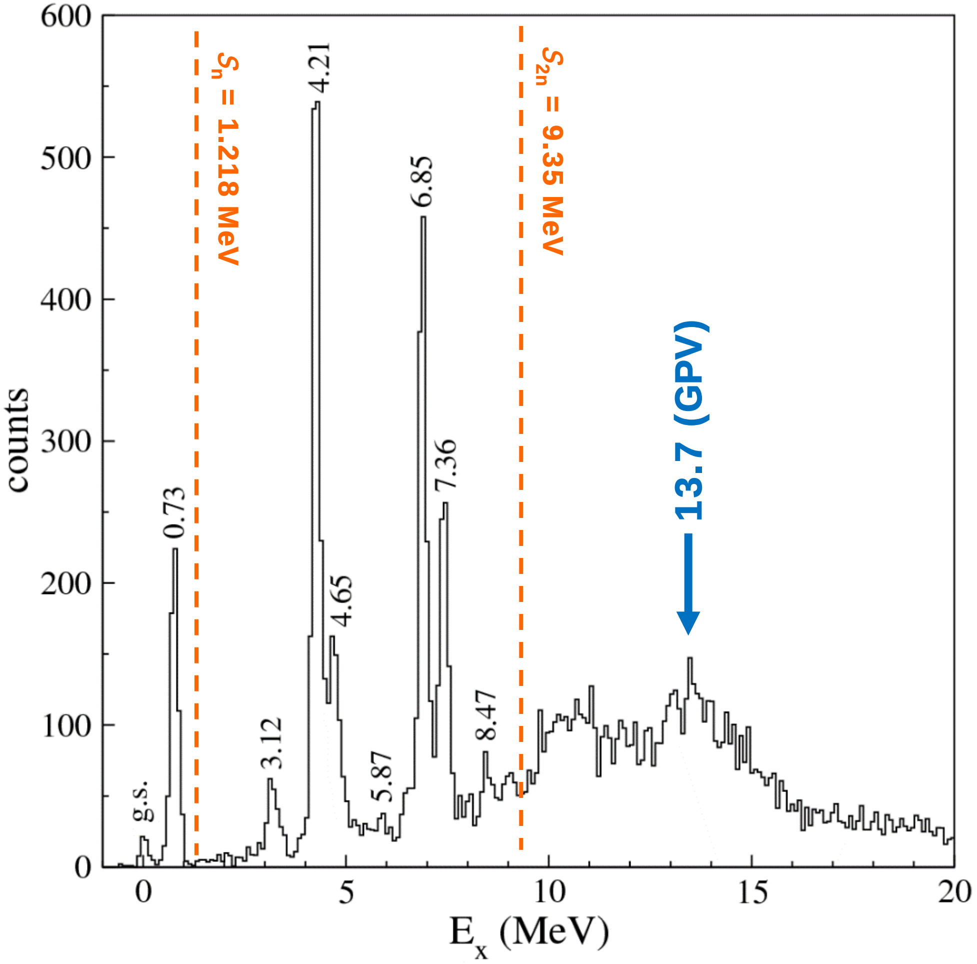
What happens if we add a neutron to the $^{14}C$ system?

**Study of the $^{13}C(^{18}O,^{16}O)^{15}C$ reaction at 84 MeV incident energy**

D. Carbone et al., PRC 95, 034603 (2017)

# $^{15}$C energy spectrum

$^{13}$C($^{18}$O,$^{16}$O)$^{15}$C



$9° < \theta_{lab} < 10°$

- Same states populated in the (t,p) reactions
- Strong population of states with $^{13}$C + 2*n* configurations
- Population of the Giant Pairing Vibration above $S_{2n}$
  - **F. Cappuzzello et al., Nat. Commun. 6, 6743 (2015)**
  - **D. Carbone, EPJ Plus (2015) 130:143**

Energy resolution ~ 200 keV

ARTICLE

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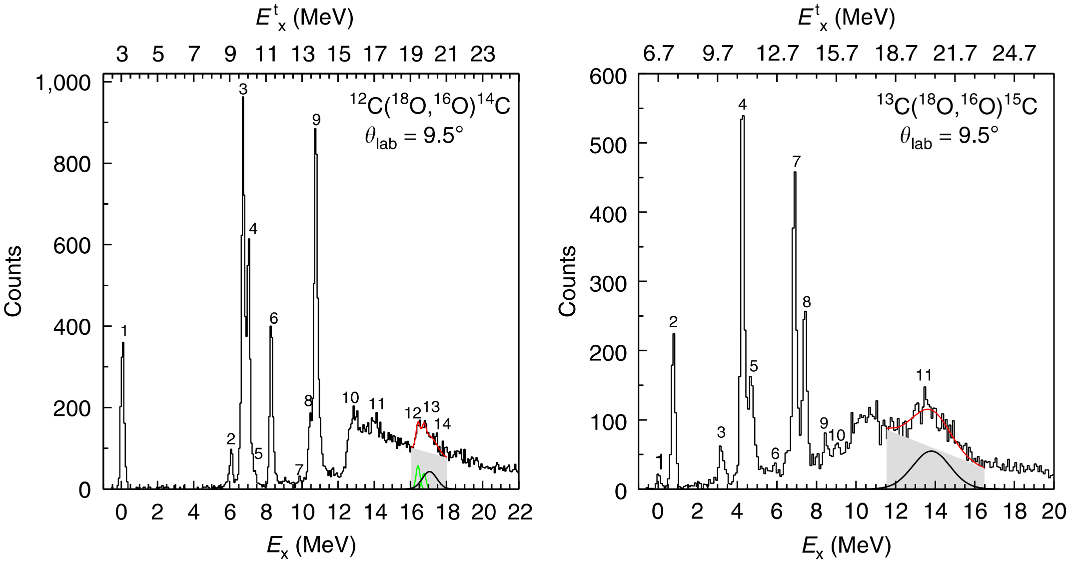
OPEN

# Signatures of the Giant Pairing Vibration in the $^{14}$C and $^{15}$C atomic nuclei

F. Cappuzzello[1,2], D. Carbone[2], M. Cavallaro[2], M. Bondì[1,2], C. Agodi[2], F. Azaiez[3], A. Bonaccorso[4], A. Cunsolo[2], L. Fortunato[5,6], A. Foti[1,7], S. Franchoo[3], E. Khan[3], R. Linares[8], J. Lubian[8], J.A. Scarpaci[9] & A. Vitturi[5,6]



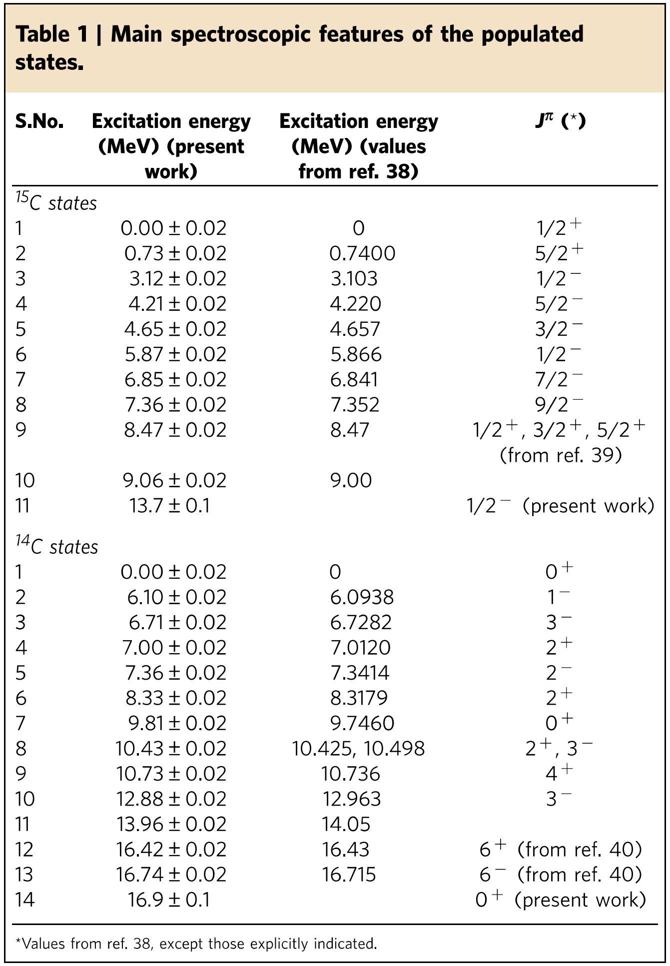
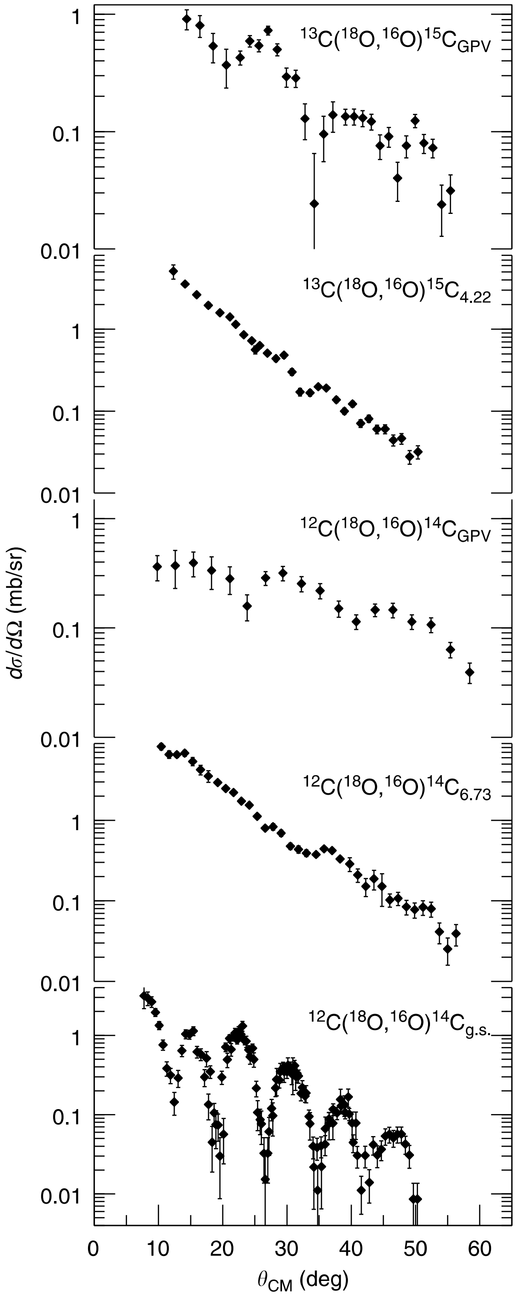
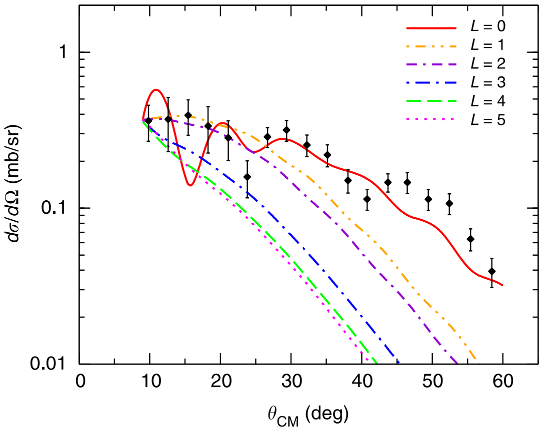


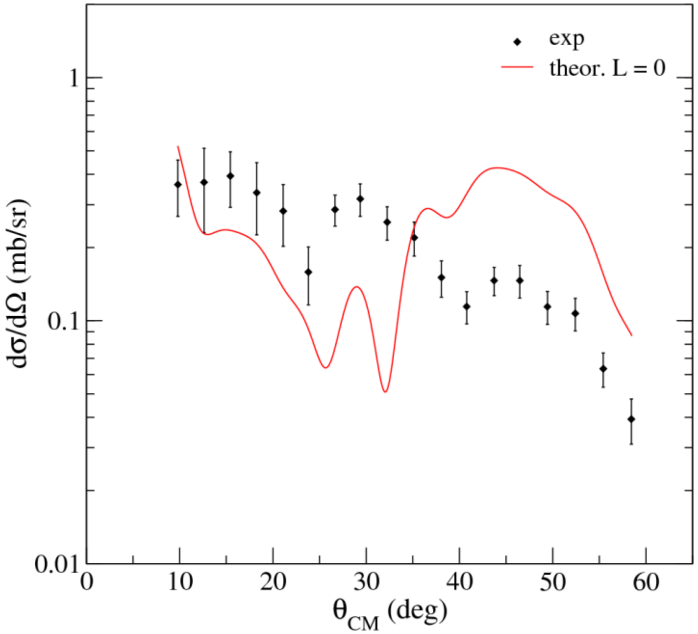
**Table 1 | Main spectroscopic features of the populated states.**

| S.No. | Excitation energy (MeV) (present work) | Excitation energy (MeV) (values from ref. 38) | $J^\pi$ (*) |
|---|---|---|---|
| *$^{15}$C states* | | | |
| 1 | 0.00 ± 0.02 | 0 | $1/2^+$ |
| 2 | 0.73 ± 0.02 | 0.7400 | $5/2^+$ |
| 3 | 3.12 ± 0.02 | 3.103 | $1/2^-$ |
| 4 | 4.21 ± 0.02 | 4.220 | $5/2^-$ |
| 5 | 4.65 ± 0.02 | 4.657 | $3/2^-$ |
| 6 | 5.87 ± 0.02 | 5.866 | $1/2^-$ |
| 7 | 6.85 ± 0.02 | 6.841 | $7/2^-$ |
| 8 | 7.36 ± 0.02 | 7.352 | $9/2^-$ |
| 9 | 8.47 ± 0.02 | 8.47 | $1/2^+$, $3/2^+$, $5/2^+$ (from ref. 39) |
| 10 | 9.06 ± 0.02 | 9.00 | |
| 11 | 13.7 ± 0.1 | | $1/2^-$ (present work) |
| *$^{14}$C states* | | | |
| 1 | 0.00 ± 0.02 | 0 | $0^+$ |
| 2 | 6.10 ± 0.02 | 6.0938 | $1^-$ |
| 3 | 6.71 ± 0.02 | 6.7282 | $3^-$ |
| 4 | 7.00 ± 0.02 | 7.0120 | $2^+$ |
| 5 | 7.36 ± 0.02 | 7.3414 | $2^-$ |
| 6 | 8.33 ± 0.02 | 8.3179 | $2^+$ |
| 7 | 9.81 ± 0.02 | 9.7460 | $0^+$ |
| 8 | 10.43 ± 0.02 | 10.425, 10.498 | $2^+$, $3^-$ |
| 9 | 10.73 ± 0.02 | 10.736 | $4^+$ |
| 10 | 12.88 ± 0.02 | 12.963 | $3^-$ |
| 11 | 13.96 ± 0.02 | 14.05 | |
| 12 | 16.42 ± 0.02 | 16.43 | $6^+$ (from ref. 40) |
| 13 | 16.74 ± 0.02 | 16.715 | $6^-$ (from ref. 40) |
| 14 | 16.9 ± 0.1 | | $0^+$ (present work) |

*Values from ref. 38, except those explicitly indicated.

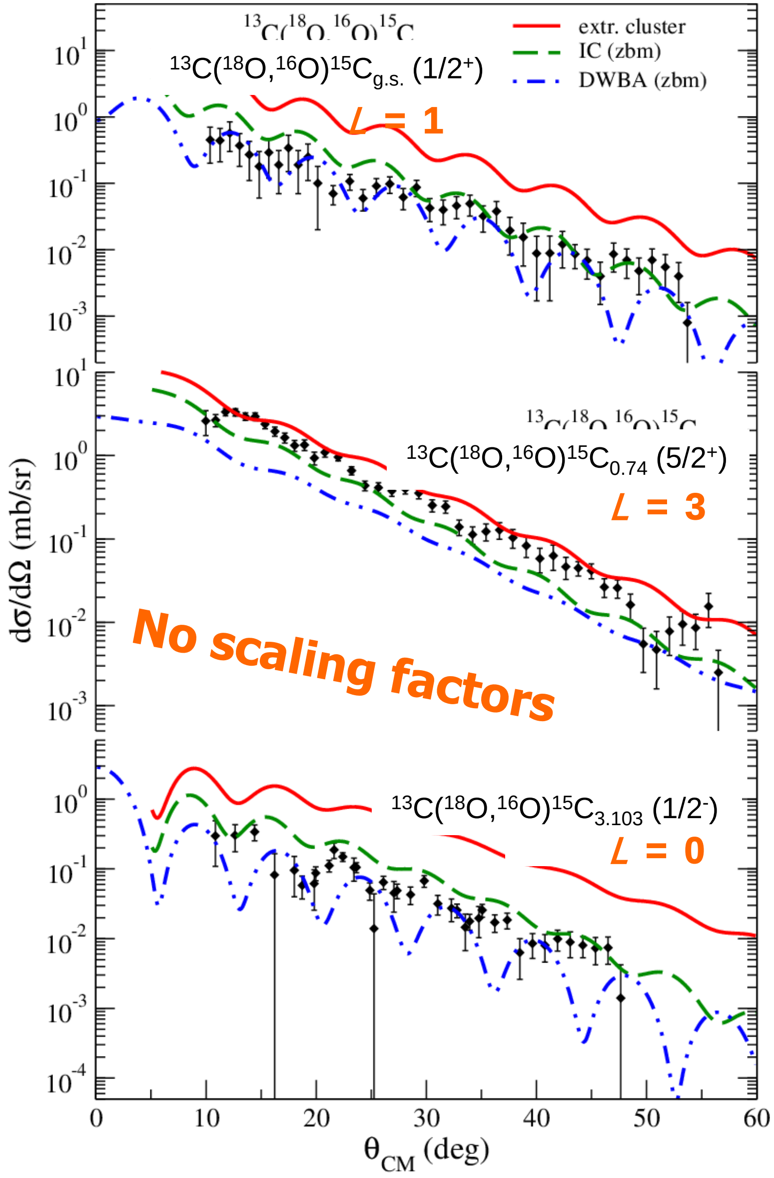






**Supplementary Figure 7** – **Comparison with calculations.** Discretized continuum scheme calculations for the *L* = 0 case (red line) and experimental cross section angular distribution for the $^{14}$C resonance at 16.9 ± 0.1 MeV. No scaling factors are used.

# CRC and DWBA calculations



**No scaling factors**

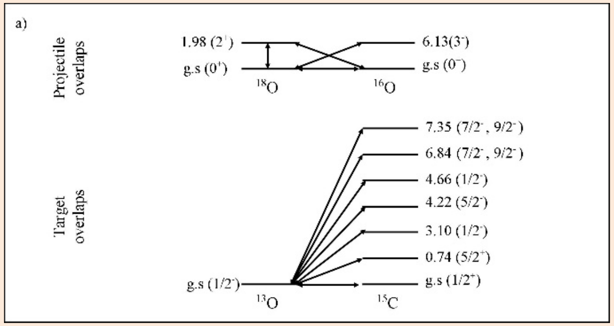
## Extreme cluster model

- Relative motion of the 2n frozen and separated by the c.m.
- Only the term with the 2n coupled to S = 0 participates to the transfer
- S.A. = 1 for all configurations

## Independent coordinate model

- The transfer is described taking into account spectroscopic information obtained by shell model calculations

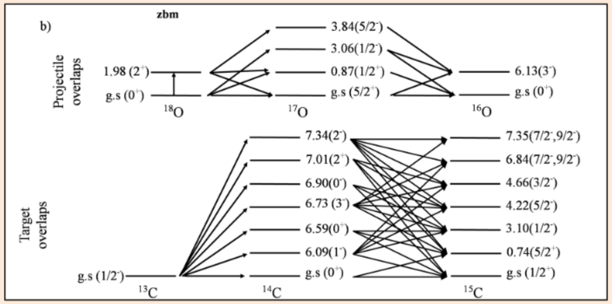
**Coupling scheme**



## Sequential transfer (DWBA)

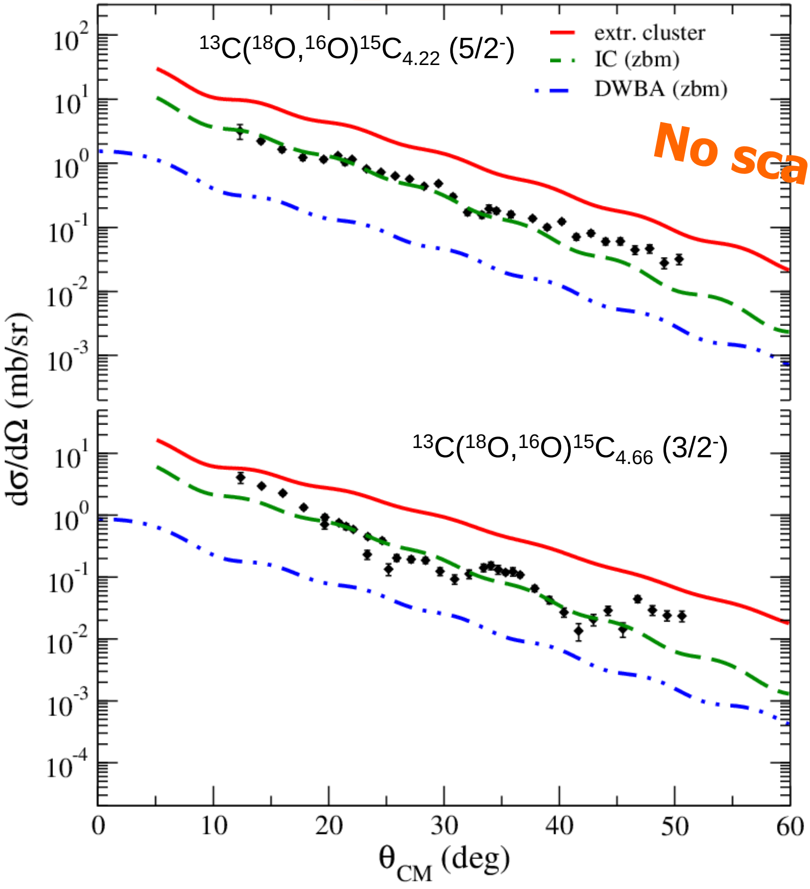
- Introducing the $^{17}O$ + $^{14}C$ intermediate partition

**Coupling scheme**

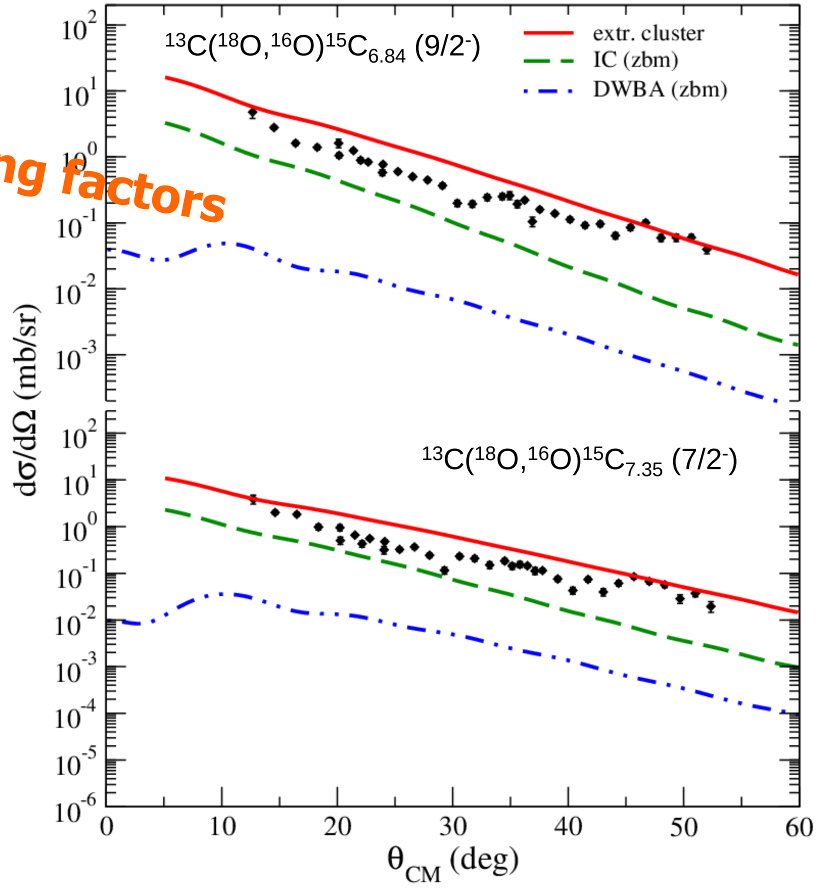


# CRC and DWBA calculations

*L* = 2



*L* = 4



**No scaling factors**

**Extreme cluster model** overestimate the cross section (S.A. = 1)

**Independent coordinate** model describes quite well the cross section

**Sequential transfer (DWBA)** underestimate the cross section

# Microscopic cluster calculations

Wave functions for two particles in an harmonic oscillator common potential (*j-j* coupling)

⇨ wave functions in terms of the relative and centre of mass coordinates of the two particles (*LS* coupling)

**(n,l)** internal cluster state
**(N,L)** cluster motion relative to the core

$$S_{\alpha J\beta J'}\left[(nl)(NL)\Lambda S;J\right]=\sum_{n_1l_1n_2l_2}\sum_{j_1j_2}\hat{S}\hat{L}\hat{j}_1\hat{j}_2\begin{Bmatrix} l_1 & 1/2 & j_1 \\ l_2 & 1/2 & j_2 \\ \Lambda & S & J \end{Bmatrix}C^L(n_1l_1n_2l_2;nlNL)\,S_{\alpha J\beta J'}(n_1l_1j_1n_2l_2j_2;J)$$

$$\hat{a}=\sqrt{2a+1}$$

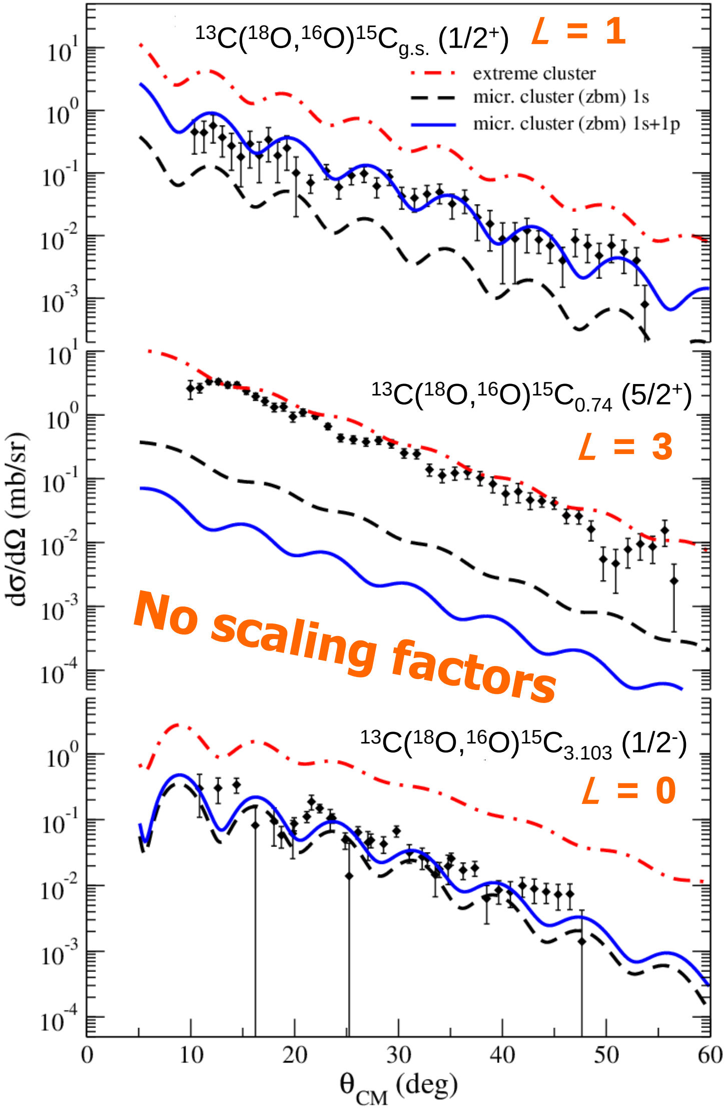
Moshinsky coefficients

S.A. in j-j coupling

**Two neutron amplitudes – zbm interaction**

| Initial state | $j_1j_2$ | $J_{12}$ | Final state | Spectr. Amp. | n | l | N | L | Λ | S | Spec. Amp. (c.m.) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $^{13}C_{g.s.}(1/2^-)$ | $(p_{1/2}s_{1/2})$ | 0 | $^{15}C_{g.s.}(1/2^+)$ | -0.641 | 1 | 0 | 2 | 1 | 1 | 1 | -0.292 |
| | | | | | 1 | 1 | 1 | 2 | 1 | 1 | 0.338 |
| | | | | | 1 | 1 | 2 | 0 | 1 | 1 | -0.075 |
| | $(p_{1/2}s_{1/2})$ | 1 | | -1.110 | 1 | 0 | 2 | 1 | 1 | 0 | 0.292 |
| | | | | | 1 | 1 | 1 | 2 | 1 | 0 | -0.338 |
| | | | | | 1 | 1 | 2 | 0 | 1 | 0 | 0.075 |
| | | | | | 1 | 0 | 2 | 1 | 1 | 1 | -0.413 |
| | | | | | 1 | 1 | 1 | 2 | 1 | 1 | 0.477 |
| | | | | | 1 | 1 | 2 | 0 | 1 | 1 | -0.107 |

# Microscopic cluster calculations



No scaling factors

## Extreme cluster model

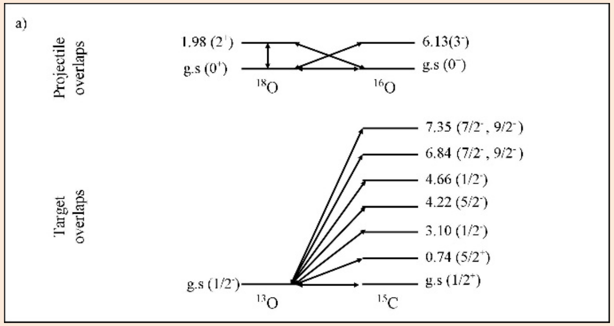
## Microscopic cluster 1s

- Taking into account configurations with n = 1 l = 0

## Microscopic cluster 1s + 1p

- Taking into account configuration with n = 1 l = 0, 1

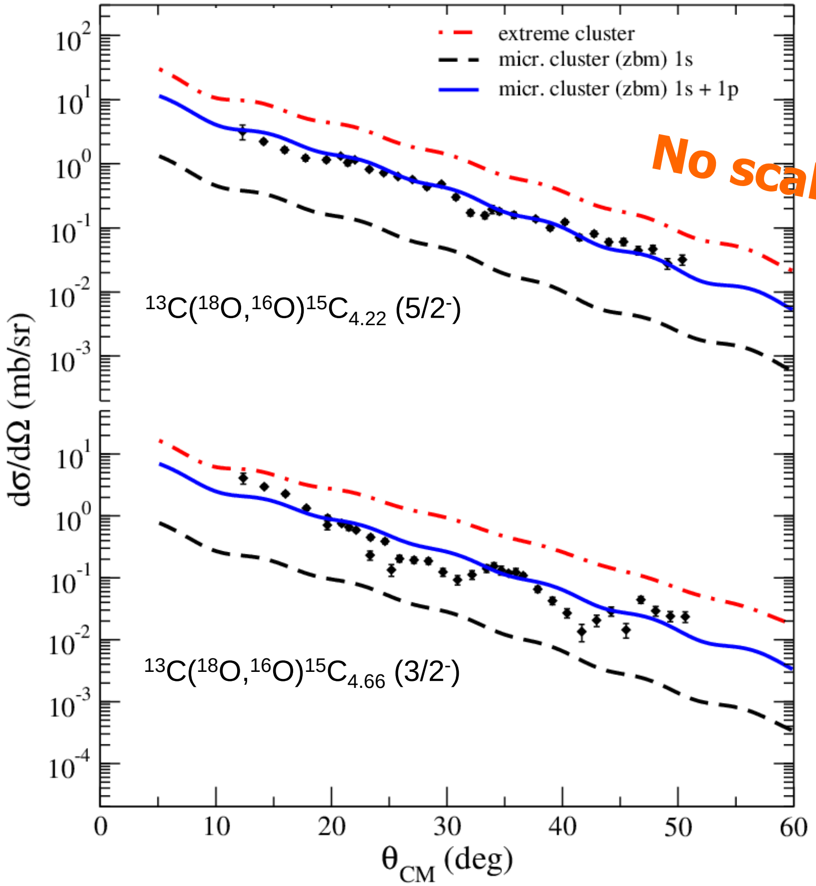
**Coupling scheme**



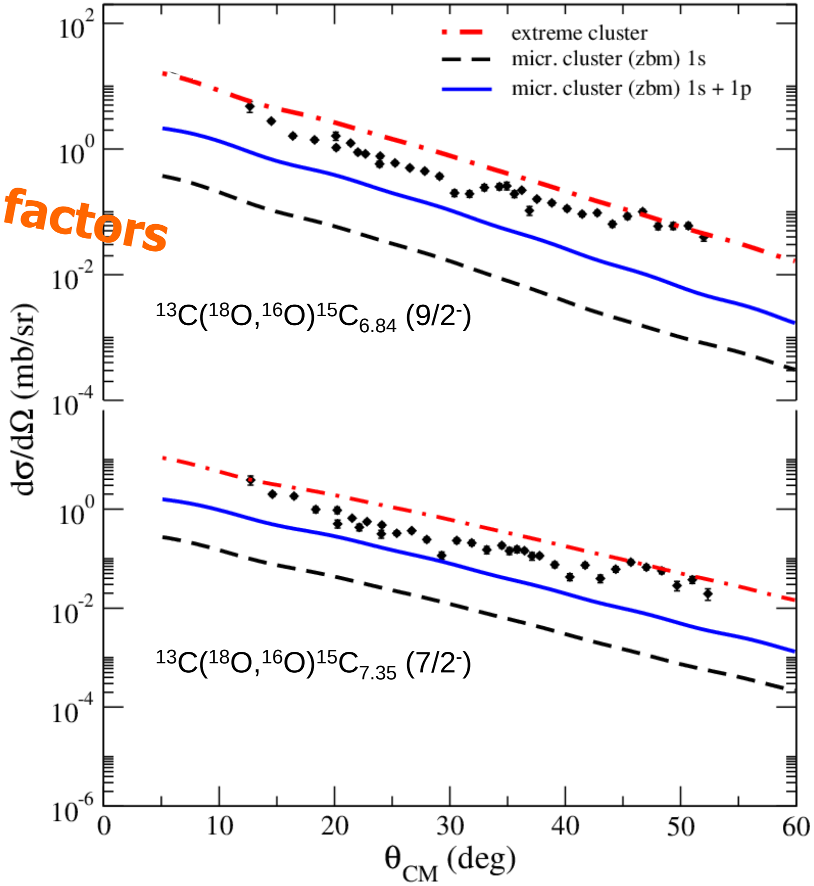
- ➢ Transitions to ground and 3.103 MeV states **reproduced rather well** with 1s + 1p waves
- ➢ Transition to 0.74 MeV state probably needs more configurations

# Microscopic cluster calculations

*L* = 2



*L* = 4



**No scaling factors**

Cross section **reproduced quite well** with 1s + 1p waves

Cross section **underestimated** with 1s + 1p waves

Relevant $d_{3/2}$ contributions expected, excluded in our model space

# New works published in 2016-2017

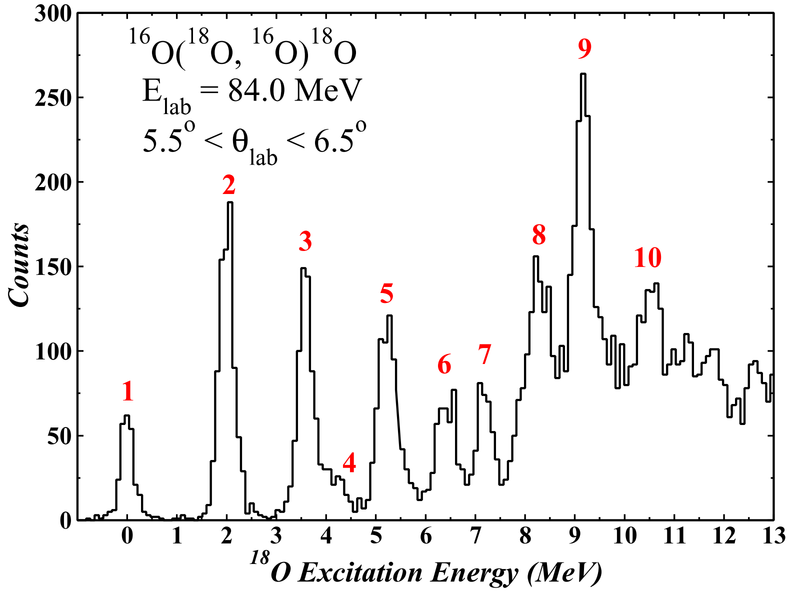
Test of model space for the <$^{18}$O|$^{16}$O> projectile overlaps

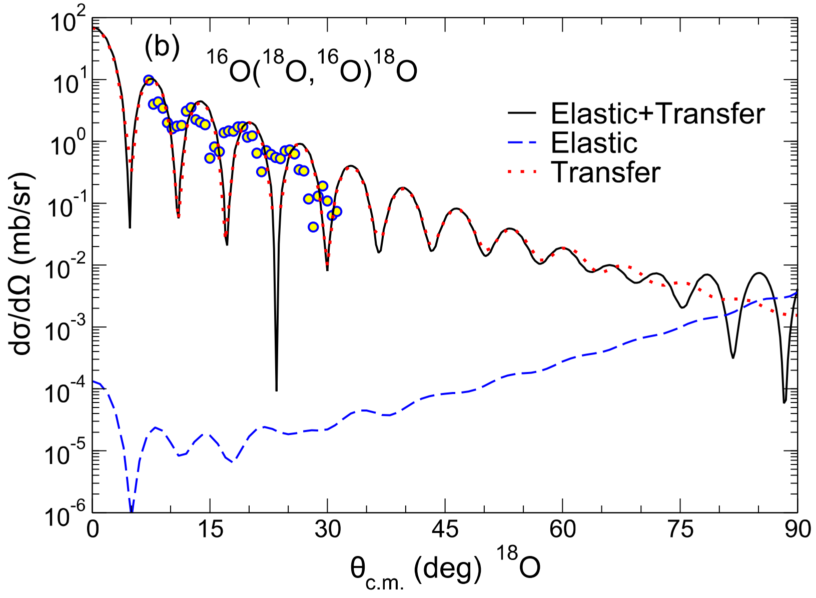
## Study of the $^{18}$O($^{16}$O,$^{18}$O)$^{16}$O reaction at 84 MeV incident energy zbm vs psdmod interactions

| Model space | valence orbitals |
|---|---|
| zbm ($^{12}$C-core) | $1p_{1/2}$, $1d_{5/2}$, $2s_{1/2}$ |
| psdmod ($^{4}$He core) | $1p_{3/2}$, $1p_{1/2}$, $1d_{5/2}$, $2s_{1/2}$, $1d_{3/2}$ |

# Experimental results

$S_n$= 8.045 MeV; $S_{2n}$= 12.189 MeV



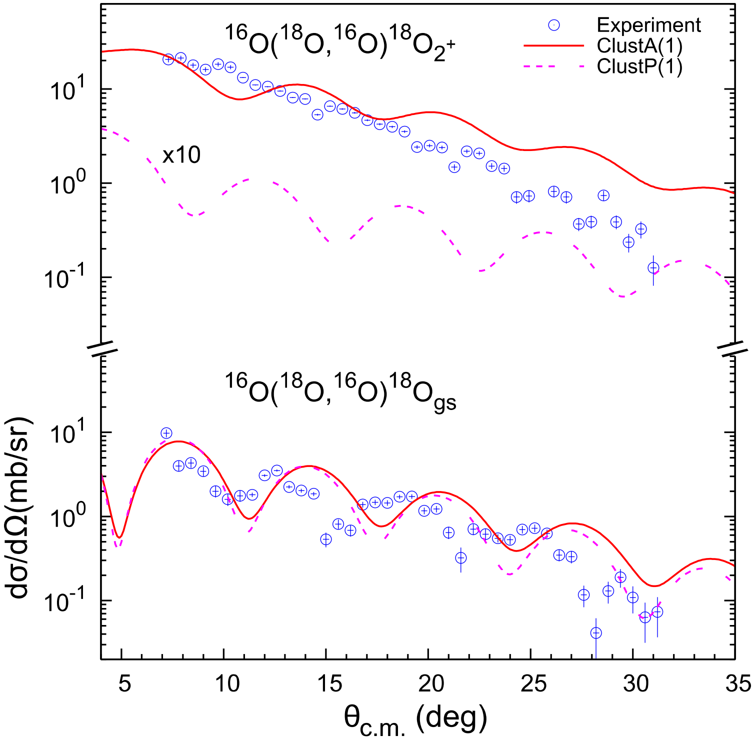


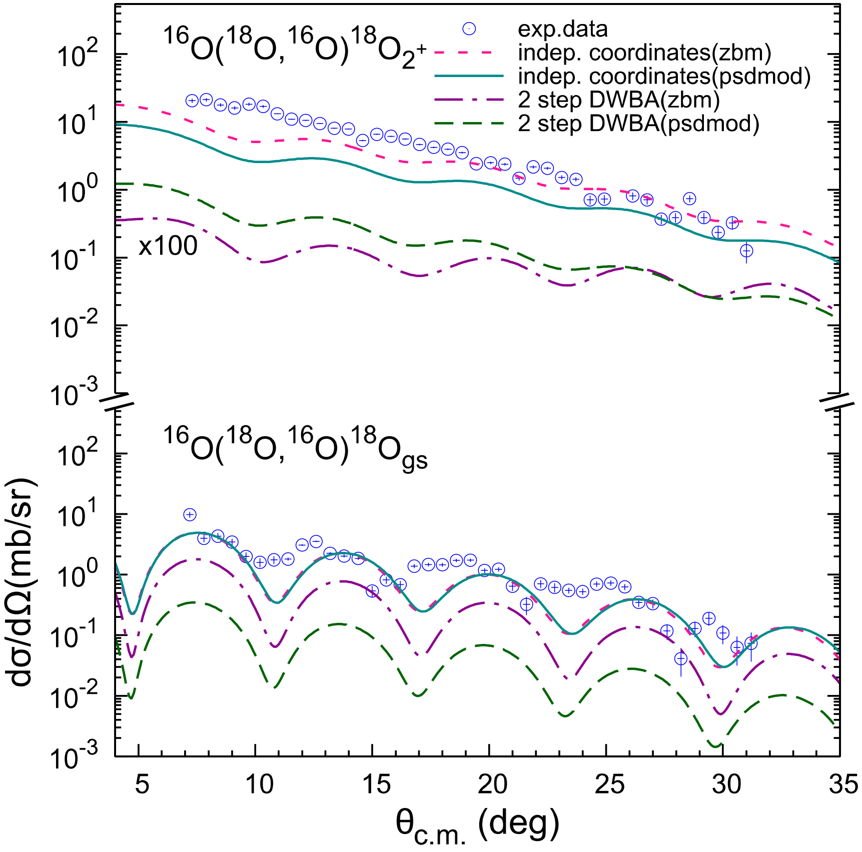
ion [37] were

considered.

M. J. Ermamatov et al., PRC 94 (2016) 024610

# Results of theoretical calculations





g.s. only S=0 (A)
2+ S=0 (A) or (P)

**Extreme cluster model works**

M. J. Ermamatov et al., PRC 94 (2016) 024610

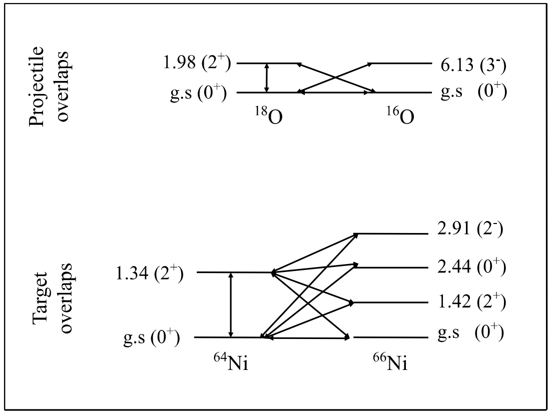
**For the lower states of projectile overlaps the zbm model- space is enough.**

The study of the higher excited states is in progress

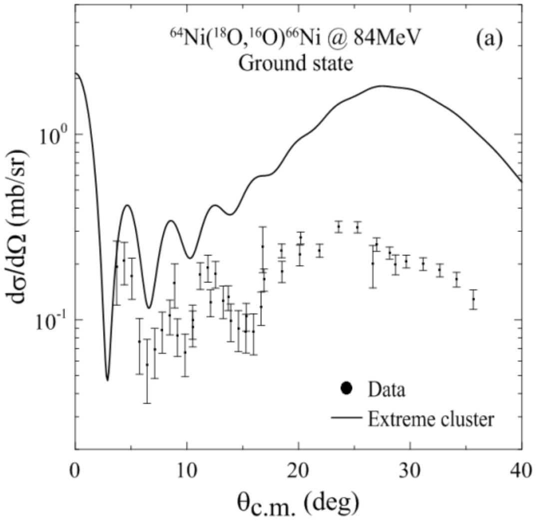
# New works in progress (some results)

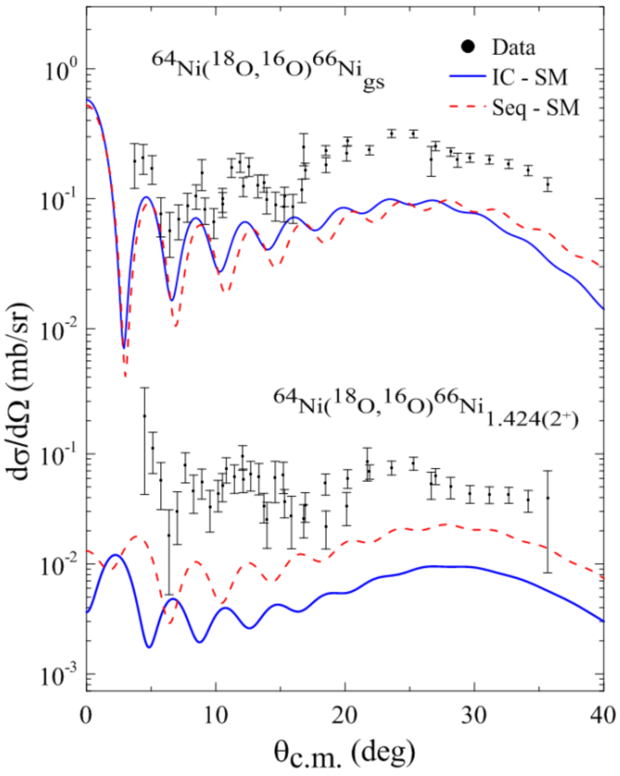
## Study of the $^{18}O(^{64}Ni,^{66}Ni)^{16}O$ reaction at 84 MeV incident energy

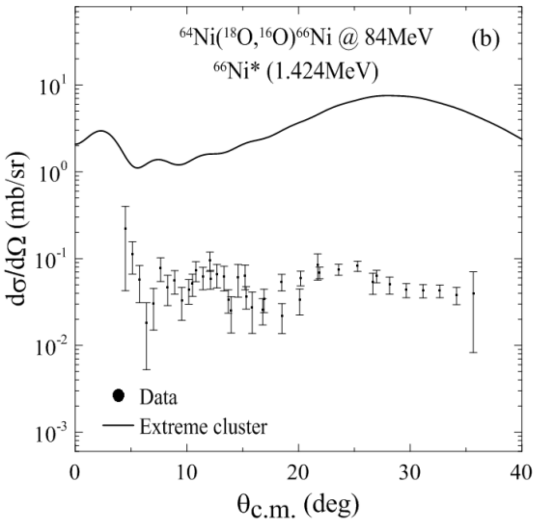
| Model space | valence orbitals |
|---|---|
| protons | $1p_{1/2}$, $1d_{5/2}$, $2s_{1/2}$ |
| neutrons | $1p_{3/2}$, $1p_{1/2}$, $1d_{5/2}$, $2s_{1/2}$, $1d_{3/2, 1}$, $1g_{7/2}$ |



# Results of theoretical calculations







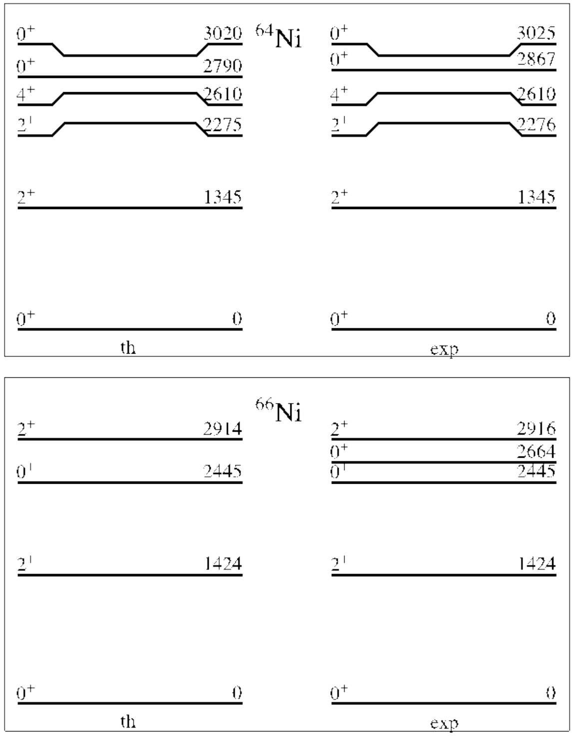
**Microscopic results:**

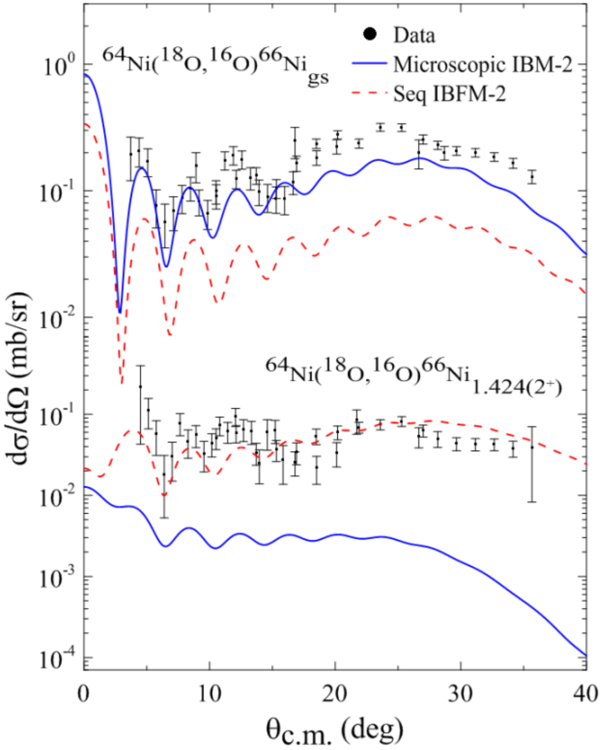
**g.s.: IC results are better, specially in the bell-shaped region. Same order: one and two step.**

**$2^+$ : Long-range correl. (coll.) dominates over the short-range (pairing)**

Cluster model is not good for $^{64,66}$Ni

# Results of theoretical calculations

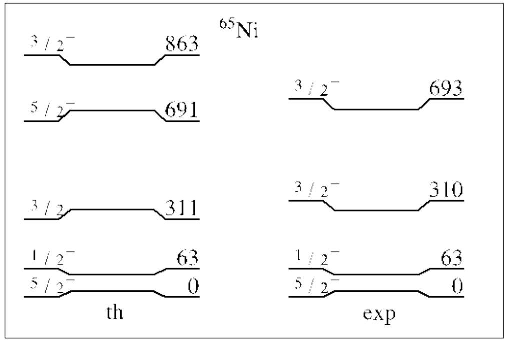




**Microscopic results:**

**g.s.: IC results are better, specially in the bell-shaped region.**

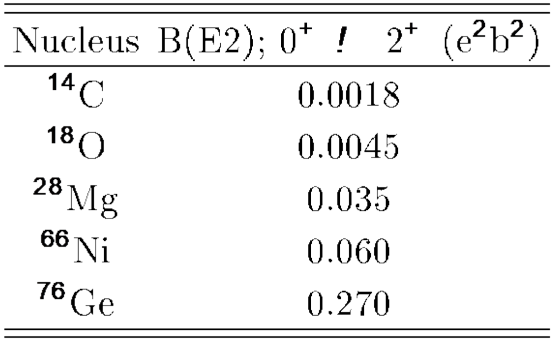
**$2^+$ : Long-range correl. (coll.) dominates over the short-range (pairing)**



For details, see R. Magana poster
B. Paes et al PRC 96.044612 (2017) -yesterday

IBM2 for $^{64,66}$Ni and IBFM for $^{65}$Ni

# Results of theoretical calculations



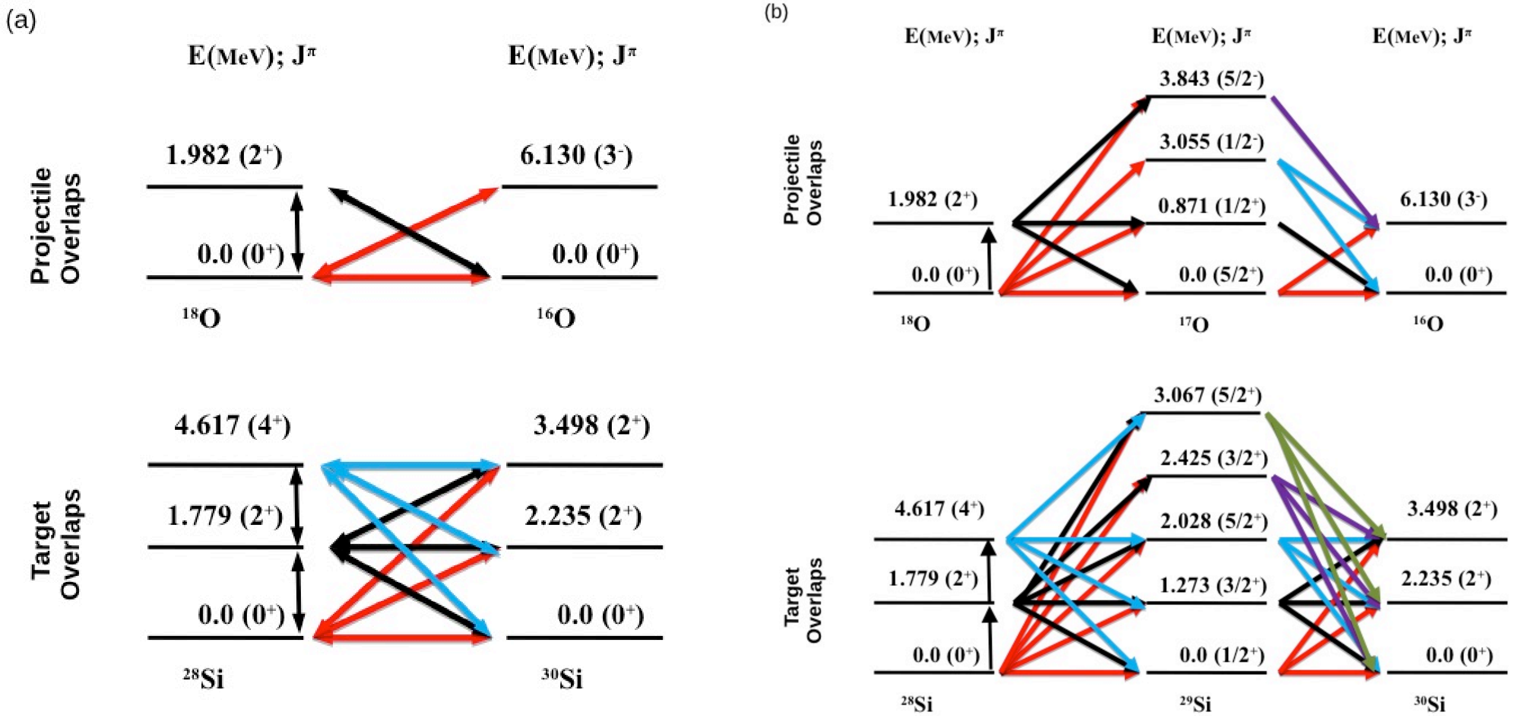
| Nucleus | B(E2); $0^+$ ! $2^+$ ($e^2b^2$) |
|---|---|
| $^{14}$C | 0.0018 |
| $^{18}$O | 0.0045 |
| $^{28}$Mg | 0.035 |
| $^{66}$Ni | 0.060 |
| $^{76}$Ge | 0.270 |

Small for $^{14}$C $^{18}$C
Big for $^{28}$Mg $^{66}$Ni $^{76}$Ge

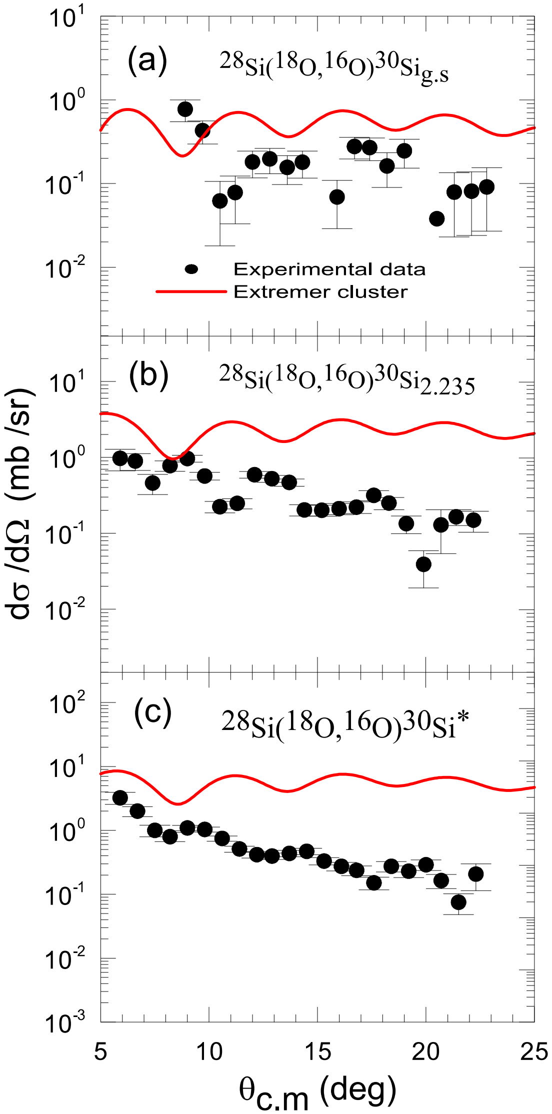
# New works in progress (some results)

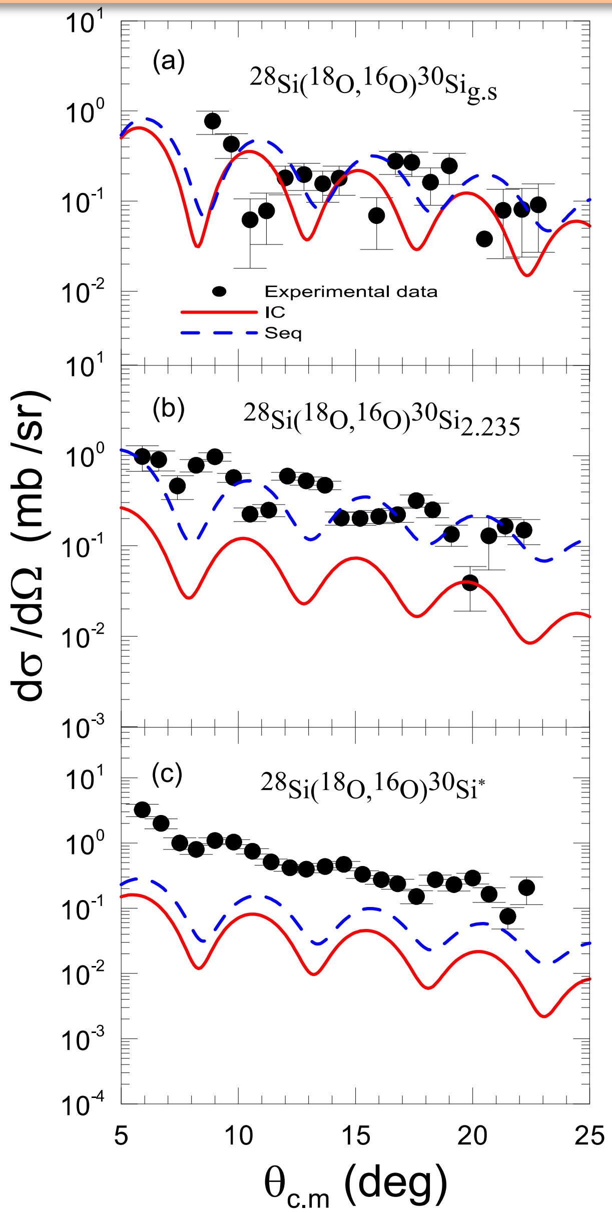
## Study of the $^{18}O(^{28}Si,^{30}Si)^{16}O$ reaction at 84 MeV incident energy

| Model space ($^4He$ core) | valence orbitals (similar to Ni) |
|---|---|
| Protons | $1p_{3/2}, 1p_{1/2}, 1d_{5/2}, 2s_{1/2}, 1d_{3/2}$ |
| neutrons | $1p_{3/2}, 1p_{1/2}, 1d_{5/2}, 2s_{1/2}, 1d_{3/2}$ |



# Results of theoretical calculations





**Microscopic results:**

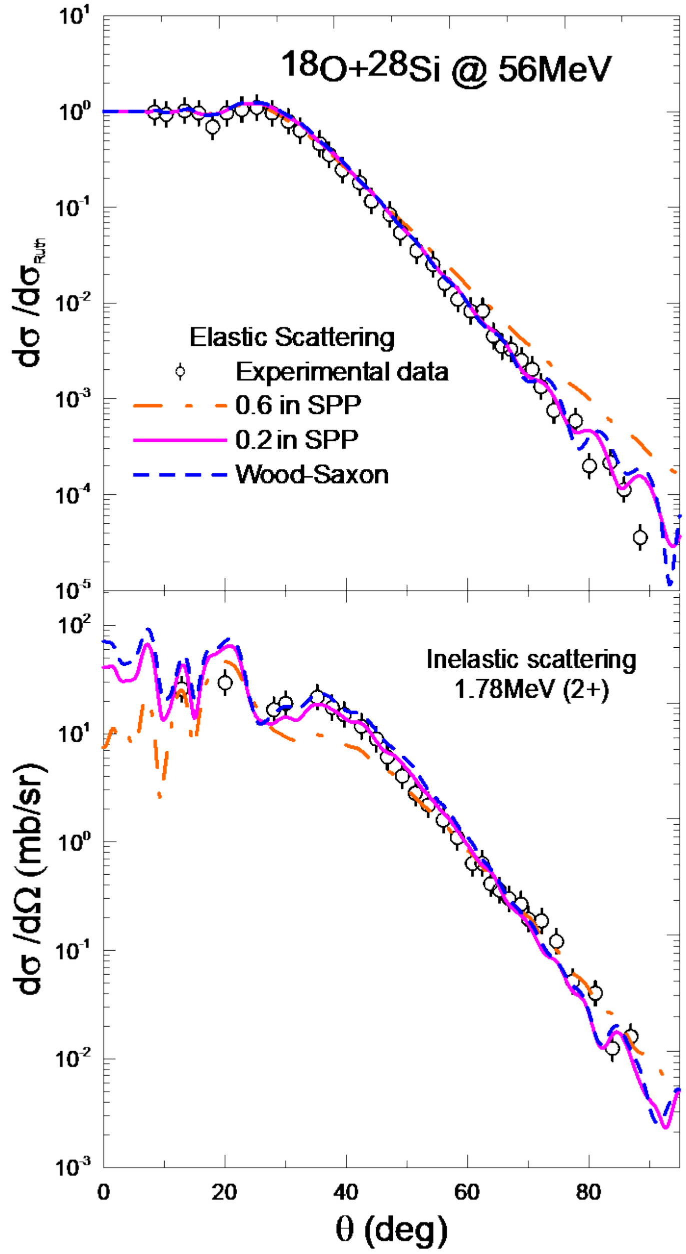
**g.s.: Two-step DWBA results are better. Same order: one and two step.**

**$2^+$ : Long-range correl. (coll.) dominates over the short-range (pairing)**

**Si* the same results as the $2^+$ state**

Cluster model is not good for $^{28,30}$Si

# Results of theoretical calculations



Does our theoretical calculations describe other observables?

- Elastic scattering
- Inelastic scattering

# Conclusions and outlooks

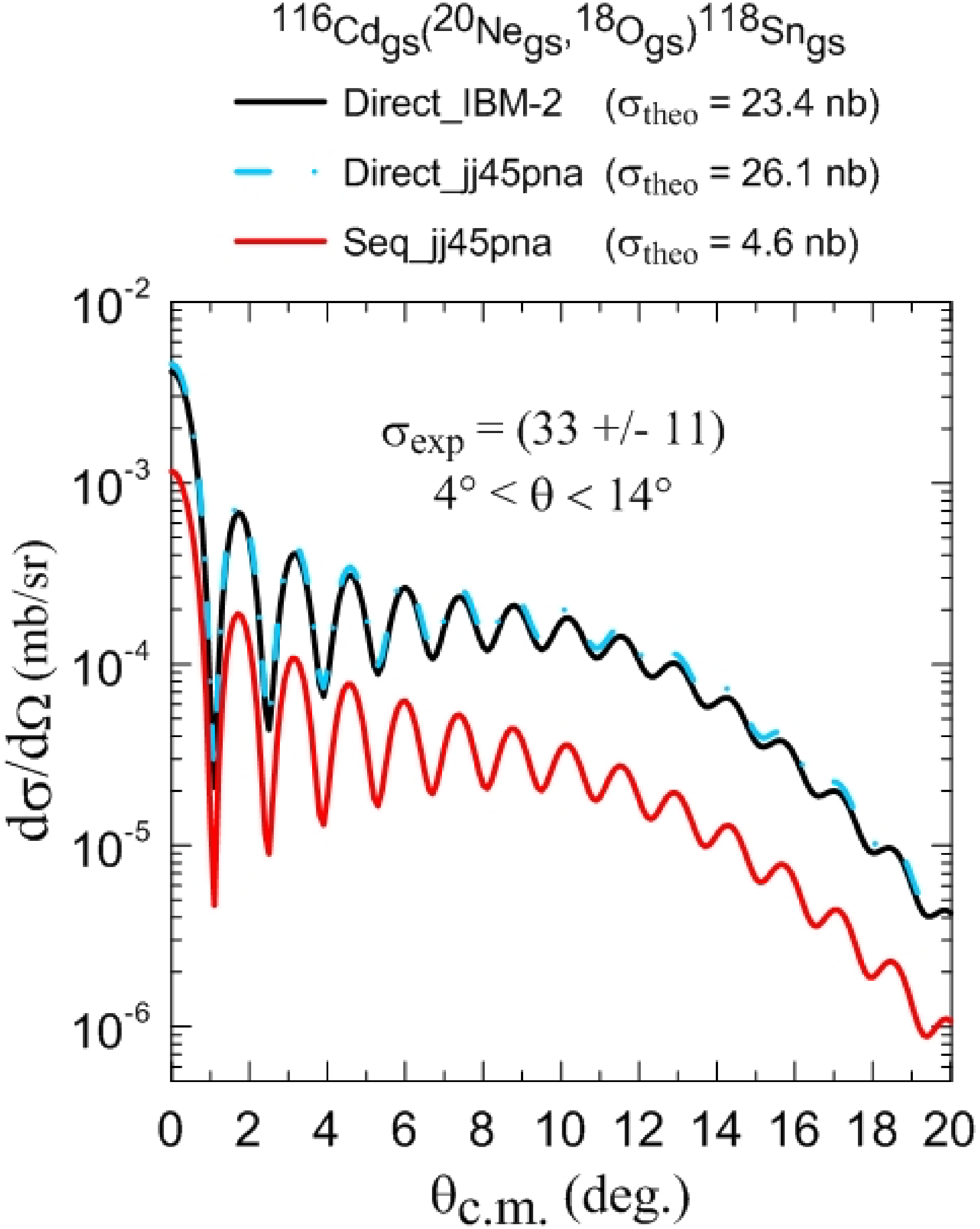
- ➢ $^{12,13}C(^{18}O,^{16}O)^{15}C$, $^{16}O(^{18}O,^{16}O)^{18}O$, $^{64}Ni(^{18}O,^{16}O)^{66}Ni$, $^{28}Si(^{18}O,^{16}O)^{30}Si$, at 84 MeV incident energy
- ➢ Four models were used to calculate the cross section:
  - ✓ Extreme cluster
  - ✓ Independent coordinate
  - ✓ DWBA
  - ✓ Microscopic cluster (only for $^{13}C$)
- ➢ no need for any "unhappiness" factor to reproduce the absolute cross sections

- ➢ In $^{13}C$ importance of a two-neutron correlation in the nuclear wave function, the extra neutron does not destroy the correlations observed in the $^{14}C$ case
- ➢ Dominance of the 1s and 1p waves in the two-neutron cluster internal wave function
- ➢Adequacy of zbm interaction for low-lying overlaps of the projectile were established for the projectile.
- ➢Dominance of long-range correlations for the excited $2^+$ state of $^{66}NI$ over the short-range pairing correlations. The opposite for the g.s.
- ➢Dominance of long-range correlations in all states of $^{30}Si$.

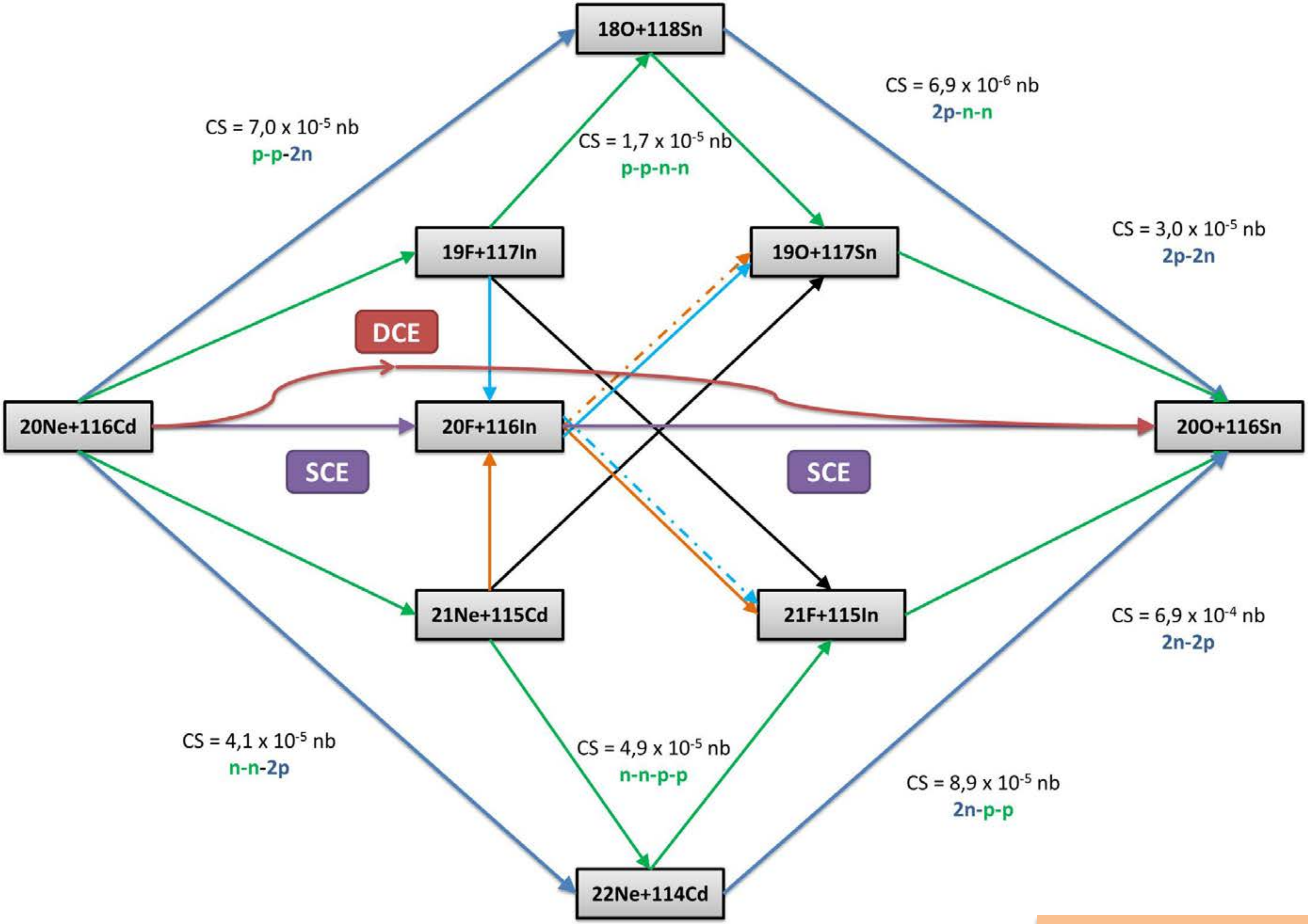
# Conclusions and outlooks

## Outlooks:

- Include other waves in the microscopic cluster calculations
- Enlarge the model space for higher energy transitions ($d_{3/2}$)
- Describe high excited states of the projectile.
- Include the deformed target ($^{28}$Si) to study the mixing of collective and single particle configurations.
- Study the 2p and np transfers to study the pairing correlations in collaboration with the structure group of Genova of Prof. Santopinto.


$^{116}Cd_{gs}(^{20}Ne_{gs},^{18}O_{gs})^{118}Sn_{gs}$
Direct_IBM-2 ($\sigma_{theo}$ = 23.4 nb)
Direct_jj45pna ($\sigma_{theo}$ = 26.1 nb)
Seq_jj45pna ($\sigma_{theo}$ = 4.6 nb)
$\sigma_{exp}$ = (33 +/- 11)
4° < θ < 14°
$d\sigma/d\Omega$ (mb/sr)
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
0
2
4
6
8
10
12
14
16
18
20
$\theta_{c.m.}$ (deg.)

# REACTIONS SCHEME CONCERNING THE $^{116}$Cd($^{20}$Ne, $^{20}$O) $^{116}$Sn



**18O+118Sn**

CS = 6,9 x $10^{-6}$ nb
**2p-n-n**

CS = 7,0 x $10^{-5}$ nb
**p-p-2n**

CS = 1,7 x $10^{-5}$ nb
**p-p-n-n**

CS = 3,0 x $10^{-5}$ nb
**2p-2n**

**19F+117In**

**19O+117Sn**

**DCE**

**20Ne+116Cd**

**20F+116In**

**20O+116Sn**

**SCE**

**SCE**

**21Ne+115Cd**

**21F+115In**

CS = 6,9 x $10^{-4}$ nb
**2n-2p**

CS = 4,1 x $10^{-5}$ nb
**n-n-2p**

CS = 4,9 x $10^{-5}$ nb
**n-n-p-p**

CS = 8,9 x $10^{-5}$ nb
**2n-p-p**

**22Ne+114Cd**

J. Lubian CNNP 2017, Catania

# Working group

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Thank you