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Correlations in multinucleon transfer reactions.

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CAPES CNPq FAPERJ

Outline

Nuclear spectroscopy via transfer reactions between heavy ions

- The (^{18}O,^{16}O) reaction (two neutron transfer correlations)

- CRC, two-step CCBA and DWBA calculation

- 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 reactions @ 84 MeV incident energy.

- Correlations in 2p transfer react.: ^{40}Ca(^{18}O,^{20}Ne)^{38}Ar

- Correlations in np transfer react.: ^{12}C(^{6}Li,^{4}He)^{14}N
  ^{17}F(^{6}Li,^{4}He)^{21}Ne

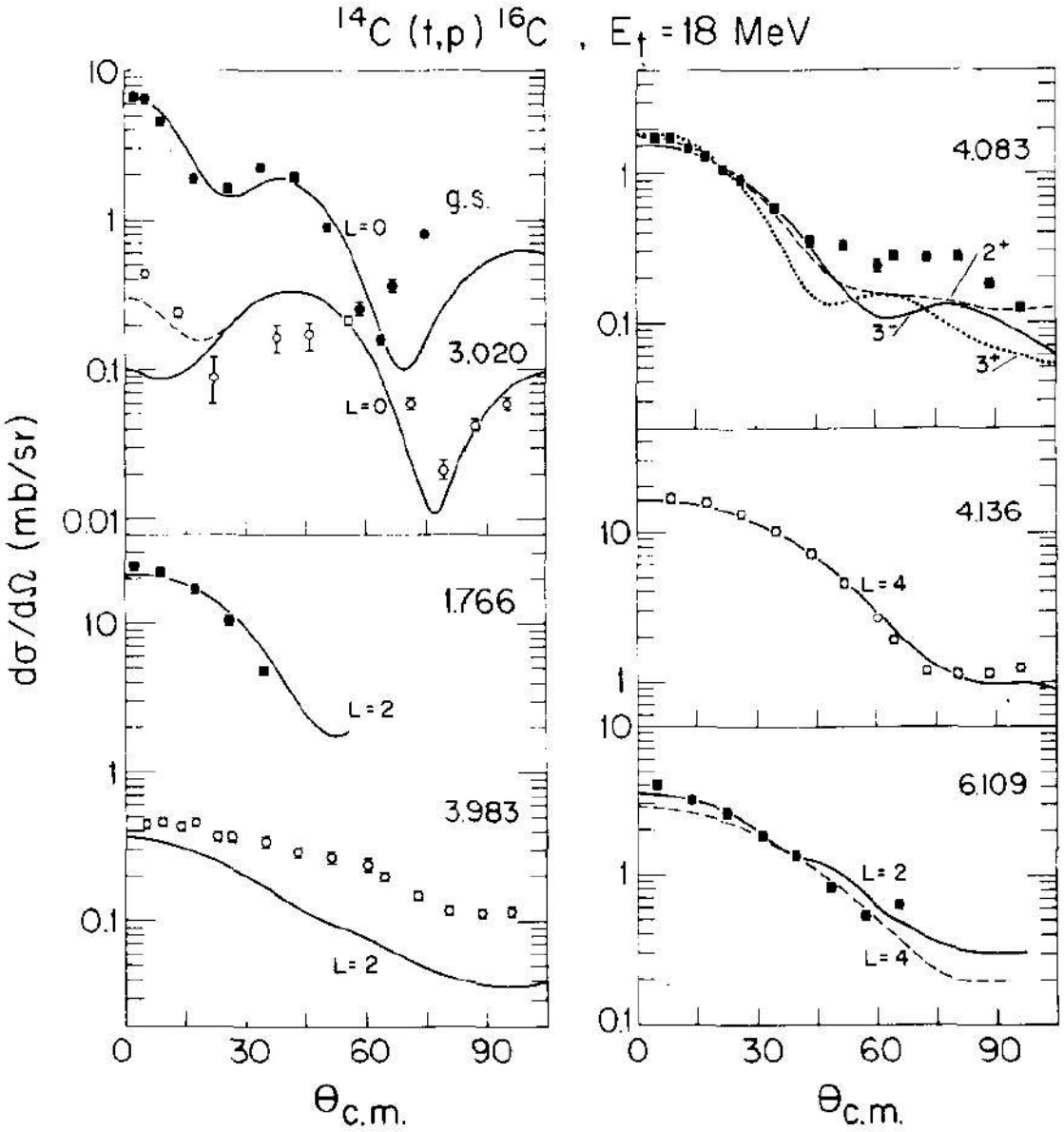
Outline

^{3}H and ^{3}He cluster transfer in the ^{6}Li + ^{89}Y reaction

Alpha clusters in nuclei. Transfer reactions. Fusion cross section

Conclusions and perspectives

Brief introduction. (t,p) reactions



Volume 70B, number 4 PHYSICS LETTERS 24 October 1977

SPECTROSCOPY OF ^{16}C ★

H.T. FORTUNE, R. MIDDLETON, M.E. COBERN,
G.E. MOORE, S. MORDECHAI, R.V. KOLLARITS
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Received 30 June 1977

The $^{14}C(t, p)^{16}C$ reaction locates five new states in ^{16}C, at excitation energies of 3020 ± 15, 3983 ± 10, 4083 ± 10, 4136 ± 10 and 6109 ± 15 keV, in addition to the g.s. and 1.76 MeV states. The 3.02 and 3.98 MeV states appear to be the second 0^+ and 2^+ 2p-2h states, respectively. The 4.14 MeV state has $J^\pi = 4^+$ and the 6.11 MeV state has $J^\pi = 2^+$, 3^-, or 4^+.

E_x (I^π)	N
0.0 (0+)	300
1.766 (2+)	400
3.020 (0+)	300
3.983 (2+)	400
4.136 (4+)	360

Main reasons for these discrepancies:

- the use of oversimplified triton wave functions
- the use of the zero-range approximation
- the use of only simultaneous transfer.
- Numerical simplifications to solve six-dimension integrals to determine transition amplitudes???

The production of triton beam was prohibited for safety reasons!

Theoretical models and main ingredients

Exact finite range CRC
and
Two-step CCBA or DWBA calculations

- **Prior representation**
- **Complex remnant**
- **Non-orthogonality corrections**

- São Paulo Potential (**SPP**) used as optical potentials *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 varied to fit the exp. separation energies
- **Deformation parameters** for collective excitations from systematics
- **Spectroscopic Amplitudes** by shell-model, IBM2, IBFM, QRPA, semi-microscopic algebraic cluster model.

Theoretical models and main ingredients

The CRC equations are in many cases of the form

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

Single nucleon states are given by

$$\phi_{JM}(\xi_c, \mathbf{r}) = \sum_{\ell jI} A^{jIJ}_{\ell sj}\ [\phi_I(\xi_c)\varphi_{\ell sj}(\mathbf{r})]_{JM}$$

$$= \sum_{\ell jI, m\mu m_s m_\ell} A^{jIJ}_{\ell sj} \langle jmI\mu|JM\rangle\, \phi_{I\mu}(\xi_c)\, \langle \ell m_\ell s m_s|jm\rangle\, Y^{m_\ell}_\ell(\hat{\mathbf{r}}) \phi^{m_s}_s \frac{1}{r} u_{\ell sjI}(r)$$

and are the solution of

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

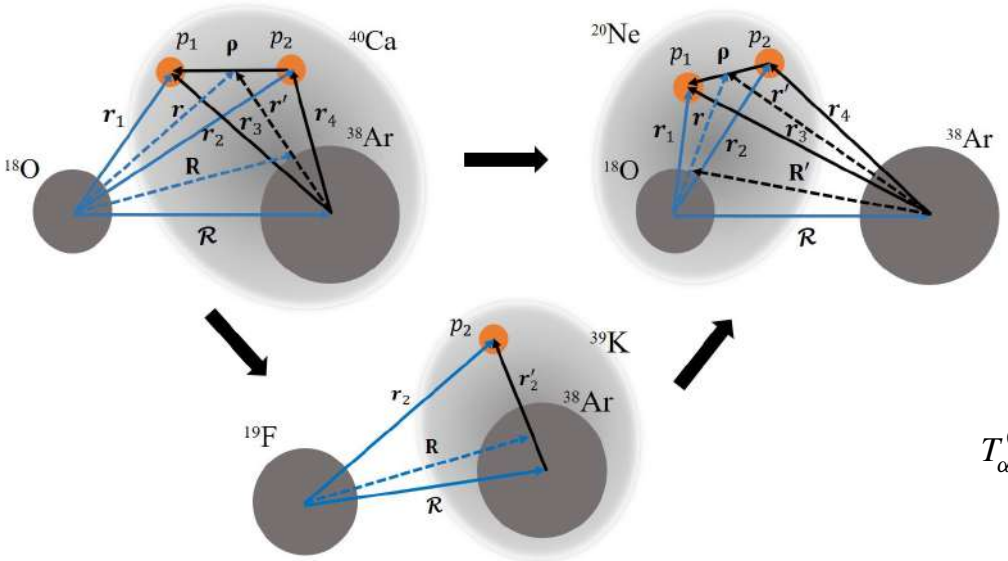
Theoretical models and main ingredients

Independent coordinate model

$$\varphi_{12}(\mathbf{r}_1,\mathbf{r}_2) = \sum_i c_i \; |(\ell_1(i),s_1)j_1(i),(\ell_2(i),s_2)j_2(i);\; J_{12}T\rangle$$
$$\rightarrow \sum_u c_i \sum_{L\ell Sj} |L,(\ell,(s_1s_2)S)j;J_{12}T\rangle\, \phi^{J_{12}T,i}_{L(\ell S)j}(r,\rho)$$

$$\phi^{J_{12}T,i}_{L(\ell S)j}(r,\rho) = \langle L,(\ell,(s_1s_2)S)j;J_{12}T|\,(\ell_1(i),s_1)j_1(i),(\ell_2(i),s_2)j_2(i);\; J_{12}T\rangle$$
$$\times\langle[Y_L(\hat{\mathbf{r}})Y_\ell(\hat{\rho})]_\lambda\,|\,[\varphi_{\ell_1s_1j_1}(\mathbf{r}_1)\varphi_{\ell_2s_2j_2}(\mathbf{r}_2)]_{J_{12}T}\rangle$$

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



$$T^{(\text{direct})}_{\alpha\beta} = \langle\Psi^{(-)}_\beta|W_\alpha|\Psi^{(+)}_\alpha\rangle$$

$$|\Psi^{(+)}_\alpha\rangle = \textstyle\sum_{ij}|\phi_{a_i}\phi_{A_j}\chi^{(+)}_\alpha\rangle = \sum_\alpha|\phi_\alpha\chi^{(+)}_\alpha\rangle$$

$$T^{(\text{seq})}_{\alpha\beta} = \sum_\gamma \langle\Psi^{(-)}_\beta|W_\gamma|\phi_\gamma\rangle\tilde{G}^{(+)}_\gamma\langle\phi_\gamma|W_\alpha|\Psi^{(+)}_\alpha\rangle \; - \langle\Psi^{(-)}_\beta|\phi_\gamma\rangle\langle\phi_\gamma|W_\alpha|\Psi^{(+)}_\alpha\rangle$$

Theoretical models and main ingredients

The São Paulo potential (SPP)

$$V_F = \int \rho_1(\mathbf{r}_1)\mathcal{V}(\mathbf{R}-\mathbf{r}_1+\mathbf{r}_2)\rho_2(\mathbf{r}_2)d\mathbf{r}_1 d\mathbf{r}_2$$

$\mathcal{V}(\mathbf{R}-\mathbf{r}_1+\mathbf{r}_2)$ is the known nucleon-nucleon M3Y interaction

$$V_{\mathrm{LE}}^{\mathrm{SPP}}(\mathbf{R},E) = V_{\mathrm{F}}(\mathbf{R})e^{4v^2/c^2}$$

SPP systematics: Two parameters fermi-Dirac distribution

$$\rho(r) = \frac{\rho_0}{1+exp\left(\frac{r-R_0}{a}\right)}$$

$$R_0 = \left(1.31A^{1/3} - 0.84\right)\ \mathrm{fm}$$

$$a = 0.56\ \mathrm{fm}$$

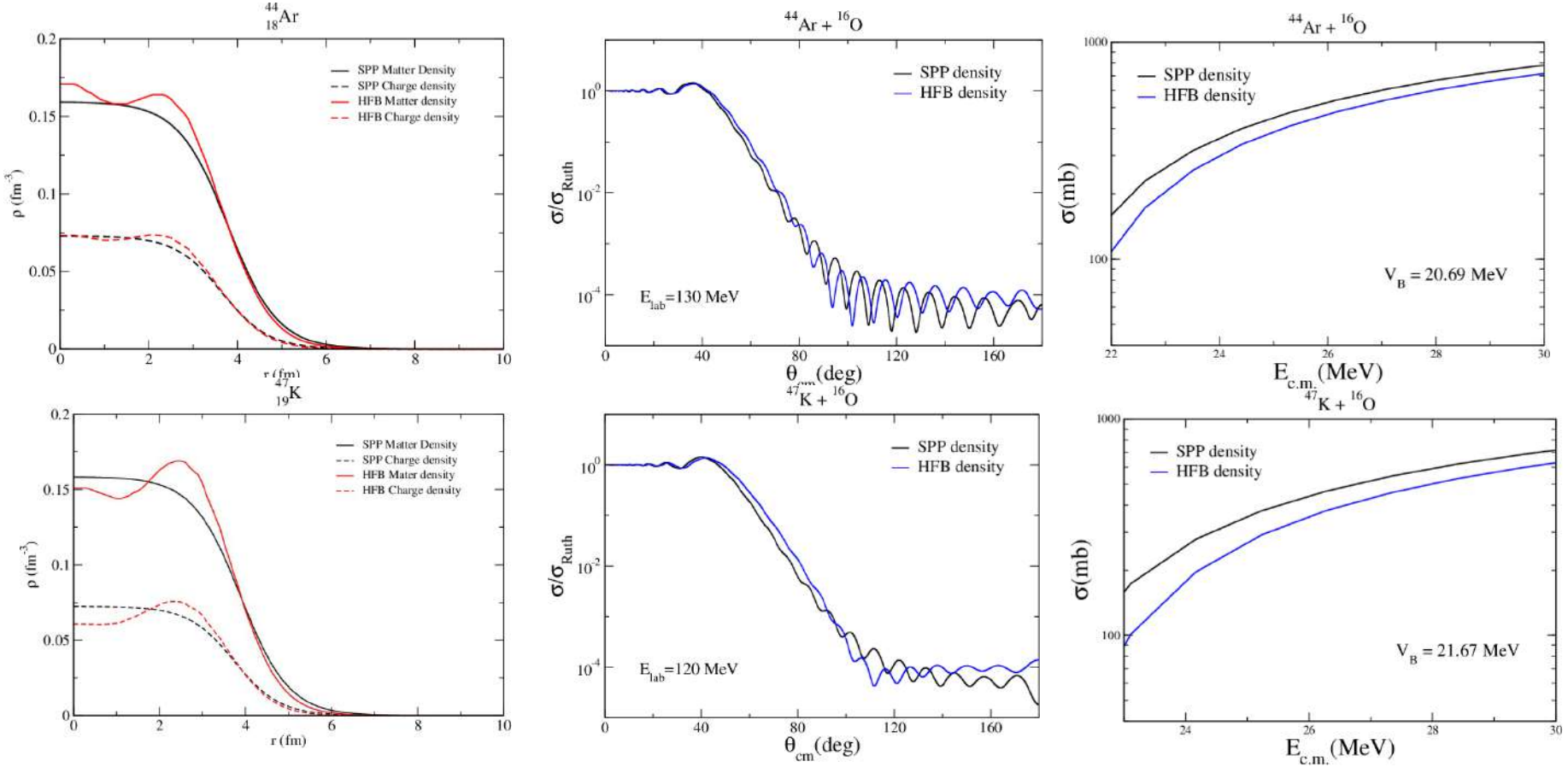
Optical potentials:

U= $(1+0.78i)\mathrm{V}^{\mathrm{SPP}}$ in DWBA and CRC or CCBA in intermediate and final partitions
U= $(1+0.60i)\mathrm{V}^{\mathrm{SPP}}$ in CRC and CCBA initial partitions (D. Pereira et al. PLB 670, 330 (2009)

Theoretical models and main ingredients

Does the SPP systematic always work?

- SPP systematic mostly works, but not always
- $a = 0.61$ fm, for ^{18}O
- $a = 0.62$ fm, for ^{17}O
- ^{A}Ar, ^{A}K ?



See more details in V. Singh et al. PRC 104, L041601 (2021)

BUT: SPP systematic is always the starting point!! Especially for nuclei around the stability line

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

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

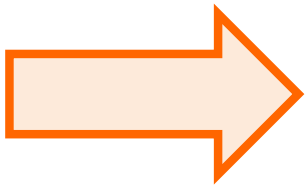
- The presence of a **correlated pair** of neutrons in the $^{18}O_{g.s.}$ wave function
- The very low polarizability of the **^{16}O core**

^{14}C is a good benchmark for considerations on the reaction mechanism, **^{64}Ni and ^{28}Si** are good benchmark for studying collective vs two particle correlations

- Comparison with (t,p) results upon availability

Studies on both

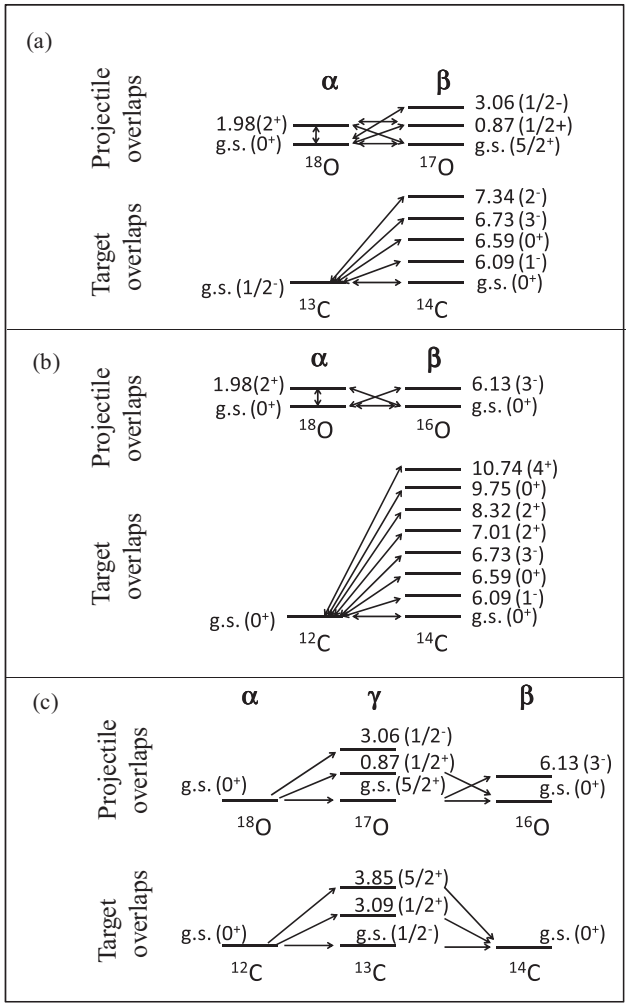
$^{13}C(^{18}O,^{17}O)^{14}C$ **1n transfer** and $^{12}C(^{18}O,^{16}O)^{14}C$ **2n transfer**

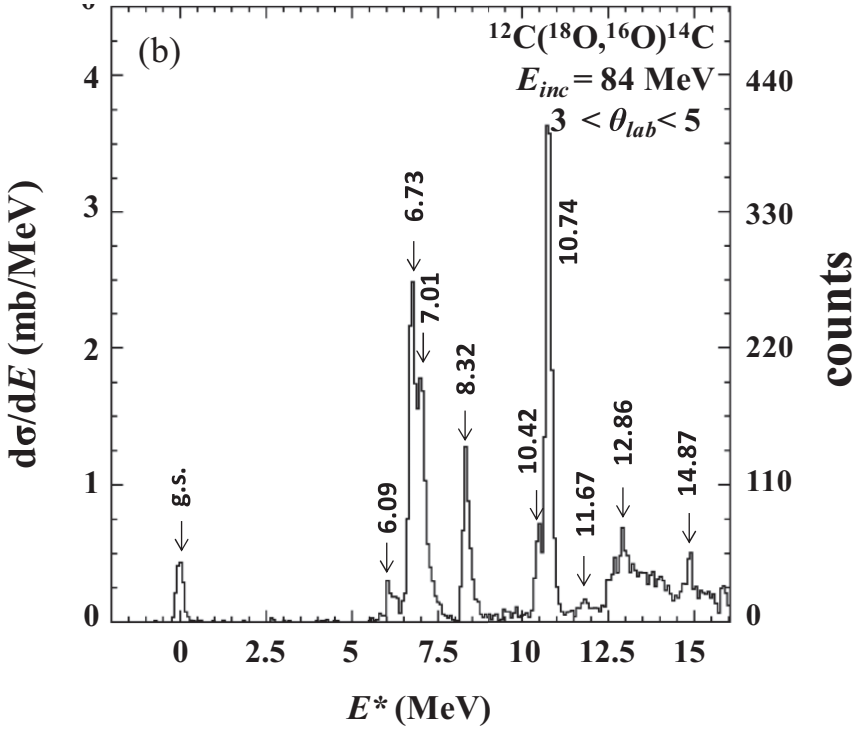


- Presence of 2n correlations in the $^{14}C_{g.s.}$ wave function
- Strong selectivity in the populated states
- Absolute cross sections reproduced without any scaling factor

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

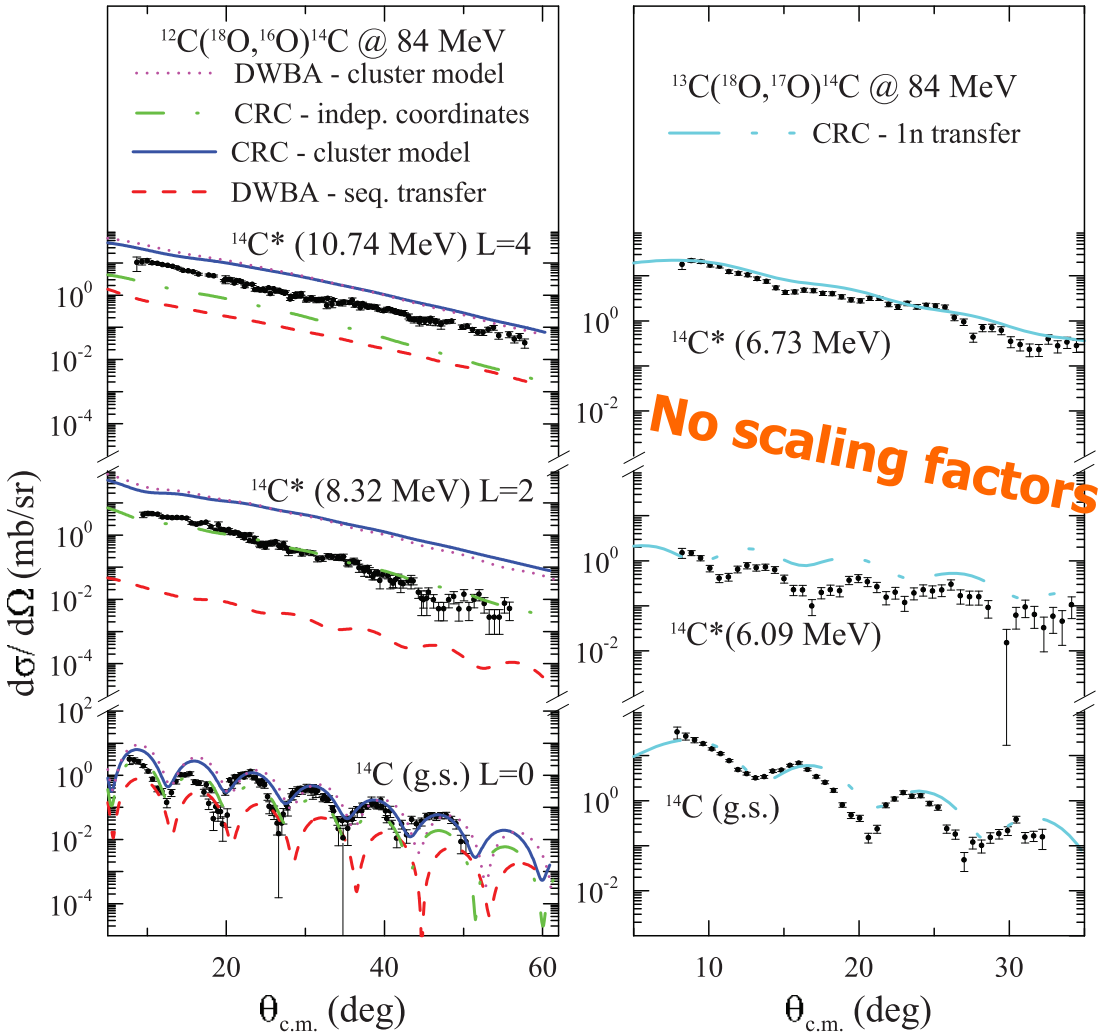
Theoretical results for $^{12}C(^{18}O,^{16}O)^{14}C$





ZBM model space (valence orbits: $1p_{1/2}$, $2s_{1/2}$, and $1d_{5/2}$)

Theoretical results for $^{12}C(^{18}O,^{16}O)^{14}C$



Presence of two-neutron correlations in ^{14}C state, especially the g.s.

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. S.A. = 1.0

Sequential transfer

(CCBA)

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

Independent coord.

(CRC)

CRC **-1n transfer**

No arbitrary scaling

S.A. from shell-model calculations using the ZBM model space

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

Works published in 2016-2017

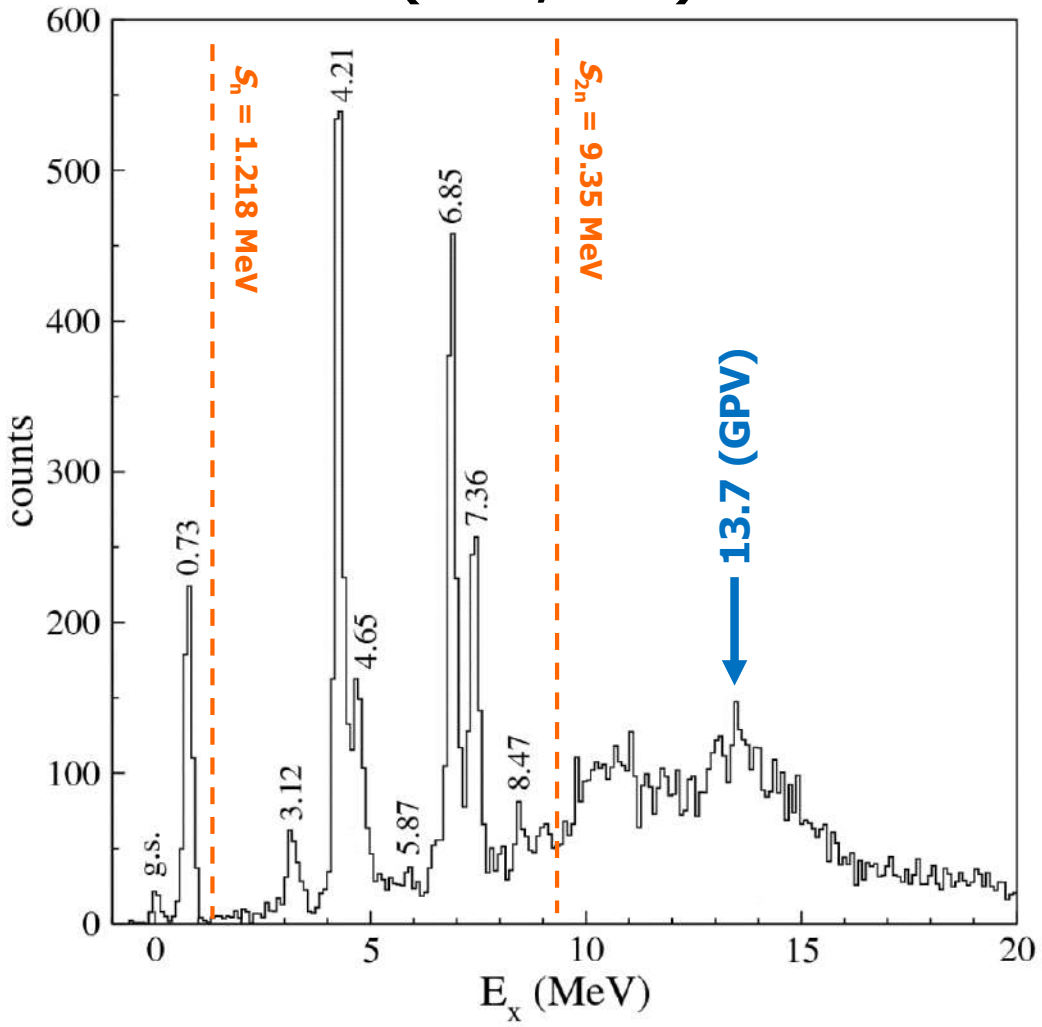
What happens if we add a neutron to the ^{14}C system?

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

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

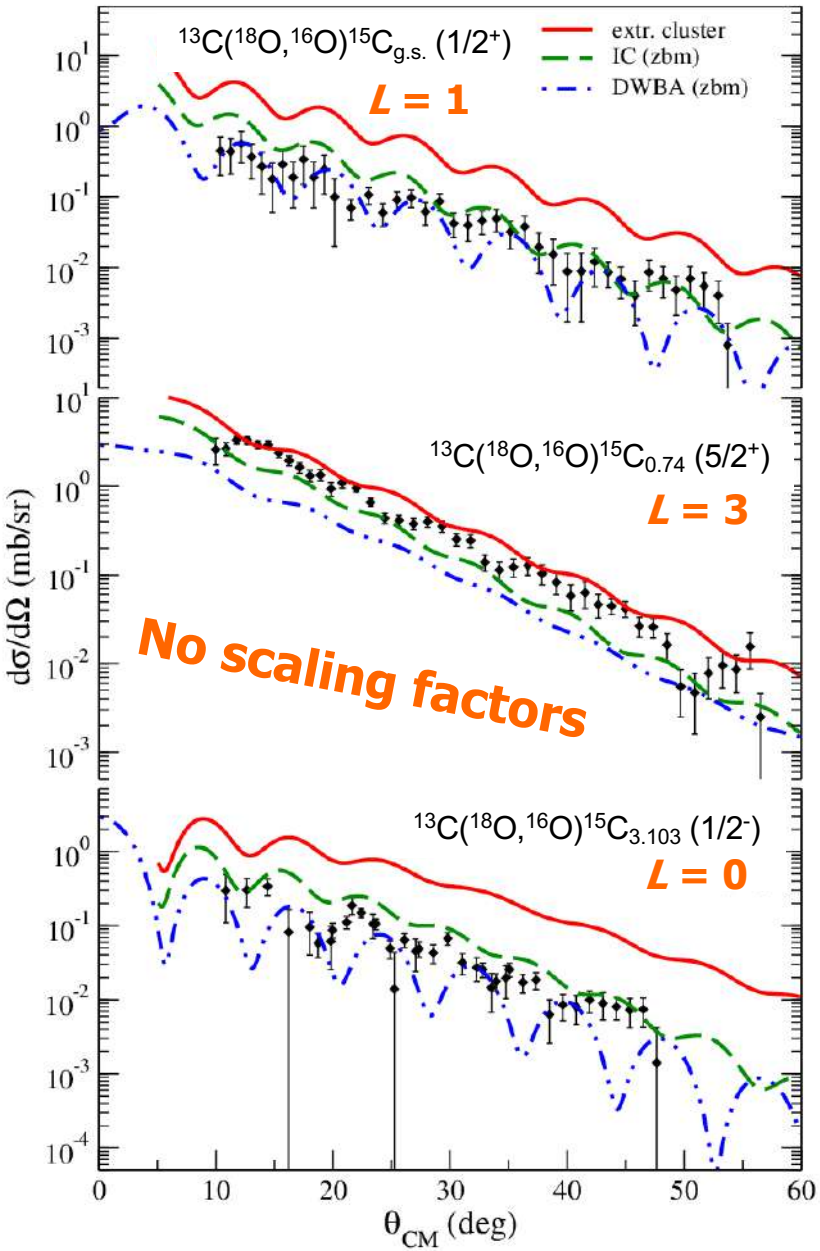


- Same states populated in the (t,p) reactions
- Strong population of states with $^{13}C + 2n$ configurations
- Population of the Giant Pairing Vibration above S_{2n}
  - F. Cappuzzello et al., Nat. Commun. 6, 6743 (2015)
  - D. Carbone, EPJ Plus (2015) 130:143

$9° < \theta_{lab} < 10°$

Energy resolution ~ 200 keV

CRC and CCBA calculations



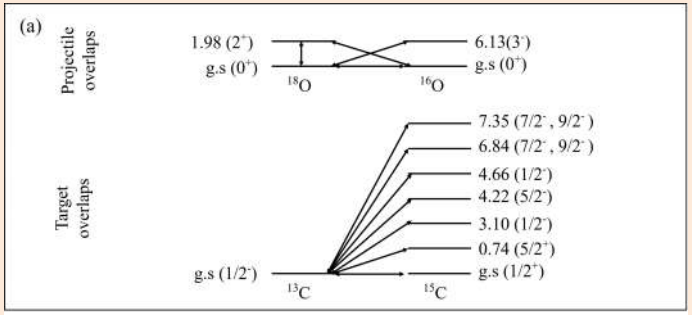
Extreme cluster model

- 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

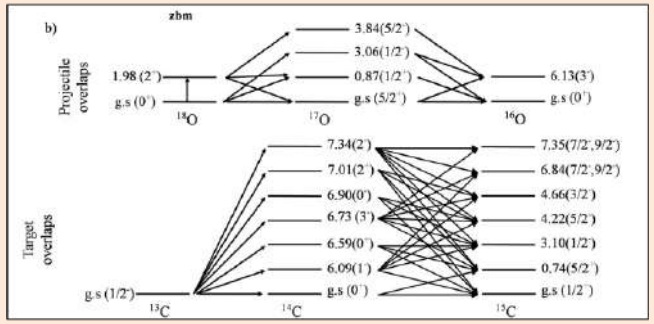
Coupling scheme



Sequential transfer (DWBA)

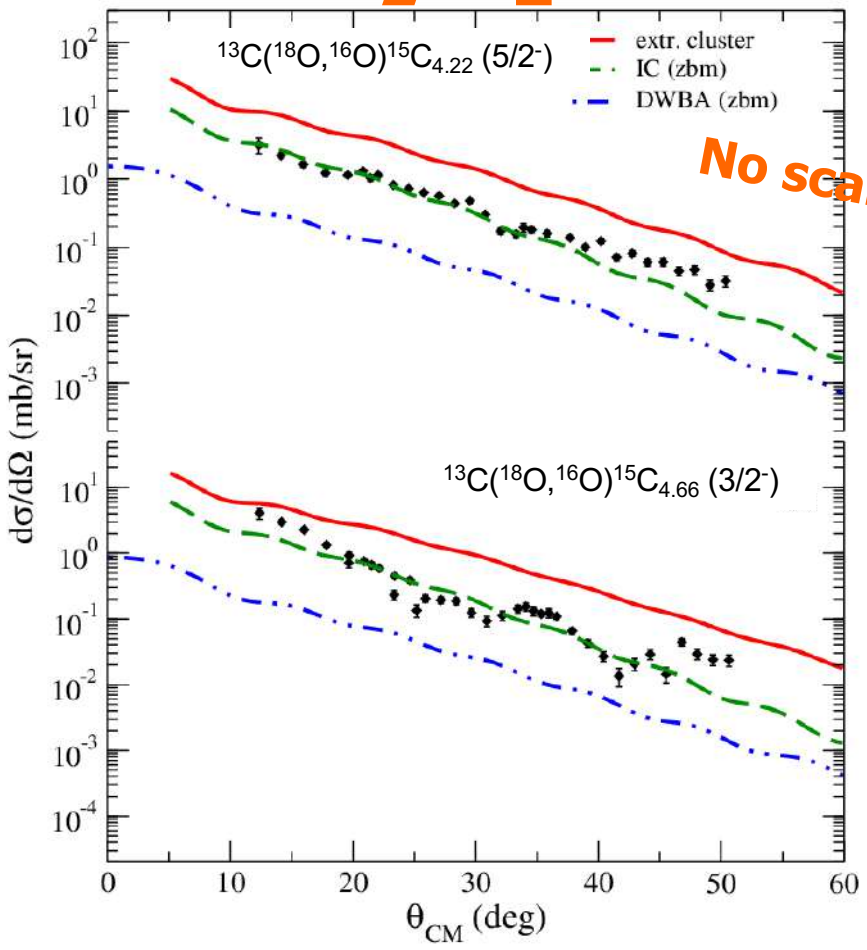
- Introducing the ^{17}O + ^{14}C intermediate partition

Coupling scheme



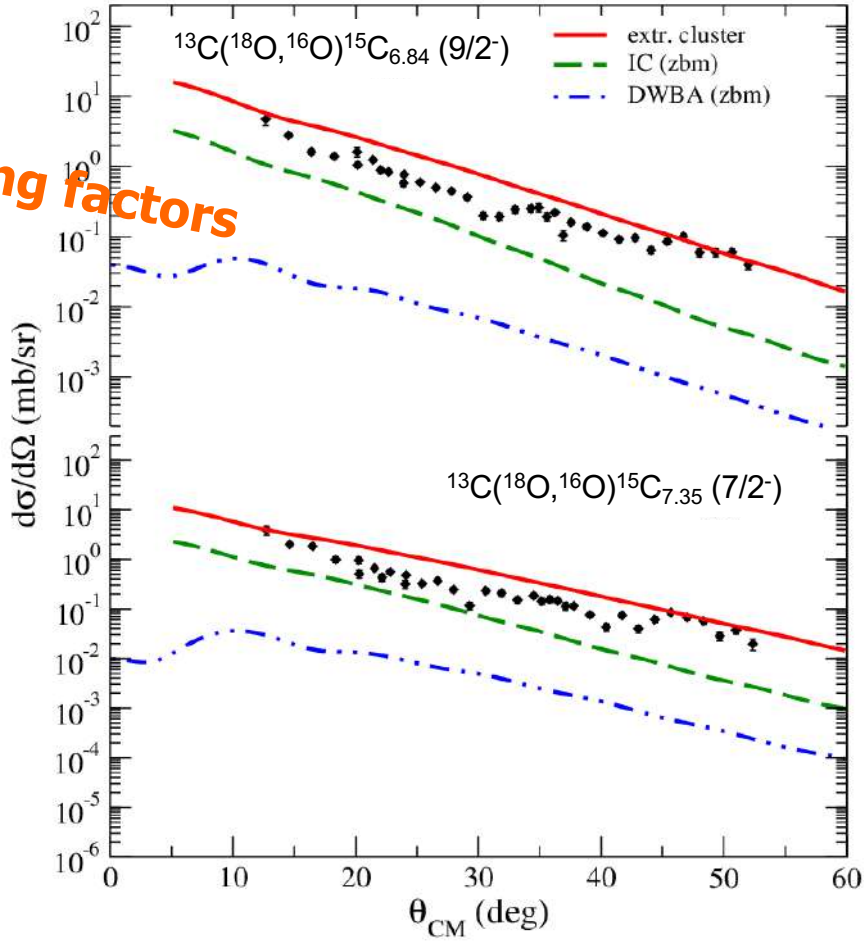
CRC and DWBA calculations

L = 2



No scaling factors

L = 4



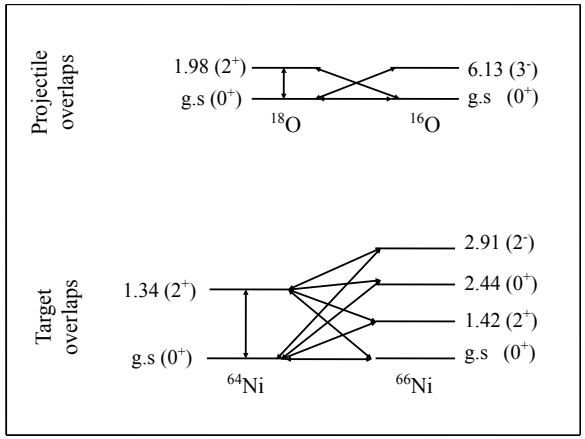
Extreme cluster model overestimate the cross section (S.A. = 1)
Independent coordinate model describes quite well the cross section
Sequential transfer (CCBA) underestimate the cross section

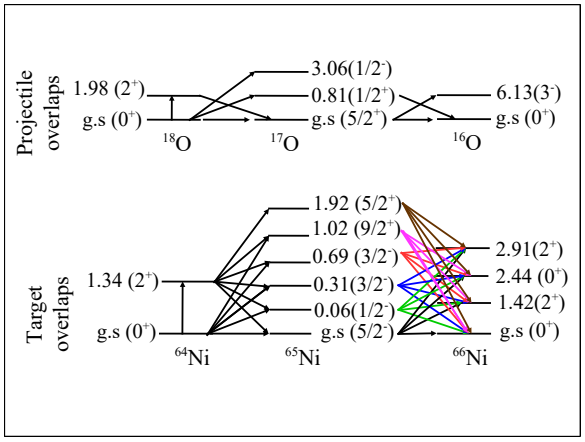
S.A. from shell-model calculations using the ZBM model space

More recent results

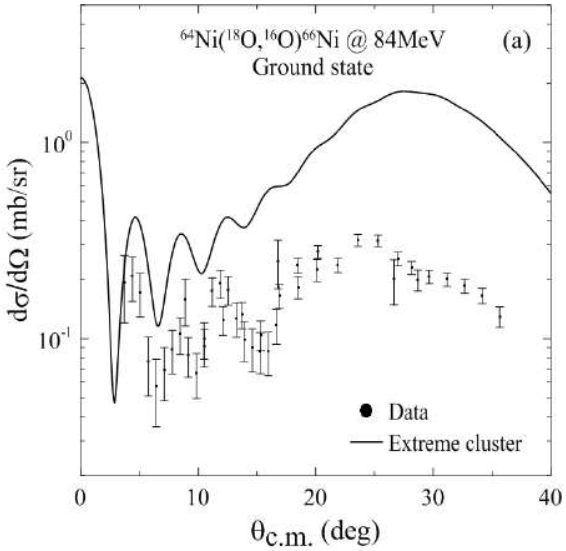
Study of the $^{18}O(^{64}Ni,^{66}Ni)^{16}O$ reaction at 84 MeV incident energy

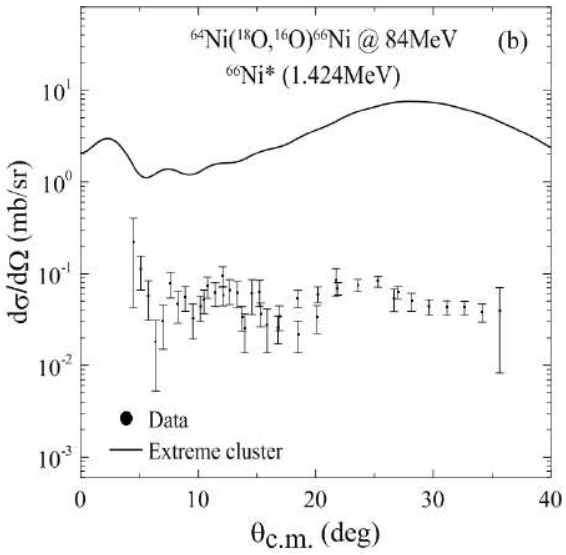
Model space	valence orbitals
protons	$1p_{1/2}$, $1d_{5/2}$, $2s_{1/2}$
neutrons	$1p_{3/2}$, $1p_{1/2}$, $1d_{5/2}$, $2s_{1/2}$, $1d_{3/2,1}$, $1g_{7/2}$

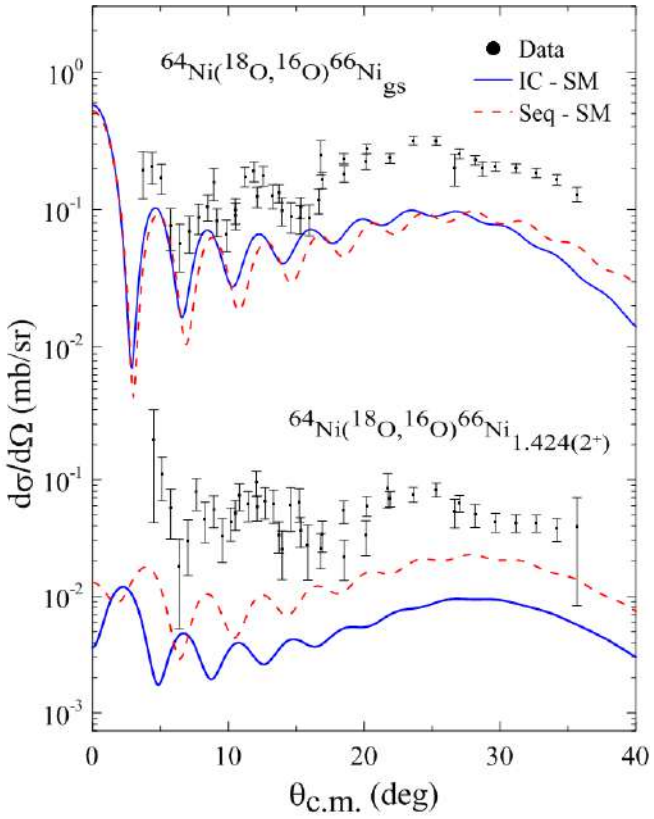




Results of theoretical calculations



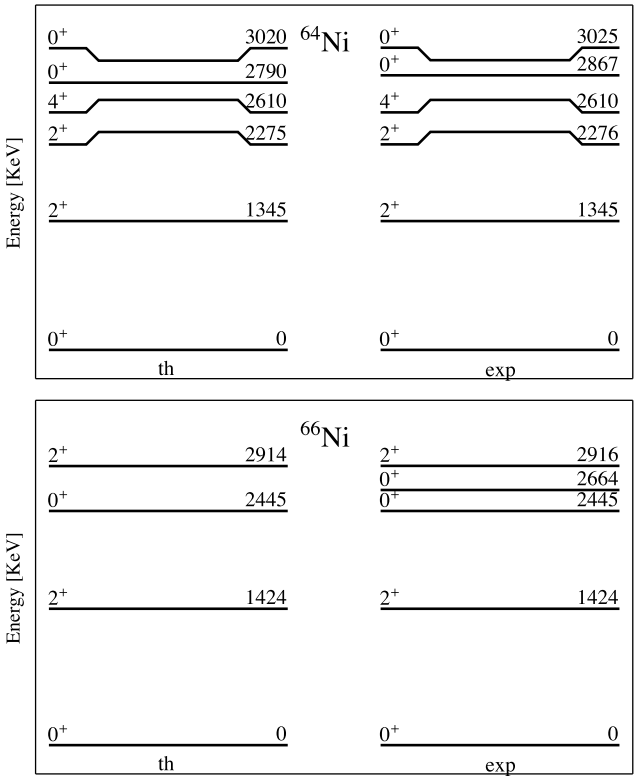


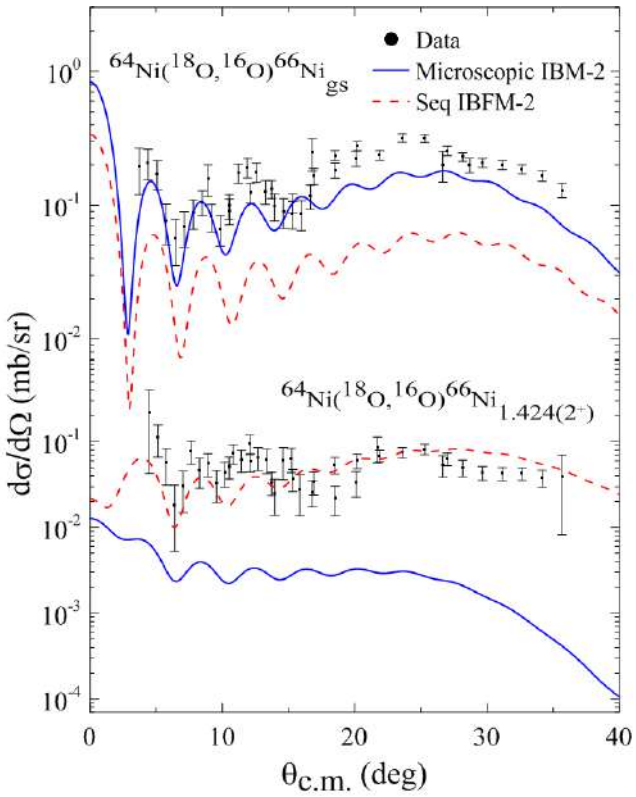


Microscopic results:
g.s.: IC results are better, specially in the bell-shaped region.
Same order: one and two step.
2^+ : Collective correl. dominates over pairing

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

Results of theoretical calculations





Microscopic results:
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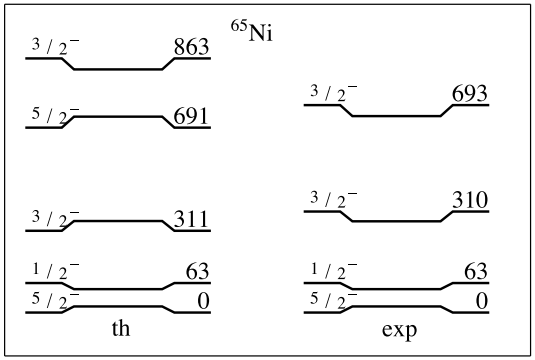
2^+ : Collective correlations dominate over the pairing



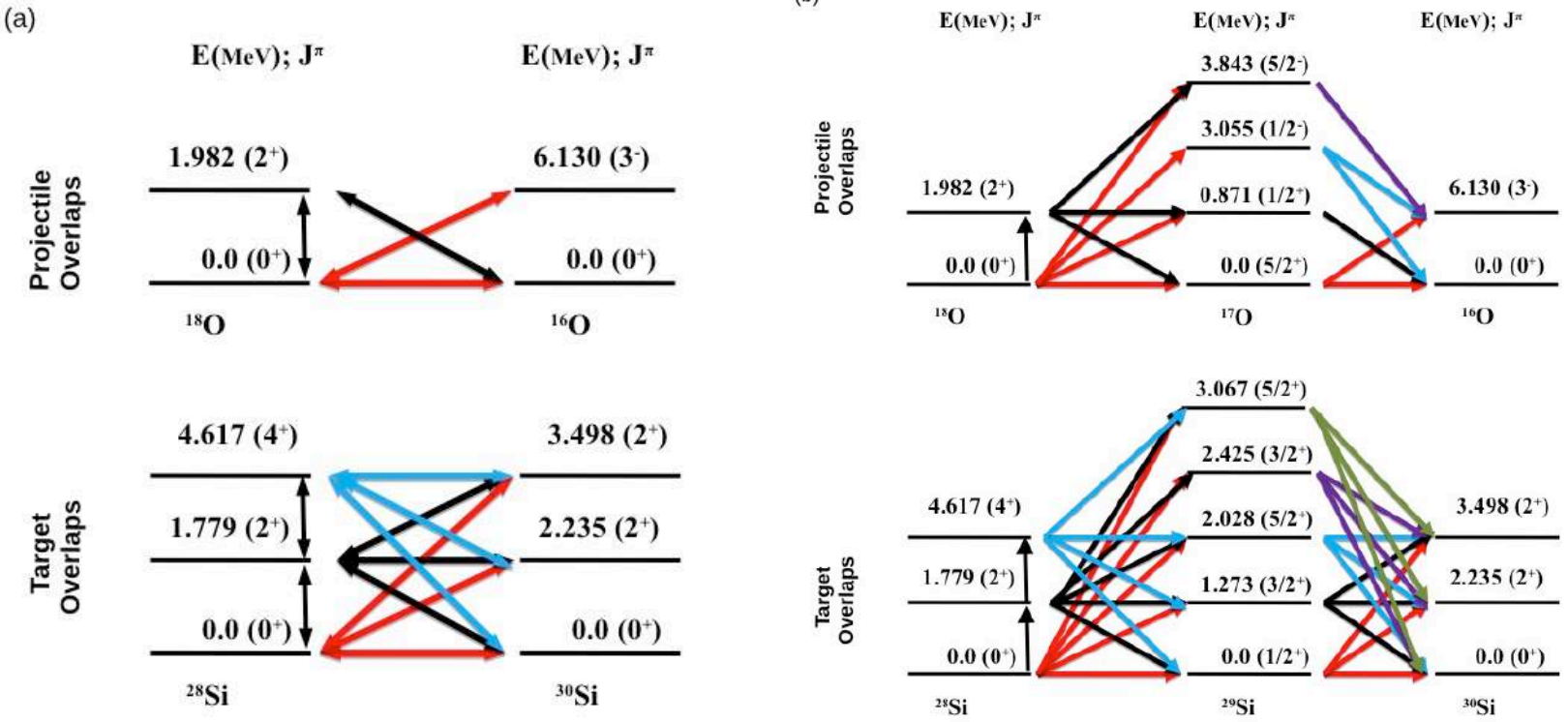
B. Paes et al PRC 96.044612 (2017)

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

More recent results

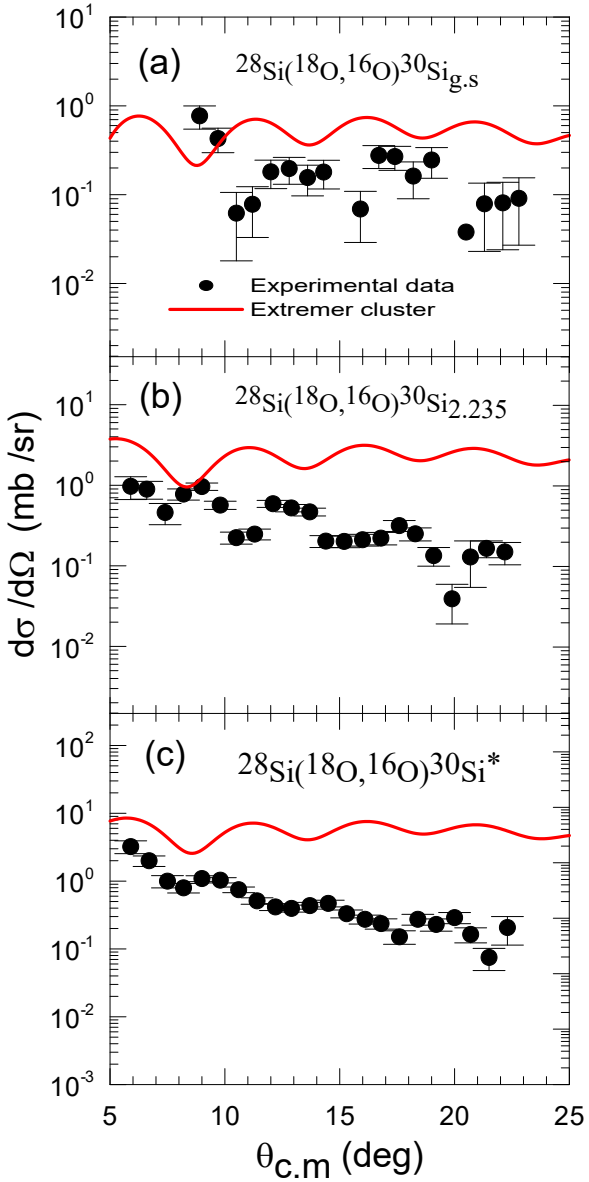
Study of the $^{18}O(^{28}Si,^{30}Si)^{16}O$ reaction at 84 MeV incident energy

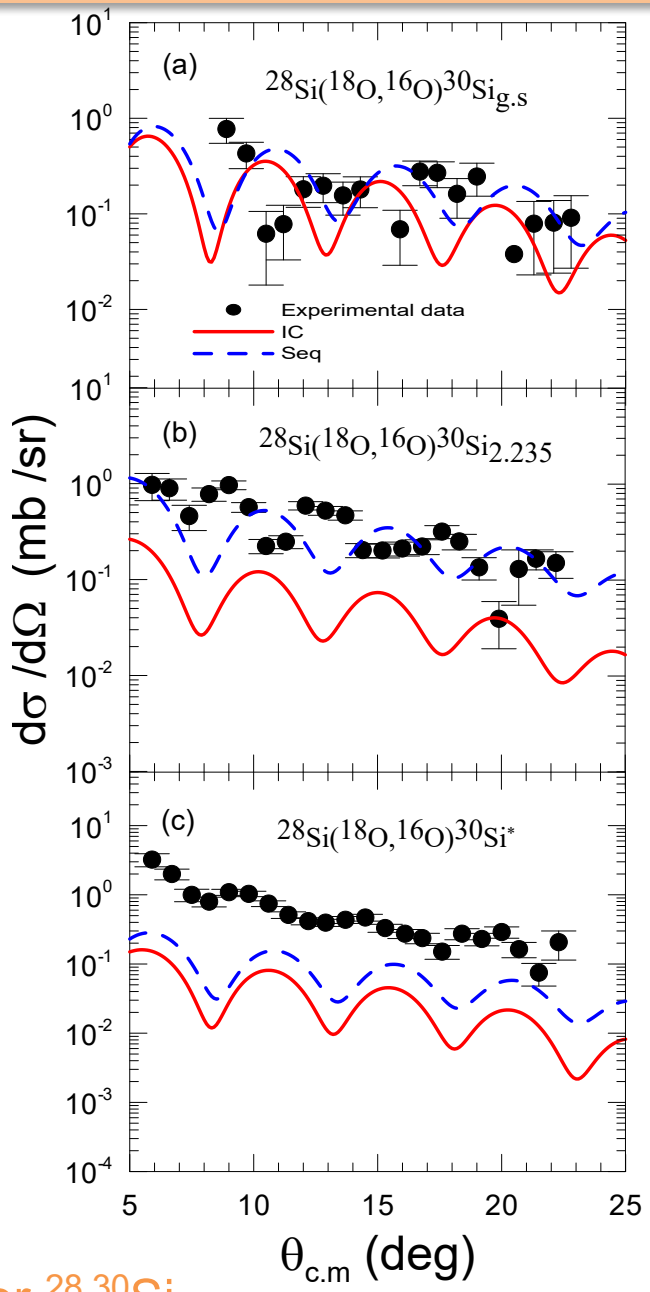
Model space (^{4}He core)	valence orbitals (similar to Ni)
Protons	$1p_{3/2}$, $1p_{1/2}$, $1d_{5/2}$, $2s_{1/2}$, $1d_{3/2}$
neutrons	$1p_{3/2}$, $1p_{1/2}$, $1d_{5/2}$, $2s_{1/2}$, $1d_{3/2}$



J. Lubian MNC in N&S, 2-6 Jun, SP 2025

Results of theoretical calculations





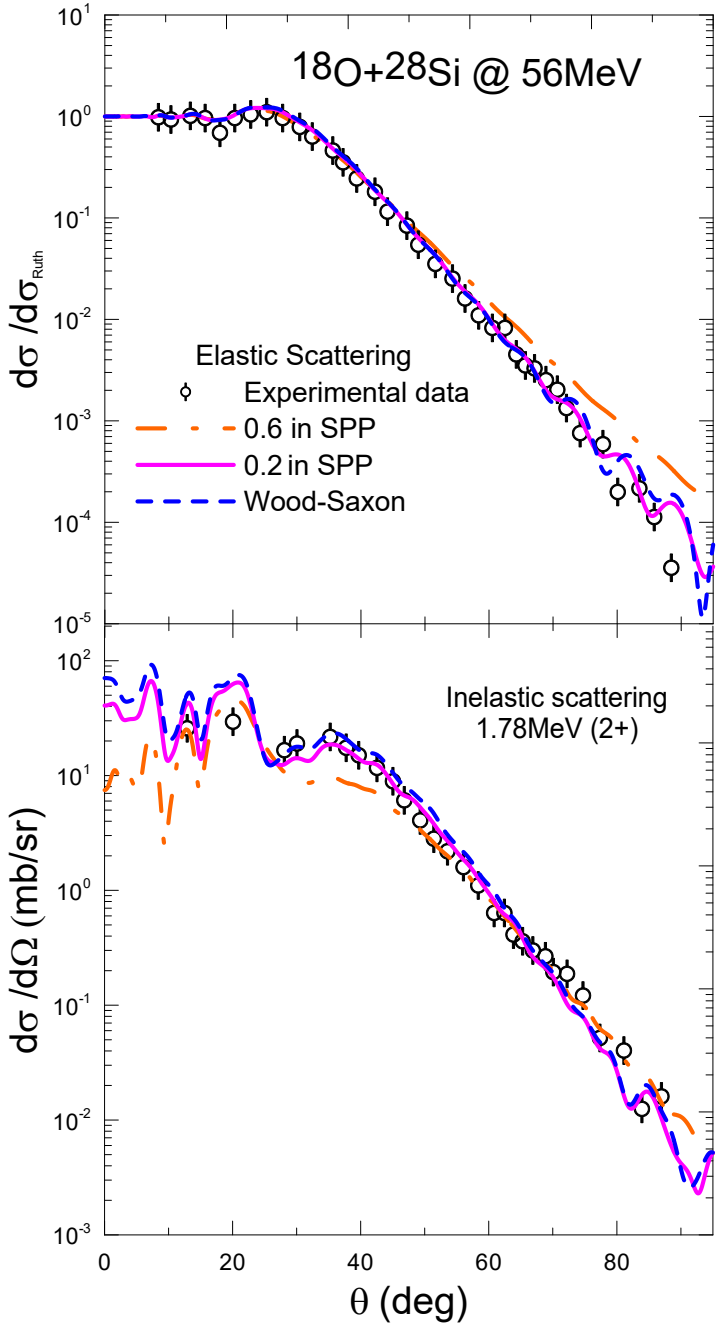
Cluster model is not good for ^{28,30}Si

Microscopic results:
g.s.: Two-step DWBA results are better. Same order: one and two step.
2^+ : Collective correlations dominate over the two-particle
Si*: the same results as the 2^+ state

Nucleus	B(E2); $0^+ \rightarrow 2^+$ (e^2b^2)
^{14}C	0.0018
^{18}O	0.0045
^{28}Mg	0.035
^{30}Si	0.022
^{66}Ni	0.060
^{76}Ge	0.270

Small for ^{14}C ^{18}C
Big for ^{28}Mg ^{30}Si ^{66}Ni ^{76}Ge

Results of theoretical calculations



Does our theoretical calculations describe other observables?

- Elastic scattering
- Inelastic scattering

Conclusions and outlooks for (^{18}O,^{16}O) reactions

- ^{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
  - ✓ CCBA
  - ✓ Microscopic cluster (only for ^{13}C)
- no need for any "unhappiness" factor to reproduce the absolute cross sections

- Two –neutron correlations in ^{14,15}C, ^{18}O
- 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 collective correlations for the excited 2^+ state of ^{66}Ni over the two neutron correlations. The opposite for the g.s.
- Dominance of collective correlations in all states of ^{30}Si.

2p-stripping reaction in the $^{18}O+^{40}Ca$ collision at 270 MeV

Spectroscopic Amplitudes for the target overlap

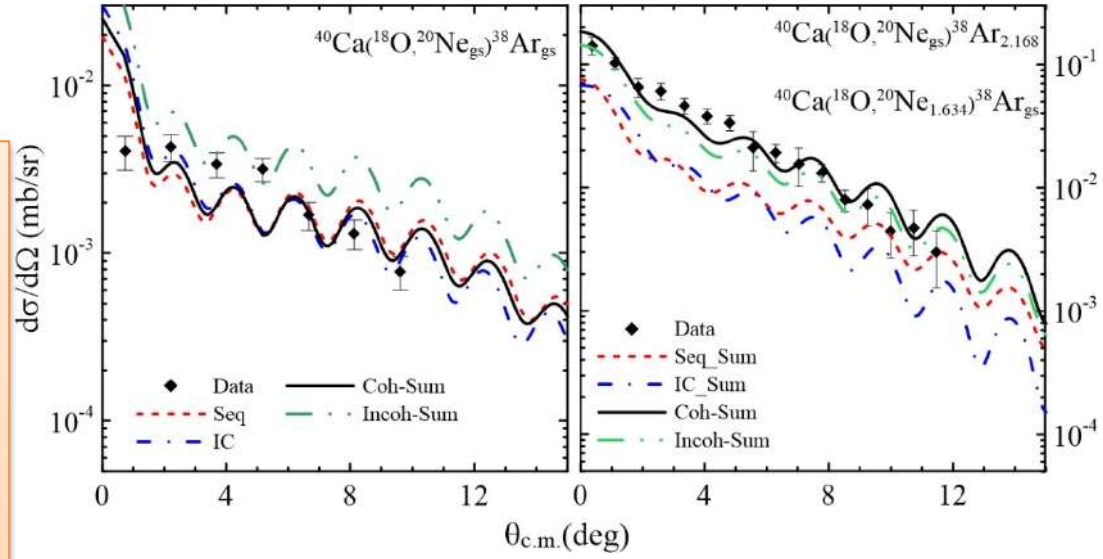
- Shell Model Calculations – NusheLLX
  - ✓ Effective Interaction: ZBMmod
  - ✓ Model Space for both protons and neutrons: $2s_{1/2}$, $1d_{3/2}$, $1f_{7/2}$ and $2p_{3/2}$

Spectroscopic Amplitudes for the proj. overlap

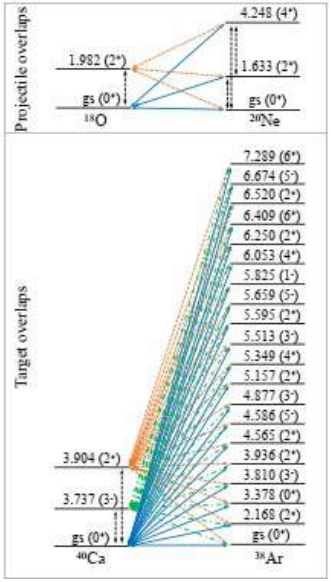
  - ✓ Effective Interaction: ZBM
  - ✓ Model Space for both protons and neutrons: $1p_{1/2}$, $1d_{5/2}$ and $2s_{1/2}$

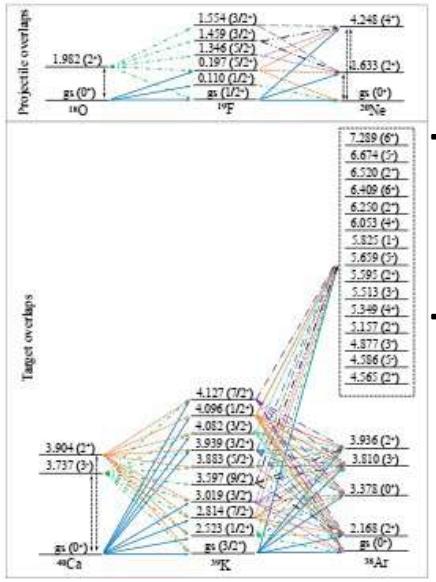
- Direct and sequential two-proton transfer processes compete one with other.
- Coupling with 2+ states of the ^{20}Ne in the final partition is very important.
- The angular distribution in the right panel are corresponding to the sum of the channels:

  $^{20}Ne(0+)+^{38}Ar^*(2+)$ and $^{20}Ne^*(2+)+^{38}Ar(0+)$



Direct 2p-transfer





Sequential 2p-transfer

d-transfer stripping reactions in the $^{6}Li+^{12}C$ and $^{6}Li+^{19}F$ collitions at 20 MeV

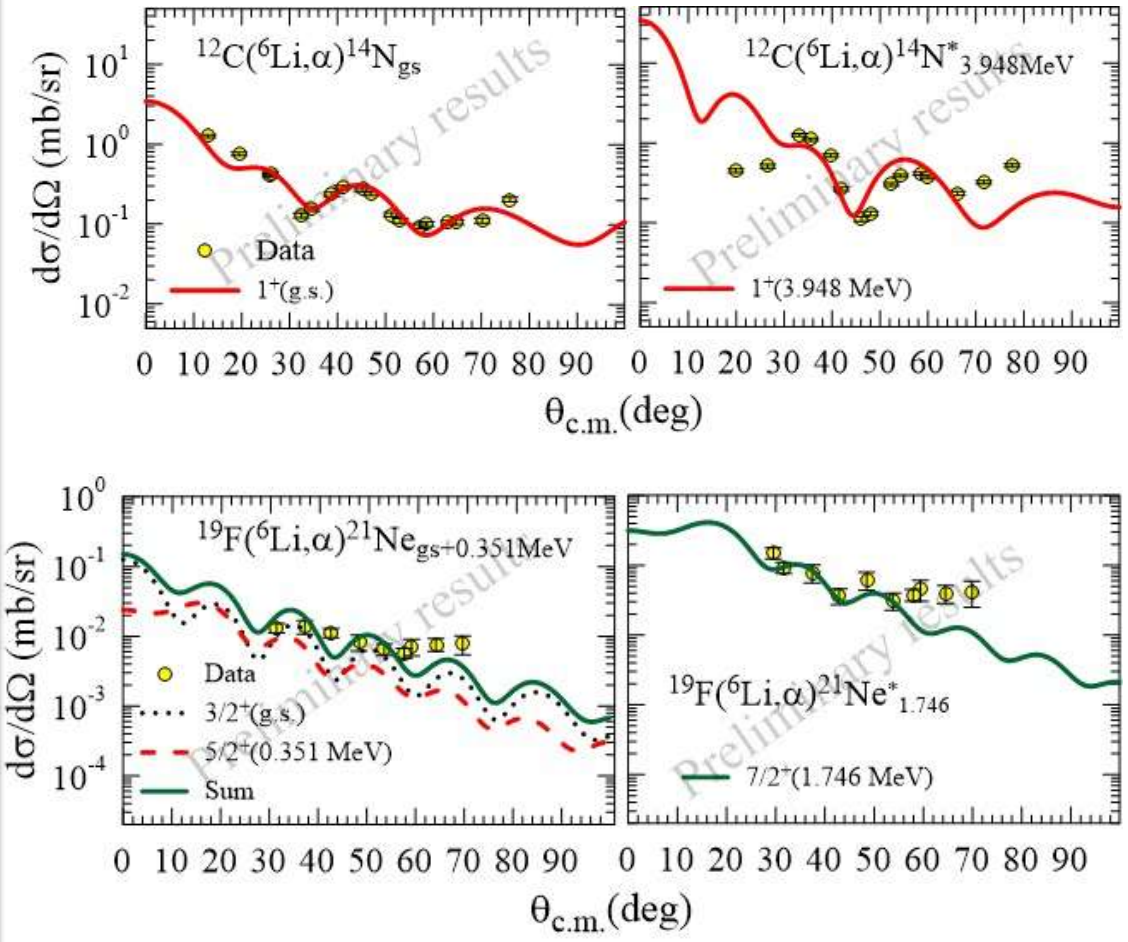
Spectroscopic Amplitudes for the target overlap

- Shell Model Calculations – NusheLLX
  - ✓ Model Space: $1p_{1/2}$, $1d_{5/2}$ and $2s_{1/2}$
  - ✓ Effective Interaction: Rewile

Spectroscopic Amplitudes for the proj. overlap

  - ✓ Taken from Phys. Rv. C, **8**, 1-8, (1973)
  - ✓ SF = 0.69 for L=0 component
  - ✓ SF = 0.04 for L=2 component

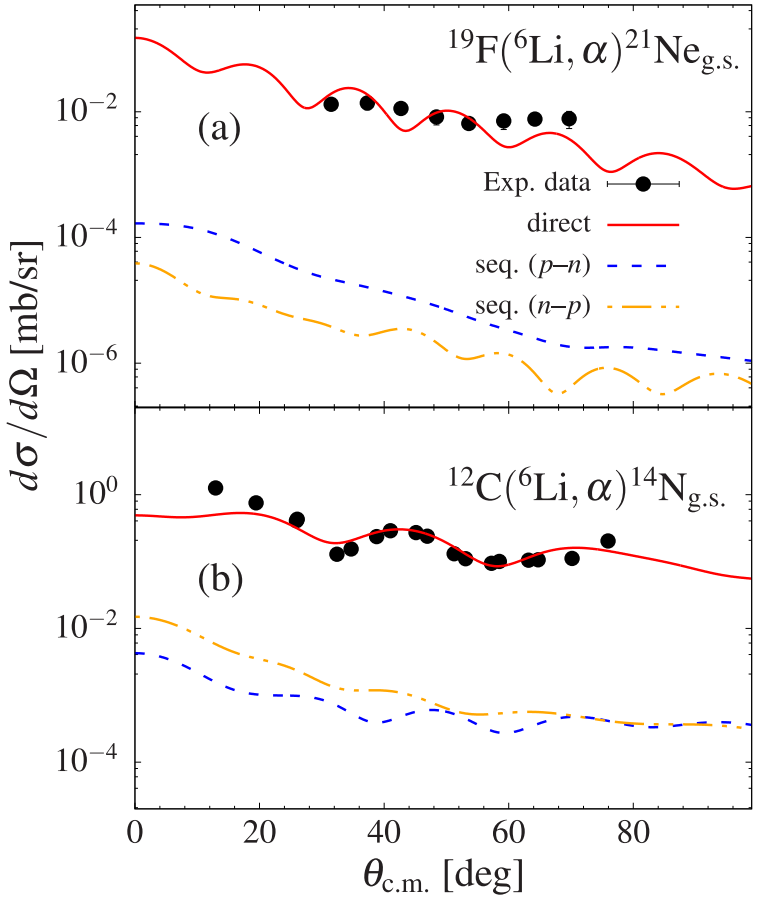
- Direct two-particle transfer is the main process in both reaction.
- Sequential pn or np mechanism are almost three order of magnitudes lower than the direct one.



J. Zamora et al. 2022, PRC 106, 014603. Data measured at Tandar Lab. at Buenos Aires

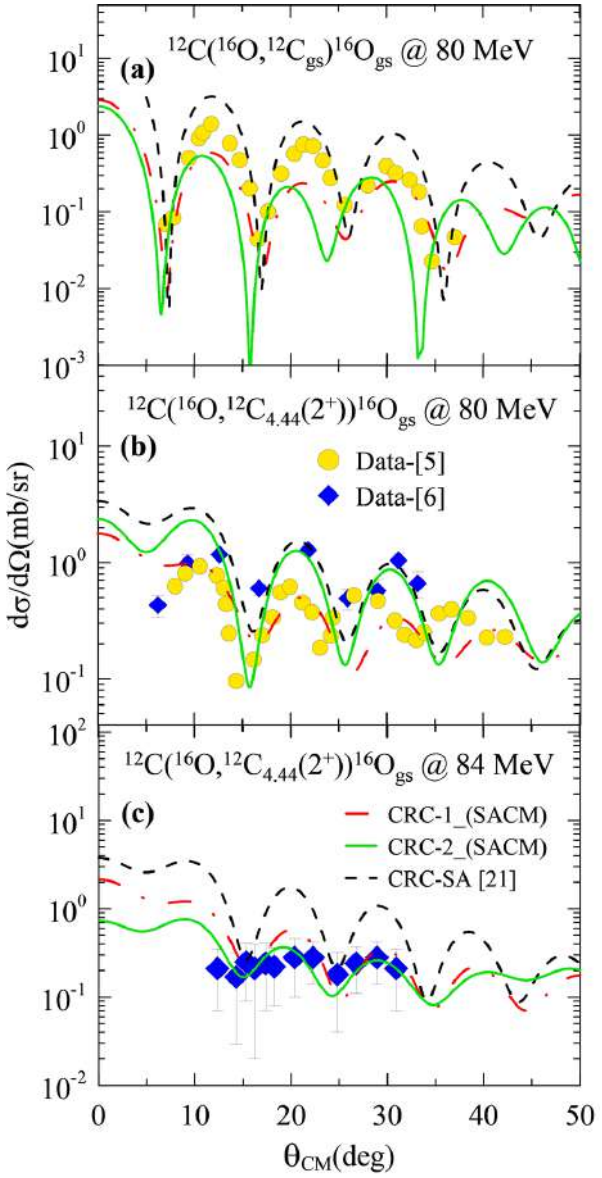
d-transfer stripping reactions in the $^{6}Li+^{12}C$ and $^{6}Li+^{19}F$ collitions at 20 MeV

Direct x Sequential mechanisms



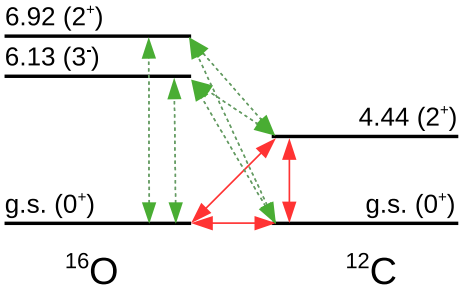
J. Zamora et al. 2022, PRC 106, 014603. Data meassured at Tandar Lab. at Buenos Aires

α–transfer reaction ($^{12}C+^{16}O$) at 20 MeV

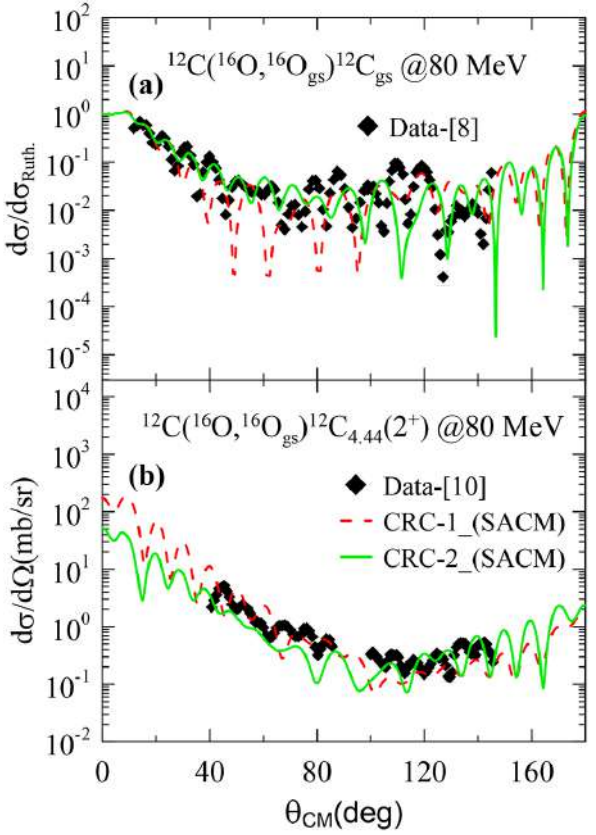


J. Ferreira et al. 2019, EPJA 55, 94.

Initial State	N L S J	Final State	SA	SA_SACM
$^{8}Be_{gs}(0^+)$	3 0 0 0	$^{12}C_{gs}(0^+)$	0,265	0,294
$^{12}C_{gs}(0^+)$	3 0 0 0	$^{16}O_{gs}(0^+)$	0,194	0,302
	4 0 0 0		0,095	-
$^{16}O_{gs}(0^+)$	4 0 0 0	$^{20}Ne_{gs}(0^+)$	-0,092	-
	5 0 0 0		-0,146	- 0,104
$^{20}Ne_{gs}(0^+)$	4 0 0 0	$^{24}Mg_{gs}(0^+)$	-0,103	-
	5 0 0 0		-0,137	- 0,228



S.A. from semi-microscopic algebraic cluster model. (by P. Hess)



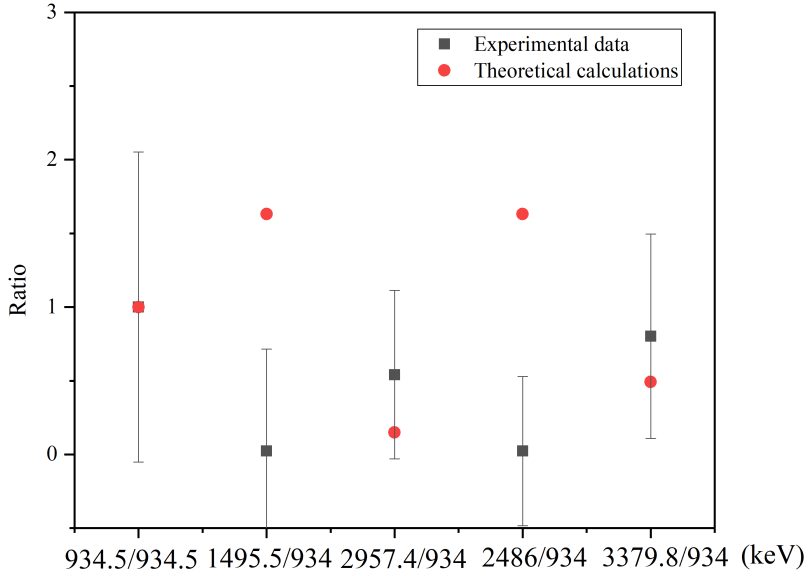
J. Lubian MNC in N&S, 2-6 Jun, SP 2025

Triton e ^{3}He transfer in ^{89}Y(^{6}Li,^{3}He)^{92}Zr and ^{89}Y(^{6}Li,^{3}H)^{92}Nb reactions at 34 MeV (unpuplished)

^{89}Y(^{6}Li,^{3}He)^{92}Zr

ECM **MCM**

Entrance channel		Outgoing channel		Q value(keV)	Integrated cross section(mb)	Integrated cross section(mb)
^{6}Li	^{89}Y	^{3}He	^{92}Zr	-96.5		
1^+ 0.0 keV (g.s.)	$1/2^-$ 0.0 (g.s.)	$1/2^+$ 0.0 keV	0^+ 0.0 keV		0.9121	2.3021E-04
	$9/2^+$ 909		2^+ 934.5		4.9480	2.3814E-05
	$3/2^-$ 1507		4^+ 1495.5		8.5555	3.8838E-05
	$5/2^-$ 1745		5^- 2486.0		13.2840	2.6415E-05
			6^+ 2957.4		11.7840	3.5430E-06
			7^- 3379.0		9.9852	1.1700E-05



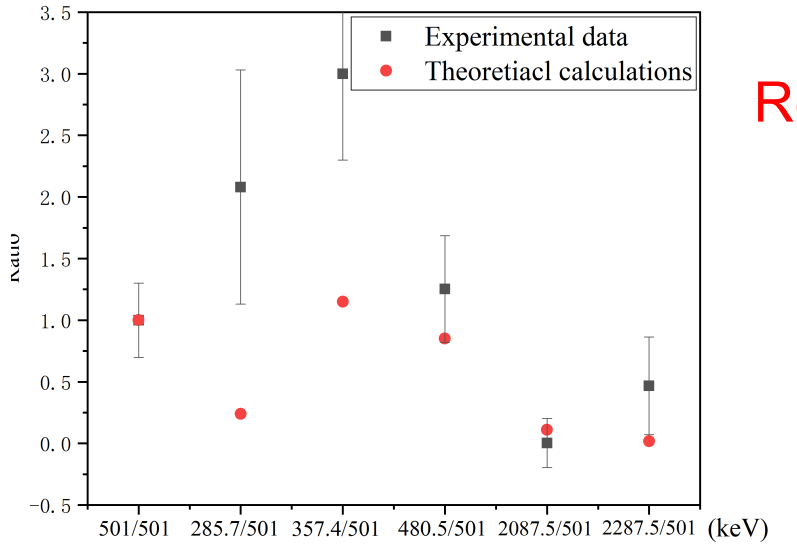
Reasonable agreement

Ratio of cross sections of ^{92}Zr excited to the first excited state (2+)

M.L. Wang, B. Pinheiro et al. 2024 (to be published)

$^{89}Y(^{6}Li,^{3}H)^{92}Nb$ ECM DMCM

Entrance channel		Outgoing channel		Q value(keV)	Integrated cross section(mb)	Integrated cross section(mb)
^{6}Li	^{89}Y	^{3}H	^{92}Nb	-2120.8		
1^+ 0.0 keV (g.s.)	$1/2^-$ 0.0 (g.s.)	$1/2^+$ 0.0 keV	7^+ 0.0 keV		5.6107	4.3966E-06
	$9/2^+$ 909		2^+ 136.0		2.3474	1.4146E-06
	$3/2^-$ 1507		3^+ 285.7		2.6697	1.0806E-06
	$5/2^-$ 1745		5^+ 357.4		7.9131	5.1893E-06
			4^+ 480.5		7.4949	3.8354E-06
			6^+ 501.0		8.0594	4.5101E-06
			2^+ 1345.5		5.2533	3.9683E-08
			9^- 2087.5		7.2290	5.3522E-07
			9^+ 2287.2		4.2783	7.6842E-08



Reasonable agreement

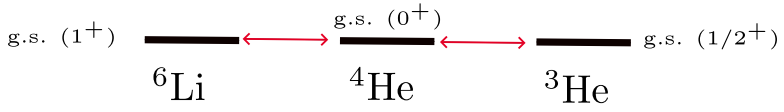
Ratio of cross sections of ^{92}Nb excited to the first excited state (2+. 501 keV)

Direct versus sequencial (d+n)

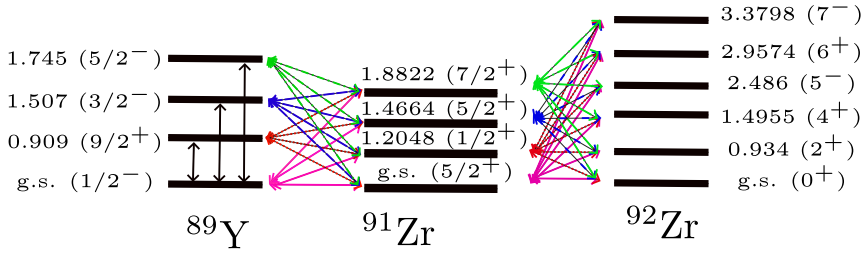
$^{89}Y(^{6}Li,^{3}He)^{92}Zr$.

3H (direct)		d+n (sequential)
Integrated cross section(mb)		Integrated cross section(mb)
2.3021E-04		9.3951E-11
2.3814E-05		3.4651E-09
3.8838E-05		1.0888E-09
2.6415E-05	>>	4.3316E-11
3.5430E-06		3.4245E-09
1.1700E-05		3.8676E-07

Projectile overlap



Target overlaps



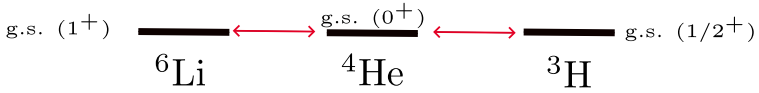
Direct cluster tranfer of ^{3}H dominates

Direct versus sequencial (d+p)

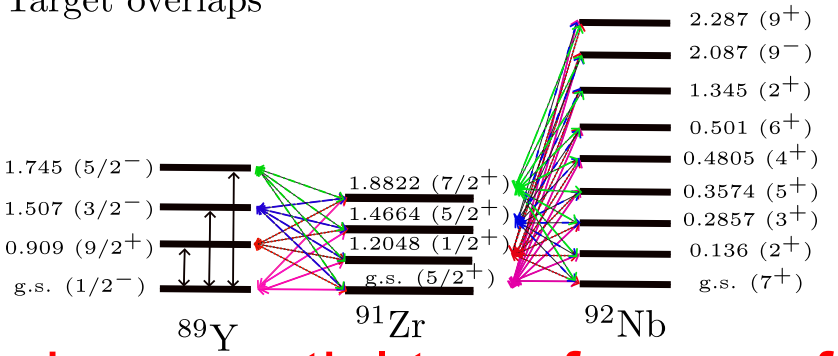
$^{89}Y(^{6}Li,^{3}H)^{92}Nb$

3He (direct)		d+p (sequential)
Integrated cross section(mb)		Integrated cross section(mb)
4.3966E-06		1.5926E-05
1.4146E-06		1.8663E-06
1.0806E-06		2.2839E-07
5.1893E-06		1.7532E-06
3.8354E-06	=	2.9726E-06
4.5101E-06		8.3991E-06
3.9683E-08		8.4902E-09
5.3522E-07		—
7.6842E-08		—

Projectile overlap

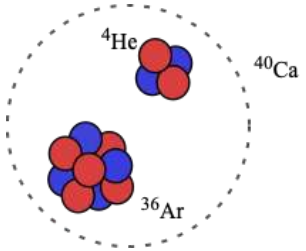


Target overlaps



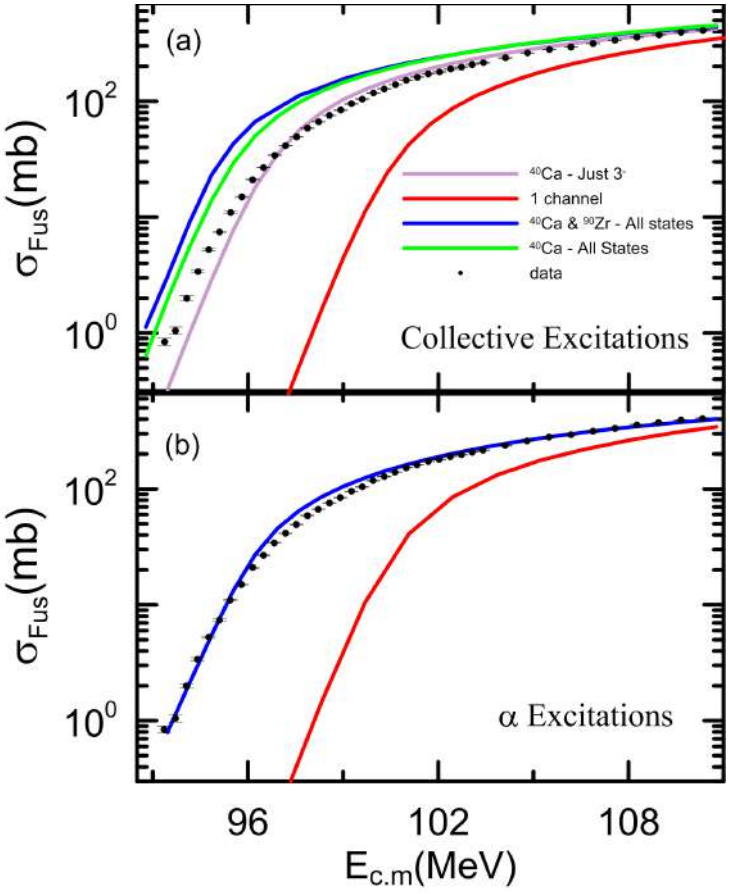
Direct cluster and sequential transfer are of the same order

Evidence of α – clustering in ^{40}Ca by studing the fusion cross section of the ^{40}Ca + ^{90}Zr



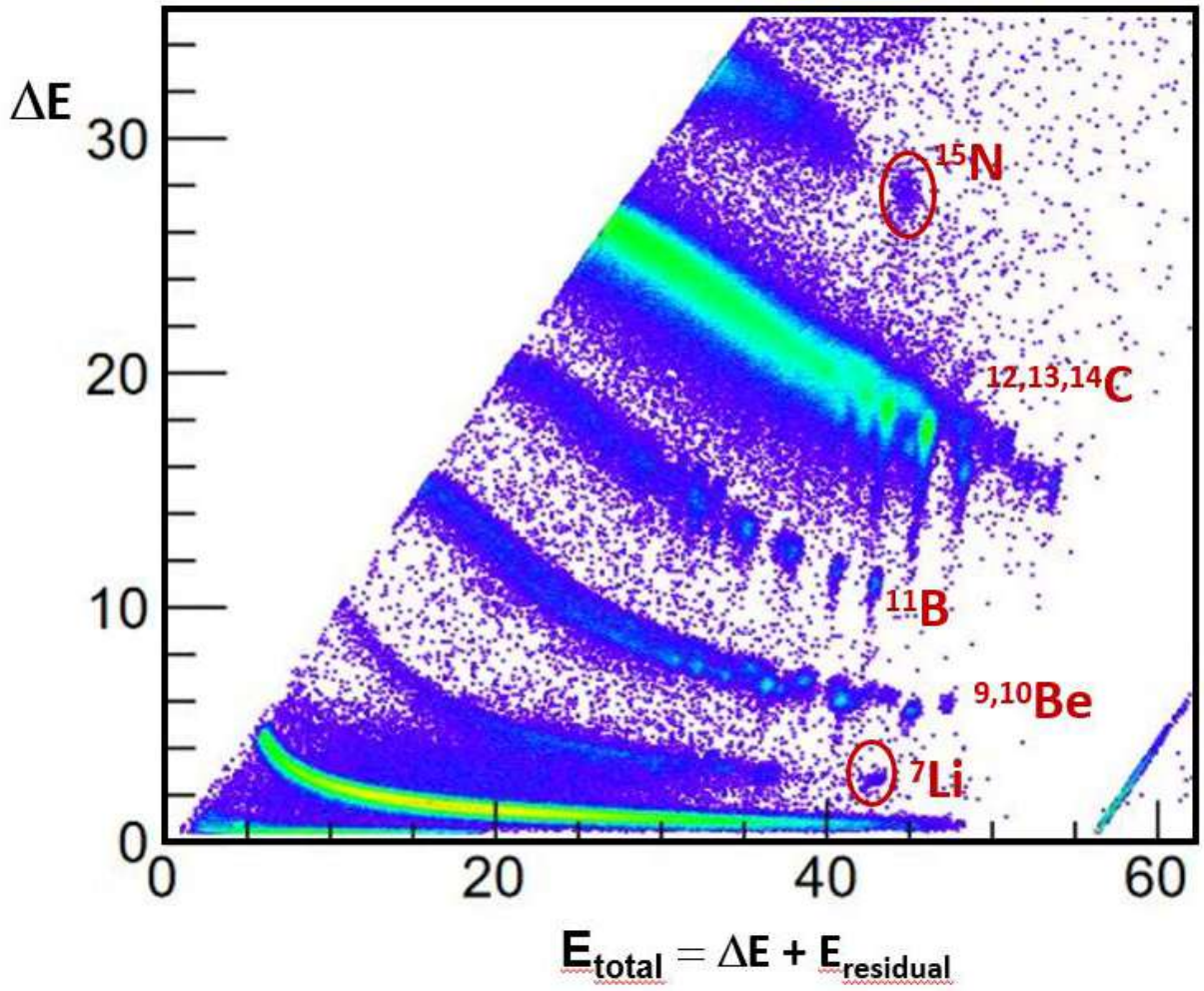
Using the cluster model the fusion cross section can be described very well independently of the Number of states considered

At the same elastic and inelastic Scattering ang. dist. Are very well Described.



F. R. Vasconcelos et al. 2025 (to be published)

Spectroscopic investigation $^{13}C+^{9}Be$ @ 55 MeV



$^{9}Be(^{13}C,^{7}Li)^{15}N$ => 6Li transfer or ^{4}He + d or d + ^{4}He? Data taken at Tandar, BA, Argentina by V. Guimarães (unpublished)

Summary

• We have shown the relevance on the 2n, 2p, and pn correlations in two-particle transfer reacitons.

• The nucleon correlations are responsable for unusual cluster configuraitons in some light nuclei.

• Alpha cluster structure may very important in describing the reaciton mechanism of N x alpha nuclei

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Thank you