ICTP-SAIFR/MITP WORKSHOP ON MULTINEUTRON CLUSTERS IN NUCLEI AND IN STARS

June 2 – 6, 2025
at Principia Institute, São Paulo, Brazil

Hints on the nucleon-nucleon correlations from the two-nucleon transfer reactions induced by heavy ions

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A picture is worth a thousand words...

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Summary

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1. Exploring heavy-ion transfers for nucleon-nucleon interactions
    a. pros and cons of heavy-ion reactions
2. Previous work with two-neutron transfer: $^{12}C(^{18}O,^{16}O)^{14}C$
    a. evidence of strong neutron-neutron correlation
3. Recent results for two-proton transfer: $^{28}Si(^{16}O,^{18}Ne)^{26}Mg$
    a. hints of proton-proton correlations and limitations
4. Recap and Perspectives

Isospin symmetry

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Nuclear structure models often assume NN interactions nearly similar between pp, nn and pn pairs.

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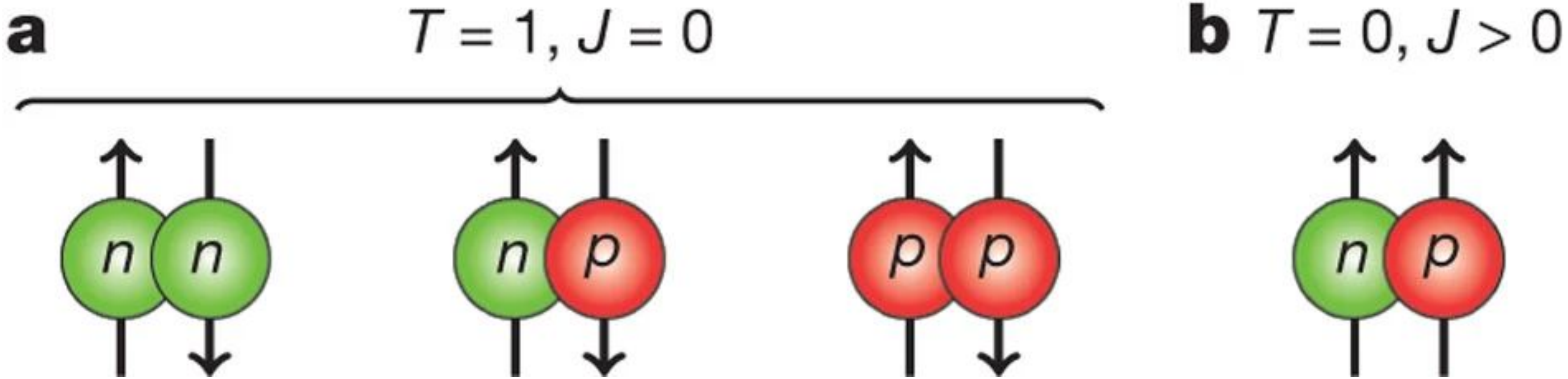
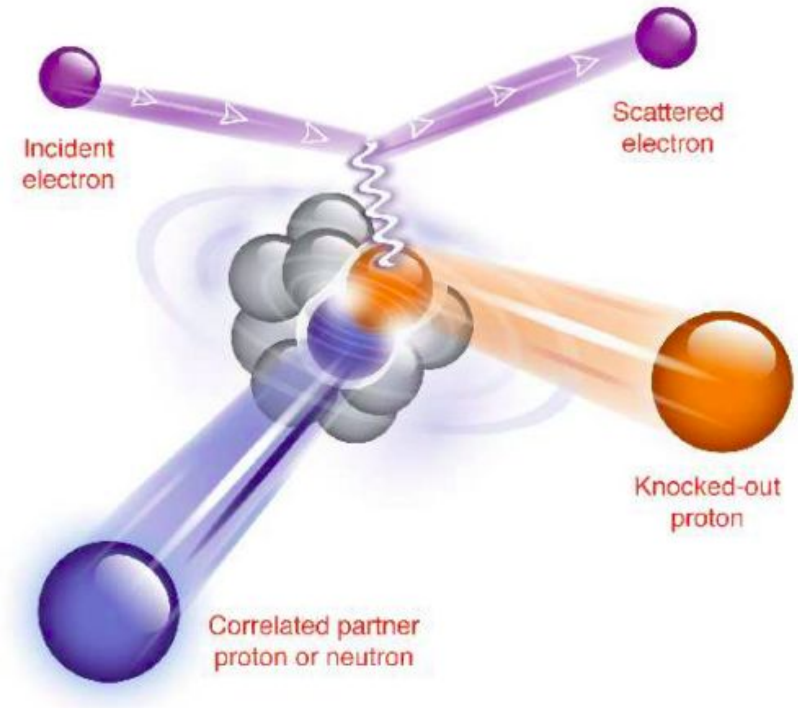


Cederwall, B., Moradi, F., Bäck, T. et al. Nature 469, 68–71 (2011).

Isospin symmetry breaking

At short distances and high energies, the two-nucleon correlations are slightly different for **nn**, **pp** and **pn**

R. Subedi et al. Science 320,1476-1478 (2008)



Isospin symmetry breaking

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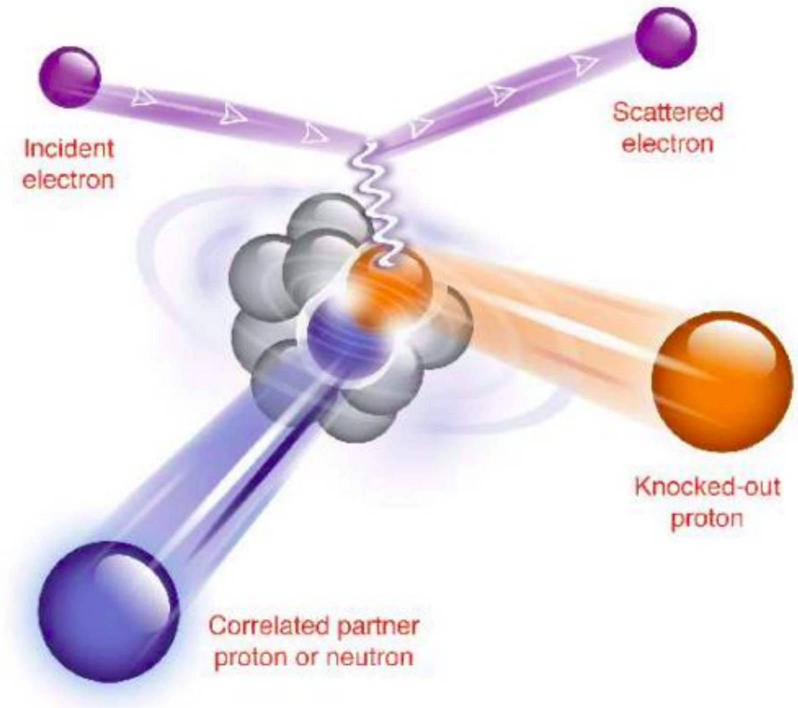

How does the *nn*, *pp* and *pn* correlations manifest itself in heavy-ion transfer reactions?

Few words about transfer reactions

Toolbox of nuclear reactions and structure

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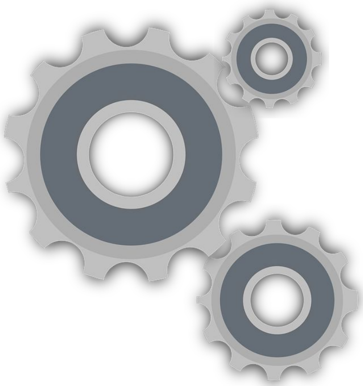
- elastic scattering
- inelastic scattering
- fusion
- **nucleon transfers**
- breakup

effects from these reaction channels can manifest themselves in the angular distribution of the elastic scattering

EXPERIMENTAL DATA



NUCLEAR STRUCTURE THEORIES (SM, QRPA, IBM, ETC)

NUCLEAR REACTION THEORIES (DWBA, CC, CRC, CDCC, ETC)

Assessing key ingredients of the nuclear structure

$$|\Psi\rangle \equiv |\Psi_{\text{s.p.}}\rangle + |\Psi_{\text{col.}}\rangle + |\Psi_{\text{pair.}}\rangle + \ \cdots$$

one-nucleon transfer reactions

two-nucleon transfer reactions

basic assumption: structure information is contained in an overlap function between projectile/target and residue

- spectroscopic factors (SF)
- Asymptotic Normalization Coefficients (ANCs)

$$\sigma = C^2 S \times \sigma_{\text{s.p.}}$$

T. Aumann et al. PPNP 118 (2021) 103847

Interlude: key concepts on pairing interaction

Two-particle transfer is a tool to study the dynamical effects of the pairing interaction. Naively,

$$\sigma_{2n} \propto \left|P^{+}\right|^{2} \quad \text{where} \left|P^{+}\right| = \sum_{i} \left[a_i^{+} a_i^{+}\right]_{00}$$

However, the above-mentioned connection is difficult and often we access the pairing response

$$\left\langle \Psi_f \left| P^{+} \right| \Psi_i \right\rangle$$

that has 2 contributions:

- pairing phase (normal / superfluid)
- shape phase (spherical / deformed)

Overview

The key idea: two-nucleon transfer cross sections are related to the pair response.

Pro: Transfers induced by heavy ions offer unique scenario to treat *nn*, *pp* and *pn* pair transfers on the same theoretical footing.

Overview

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The key idea: two-nucleon transfer cross sections are related to the pair response.

Pro: Transfers induced by heavy ions offer unique scenario to treat *nn*, *pp* and *pn* pair transfers on the same theoretical footing.

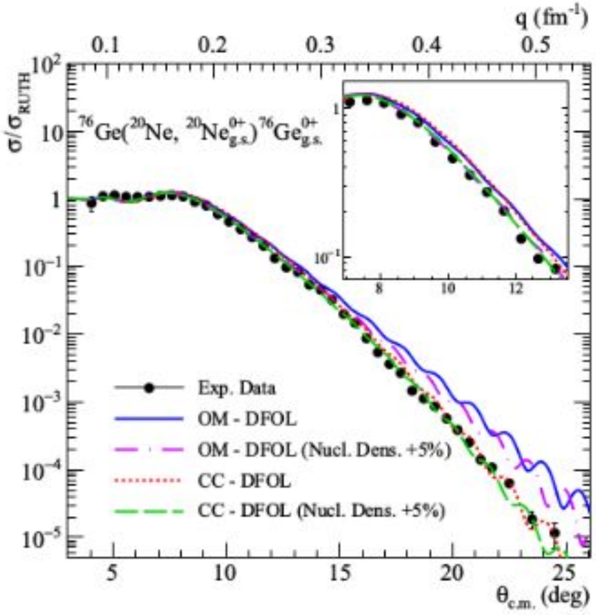
Cons: the detailed mechanisms and the configuration mixing of single-particle states impose serious difficulties.

Many channels, many problems …

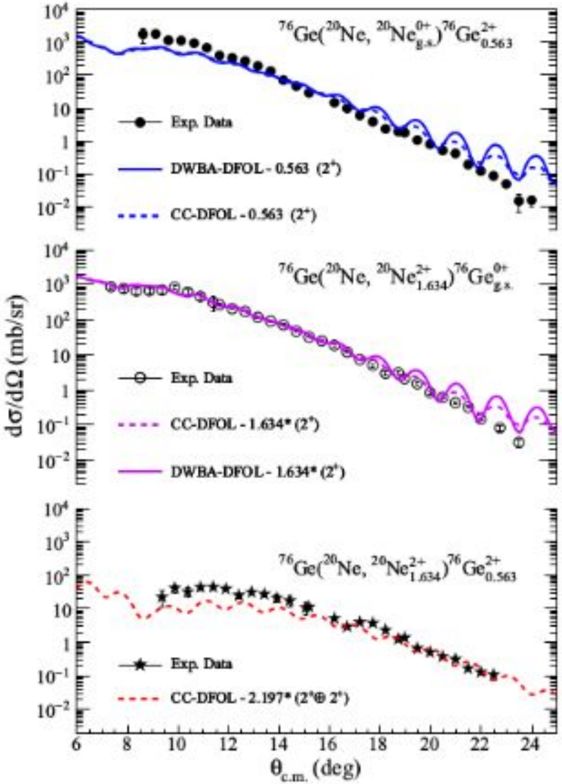
A. Spatafora et al., Phys. Rev. C. 100, 034620 (2019)

In principle, all open reaction channels must be considered … this leads to a huge model space!

Extraction of an **Initial/Final State Interaction** from elastic and inelastic scatterings

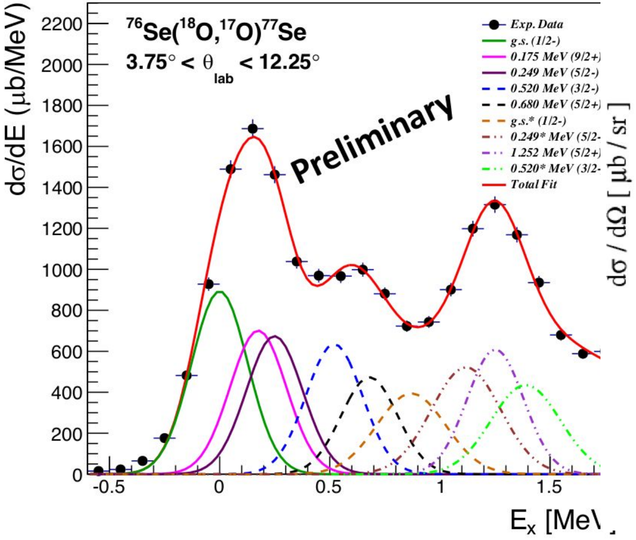


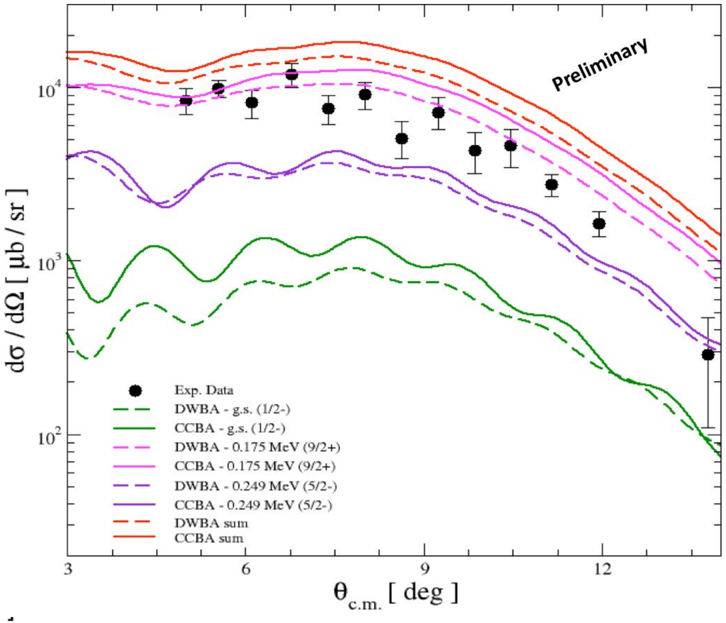
(a)DFOL Potential

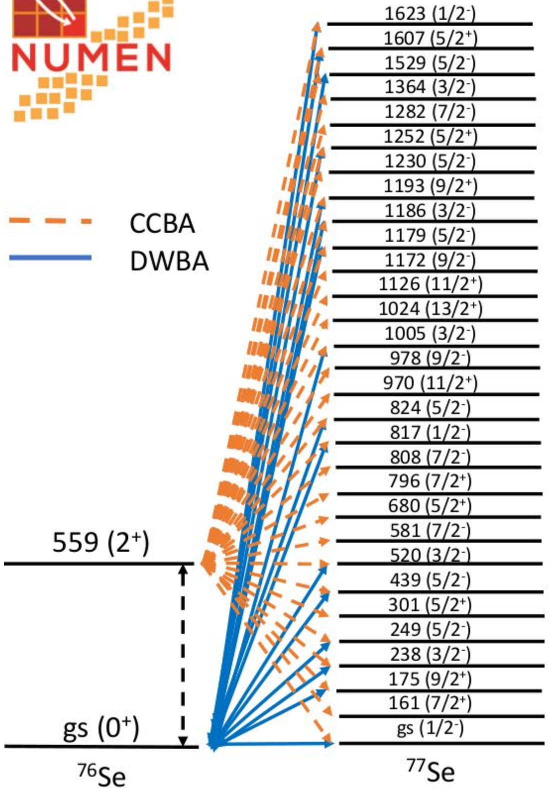


1n-transfer: $^{76}Se(^{18}O,^{17}O)^{77}Se$

Angular distribution of the x-sections for first low-lying states







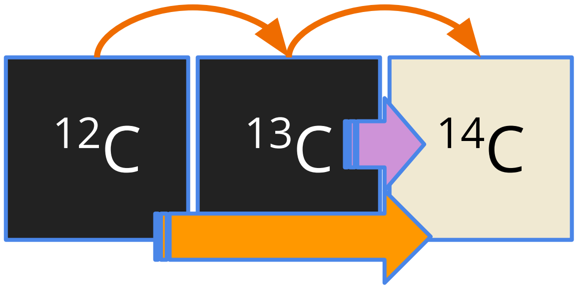
Target overlaps

Previous work on two-neutron transfer

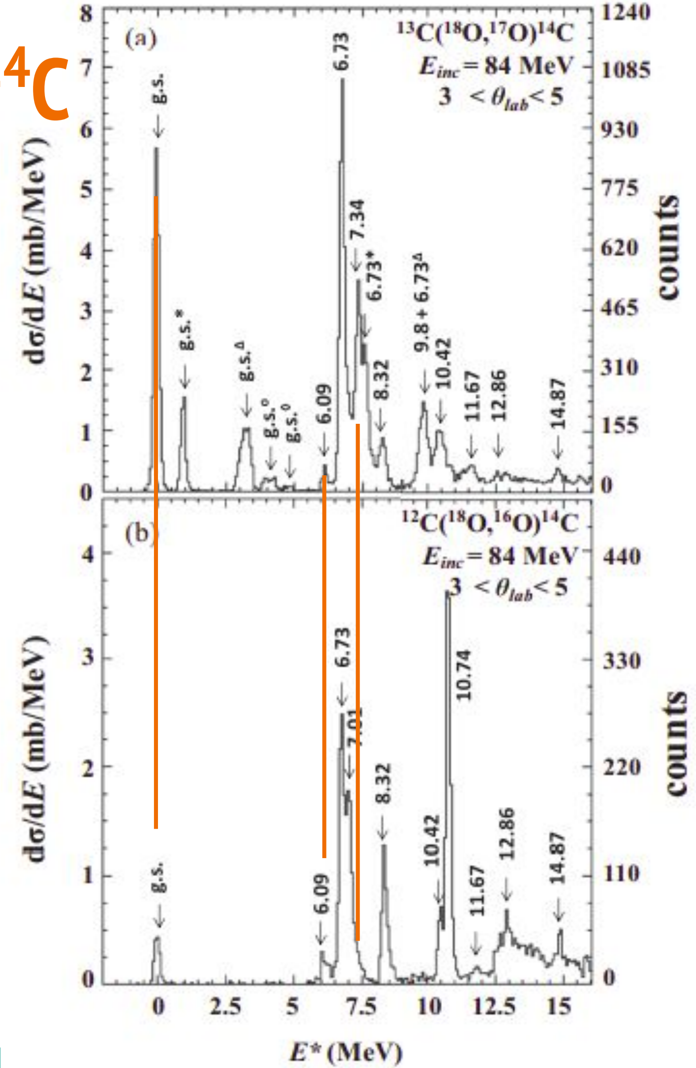
Two-neutron transfer in $^{12}C(^{18}O,^{16}O)^{14}C$

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

sequential two-nucleon transfer



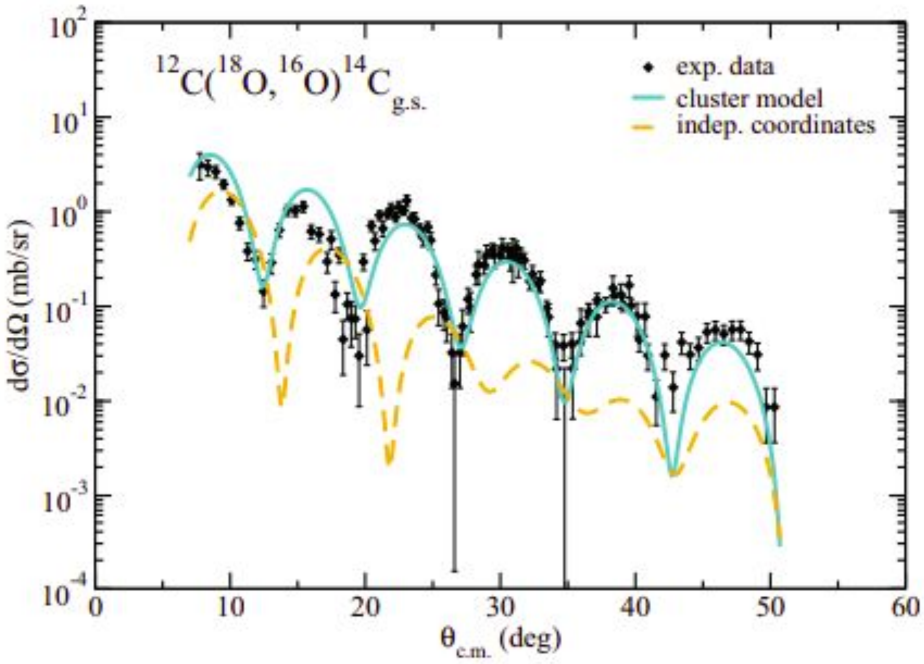
simultaneous two-nucleon transfer



Two-neutron transfer in $^{12}C(^{18}O,^{16}O)^{14}C$

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

- strong selectivity in the two-neutron transfer
- angular distribution well described by the extreme cluster model (di-neutron)



Recent results for two-proton transfer in the $^{16}O + ^{28}Si$

^{28}Si target nuclei

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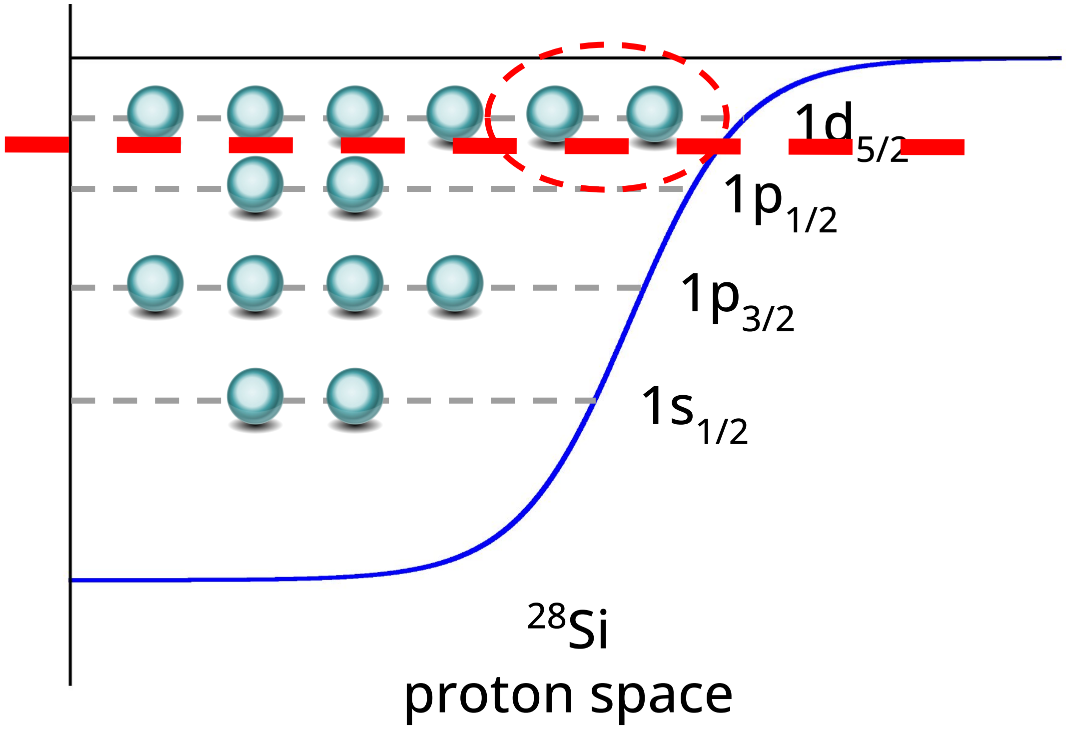
^{28}**Si** is a N = Z nucleus with protons filling the $1d_{5/2}$ shell.

The ^{16}**O nuclei** is a suitable probe since the protons populate states above the Fermi level.

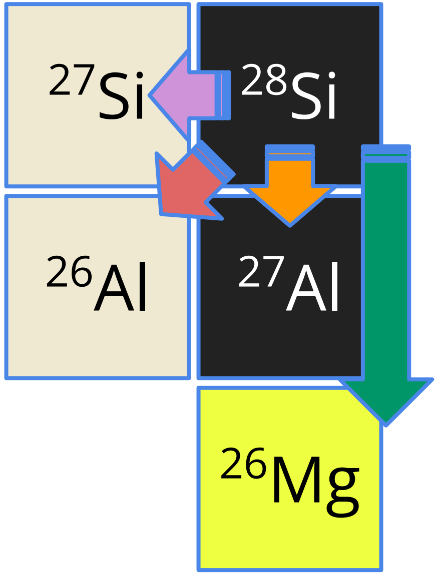


Reaction channels to be analyzed

beam: 16-O @ 240 MeV

target: 28-Si

- 1n-pickup
- 1p-pickup
- 1d-pickup
- **2p-pickup**



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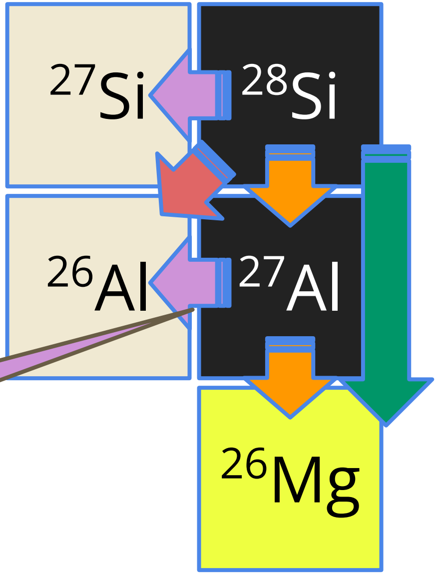


Ideally, (^{17}F,^{18}F) reaction

target: 28-Si

- 1n-pickup
- 1p-pickup
- 1d-pickup
- **2p-pickup**

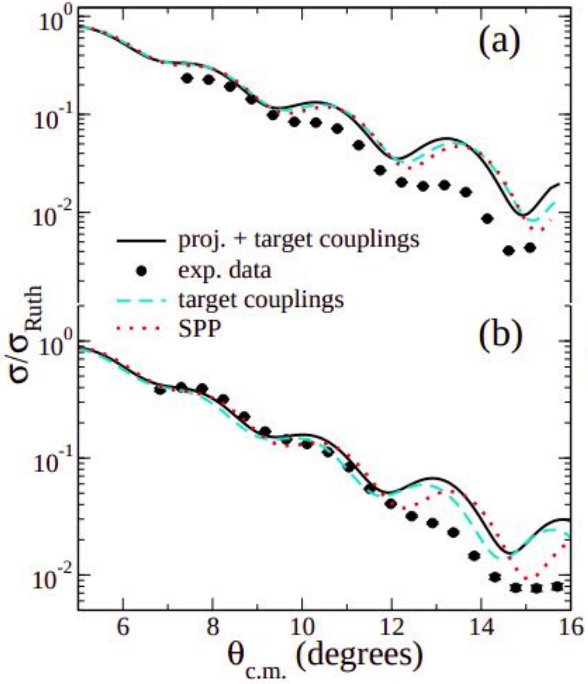
target: ^{27}Al

- 1n-pickup
- 1p-pickup

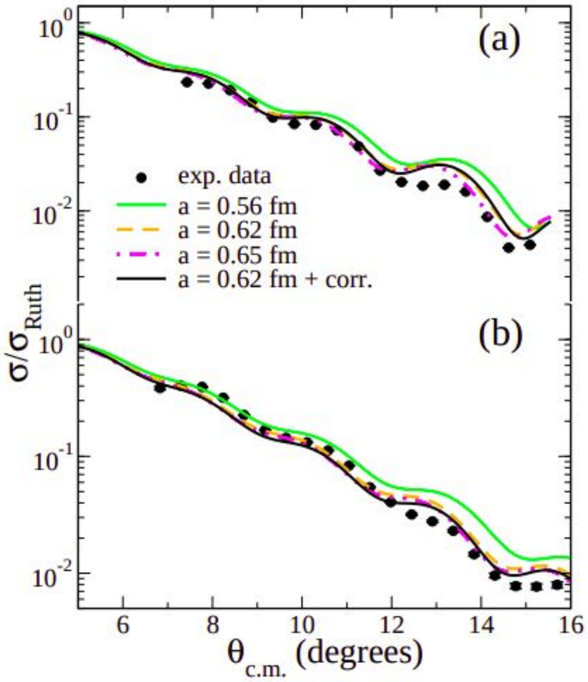
Elastic and inelastic: the $^{16}O+^{27}Al,^{28}Si$ optical potential

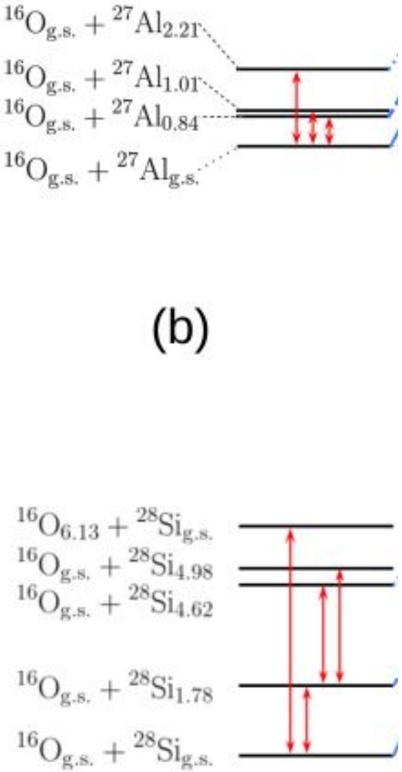
L.M. Fonseca et al. Phys. Rev. C 100, 014604 (2019)

standard CC/SPP



modified CC/SPP





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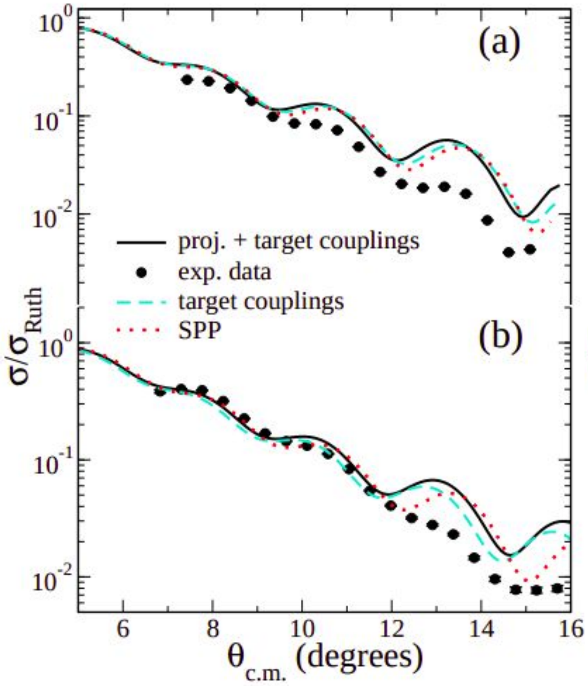

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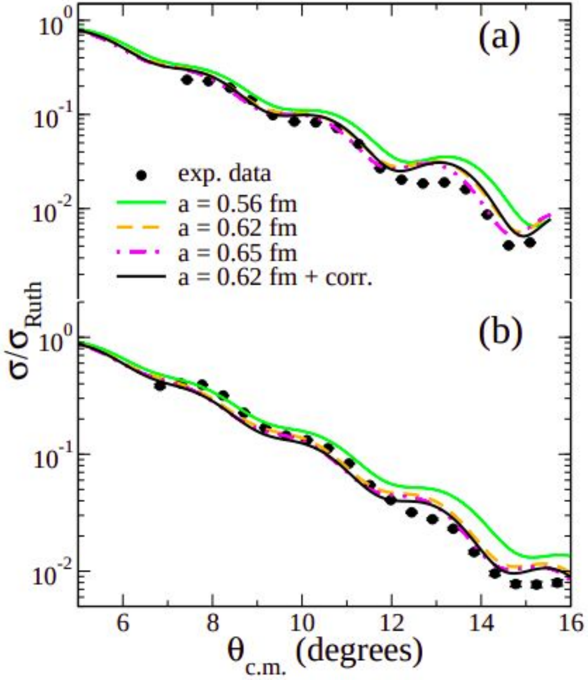

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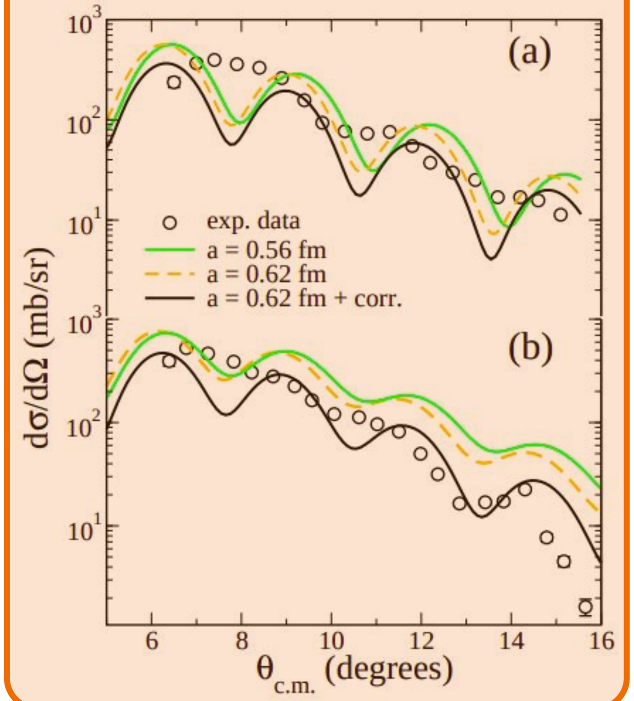

1n-stripping: nuclear structure model

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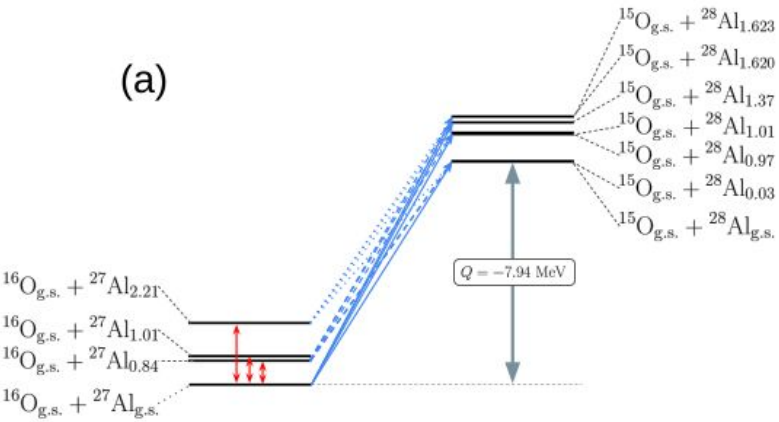
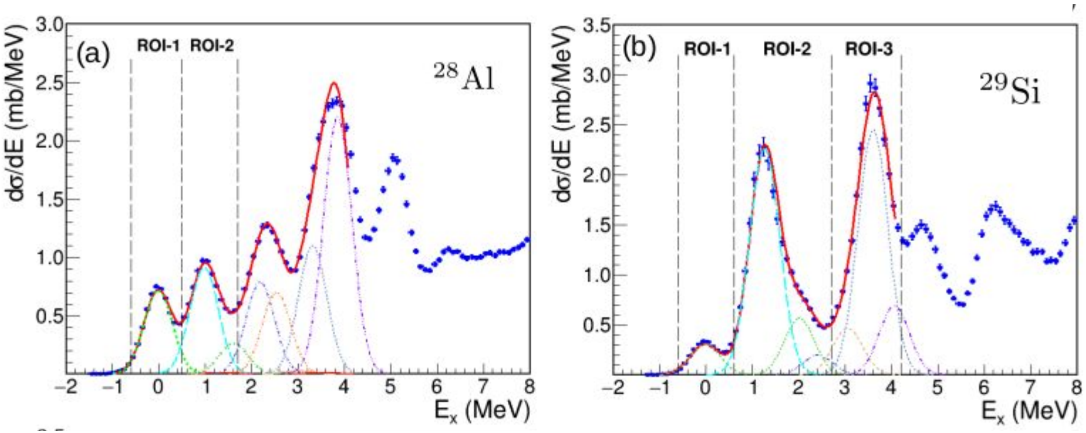
R. Linares et al. Phys. Rev. C 108, 014619 (2023)

Spectroscopic Amplitudes

Shell model
(model space and interaction)

CRC calculations for ^{27}Al(^{16}O,^{15}O)^{28}Al and ^{28}Si(^{16}O,^{15}O)^{29}Si.





1n-stripping: nuclear structure model

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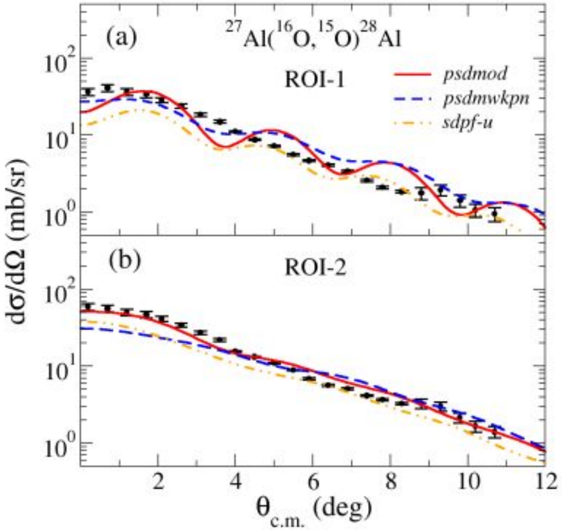
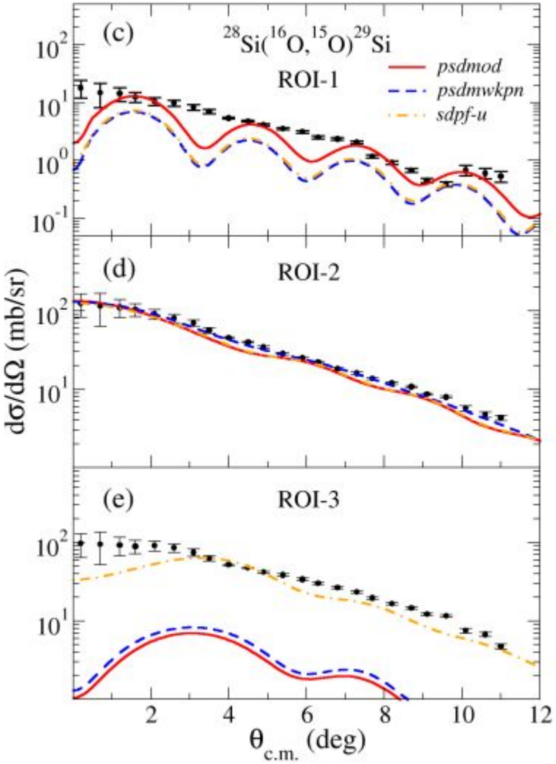
R. Linares et al. Phys. Rev. C 108, 014619 (2023)

Testing 3 shell model interactions:

1. *psdmod*
2. *psdmwkpn*
3. ***sdpf-u***





sdpf-u: This interaction describes nucleons at the $1d_{5/2}$, $1d_{3/2}$, $2s_{1/2}$, **$1f_{7/2}$**, $1f_{5/2}$, $2p_{3/2}$, and $2p_{1/2}$ sub-shells, assuming a ^{16}O core

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Overview about CRC calculations

Parameters for the calculations constrained to previous works

elastic and inelastic channels | 1n-stripping channels

system	Optical potential	Couplings to inelastic channels	Binding potentials	Spectroscopic amplitudes
$^{28}Si(^{16}O,^{17}F)^{27}Al$	$[1.0 + i*0.7]V_{spp}$	experimental B(E2); complex deformation	Wood-Saxon; depth adjusted; r_0 = 1.20 fm a_0 = 0.60 fm	NuShellX; interaction for $^{16}O\vert^{17}F$: psdmod interaction for $^{28}Si\vert^{27}Al$ and $^{27}Al\vert^{26}Mg$: sdpf-u
$^{27}Al(^{16}O,^{17}F)^{26}Mg$ l	$[1.0 + i*0.6]V_{spp}$			

sdpf-u: This interaction describes nucleons at the $1d_{5/2}$, $1d_{3/2}$, $2s_{1/2}$, $1f_{7/2}$, $1f_{5/2}$, $2p_{3/2}$, and $2p_{1/2}$ sub-shells, assuming a ^{16}O core

Proton-pickup reactions: excitation energy spectra

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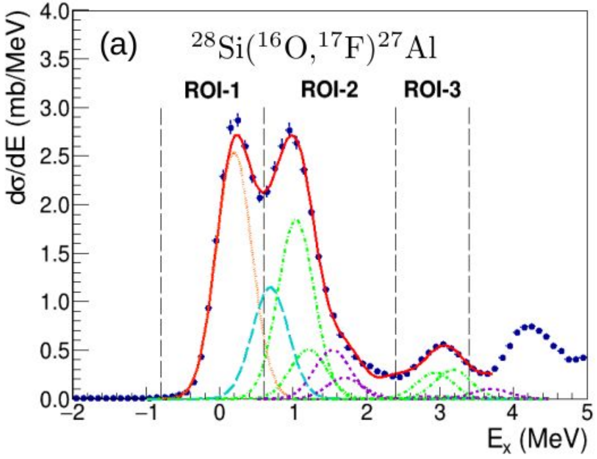
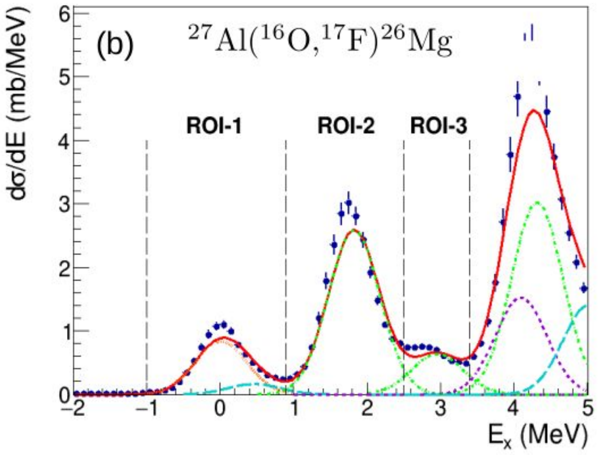
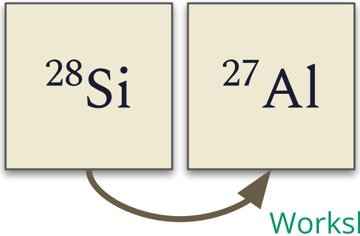
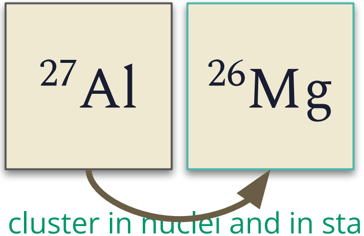
Regions of Interest









Proton-pickup reactions: excitation energy spectra

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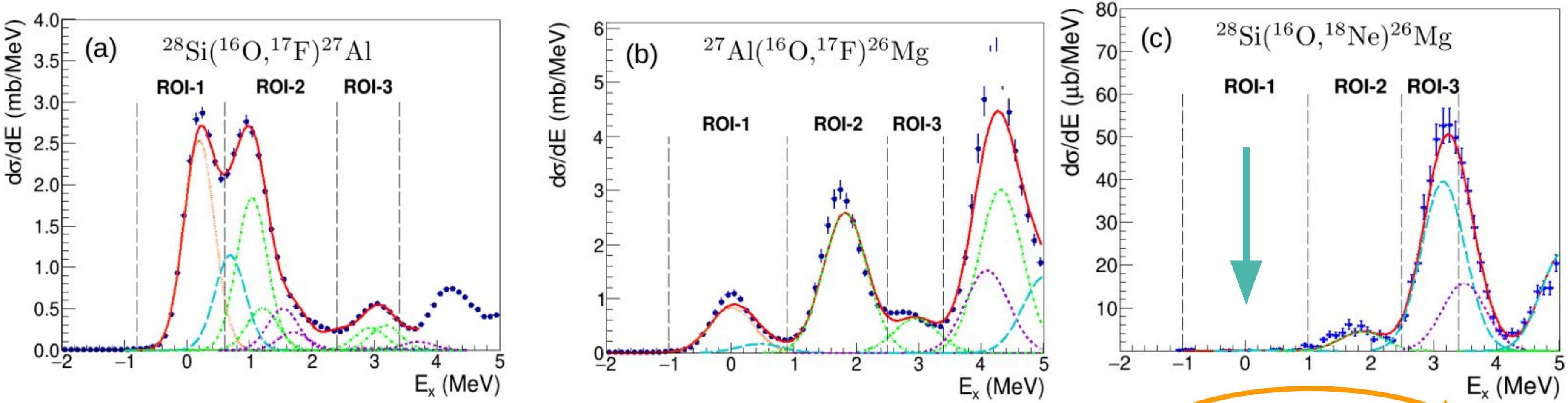
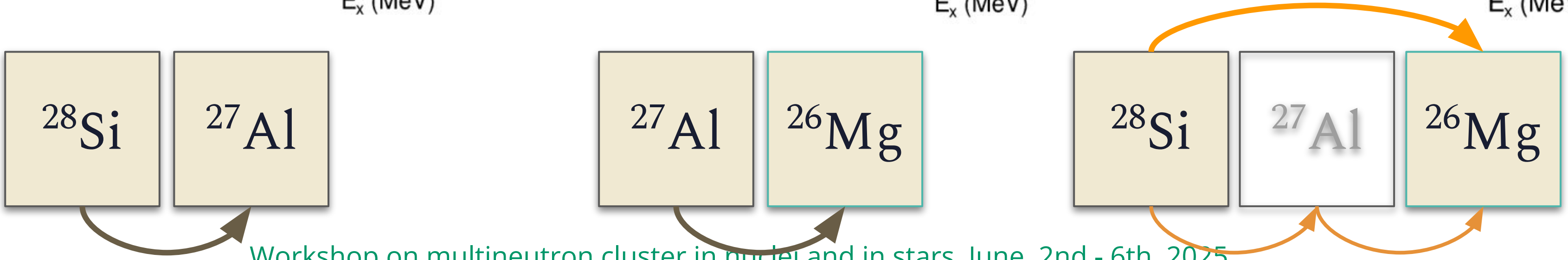
Regions of Interest

hint #1

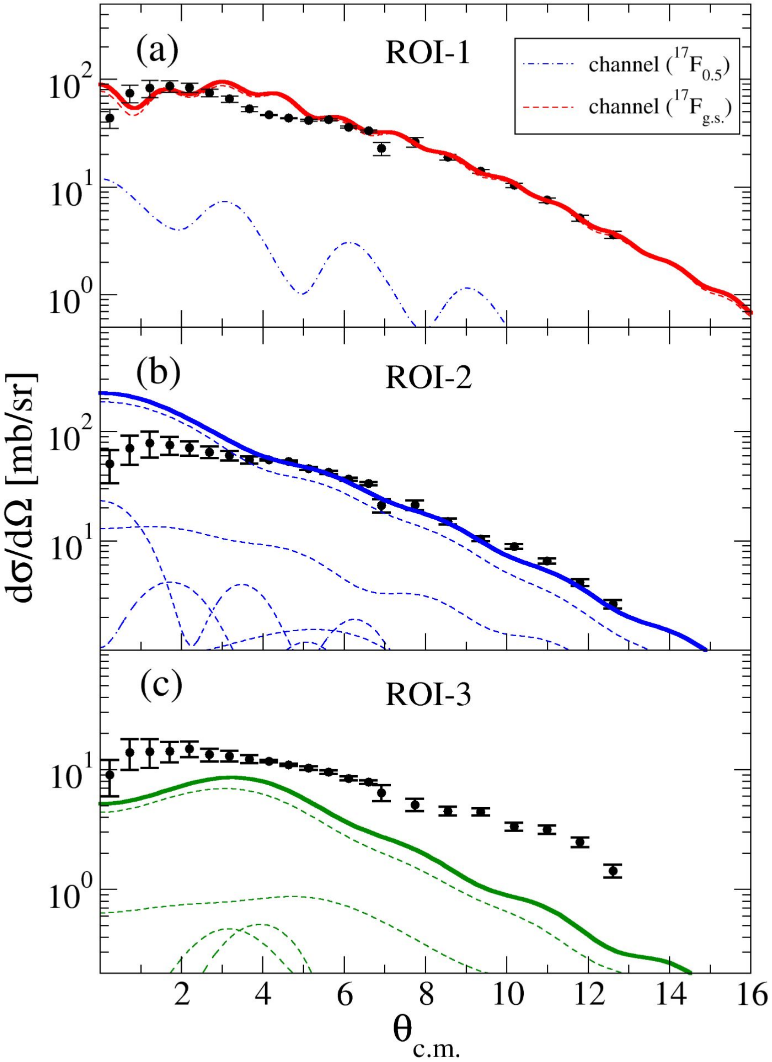




Angular distributions

$^{28}Si(^{16}O,^{17}F)^{27}Al$

1p-pickup

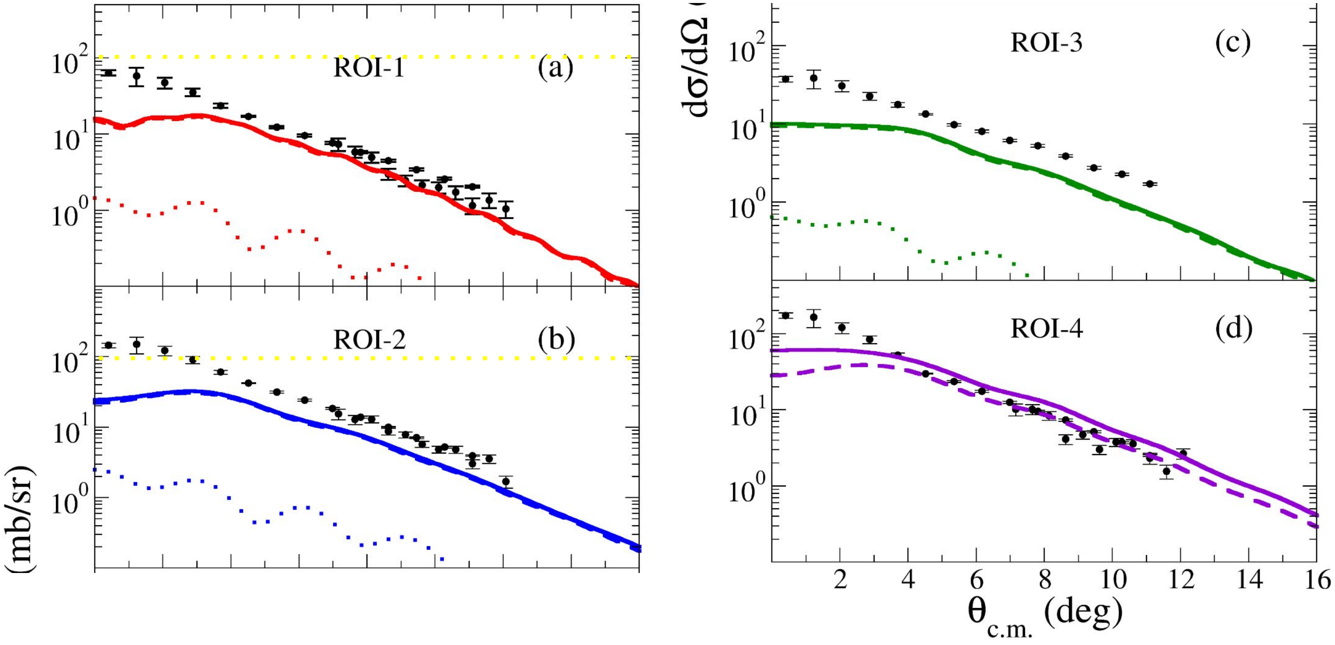


Angular distributions

Overall reasonable agreement between data and calculations, except for $\theta_{c.m.} < 2°$.

$^{27}Al(^{16}O,^{17}F)^{26}Mg$

1p-pickup

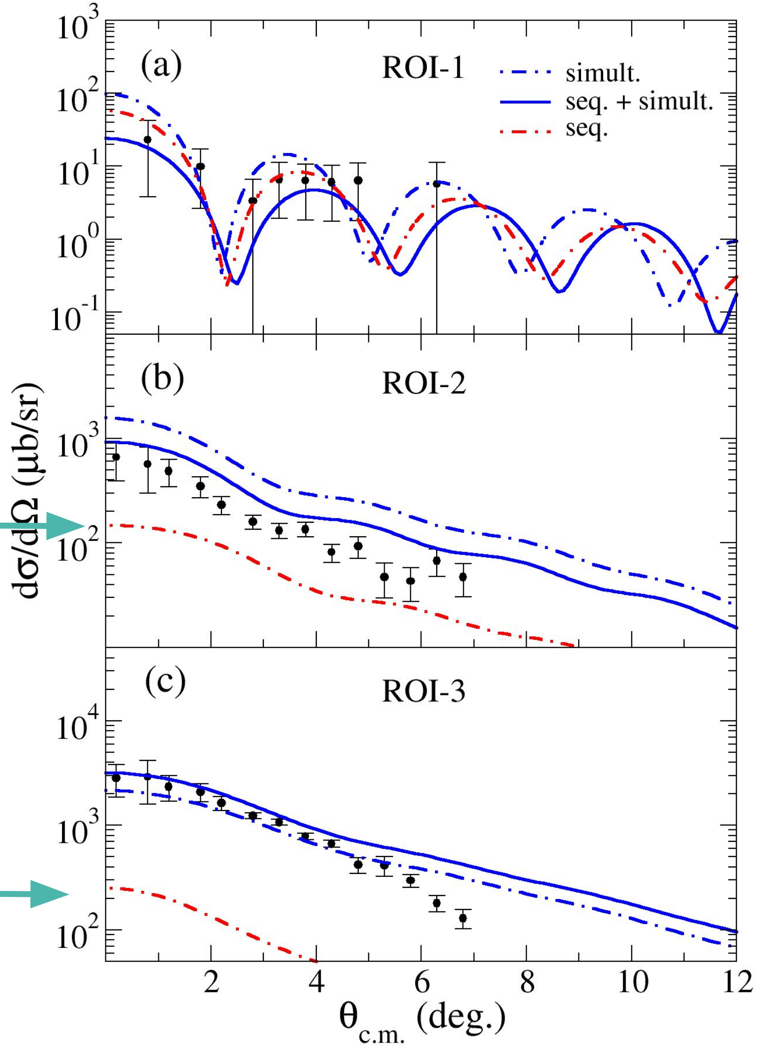


Angular distributions

$^{28}Si(^{16}O,^{18}Ne)^{26}Mg$

2p-pickup

hint #2



Transfer probabilities: in short

In the semi-classical approach, transfer cross section can be factorized

$$\frac{d\sigma(\theta)}{d\Omega}_{\text{transfer}} = \frac{d\sigma(\theta)}{d\Omega}_{\text{elastic}} \times P_{\text{transfer}}(\theta) \times F(Q, L)$$

transfer probabilities

quantal correction factor

Transfer probabilities are usually expressed in terms of the reduced distance at closest approach

$$d_0 = \frac{D}{(A_{\text{proj.}}^{1/3} + A_{\text{target}}^{1/3})}$$

which removes dependences on charge product, incident energy and masses.

Transfer probabilities

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The simplest picture for uncorrelated sequential transfer suggests that

$$P_{\text{seq.}} = (P_{1n})^2$$

Any deviation from this relationship may be interpreted as manifestation of pairing interaction.

Transfer probabilities: results

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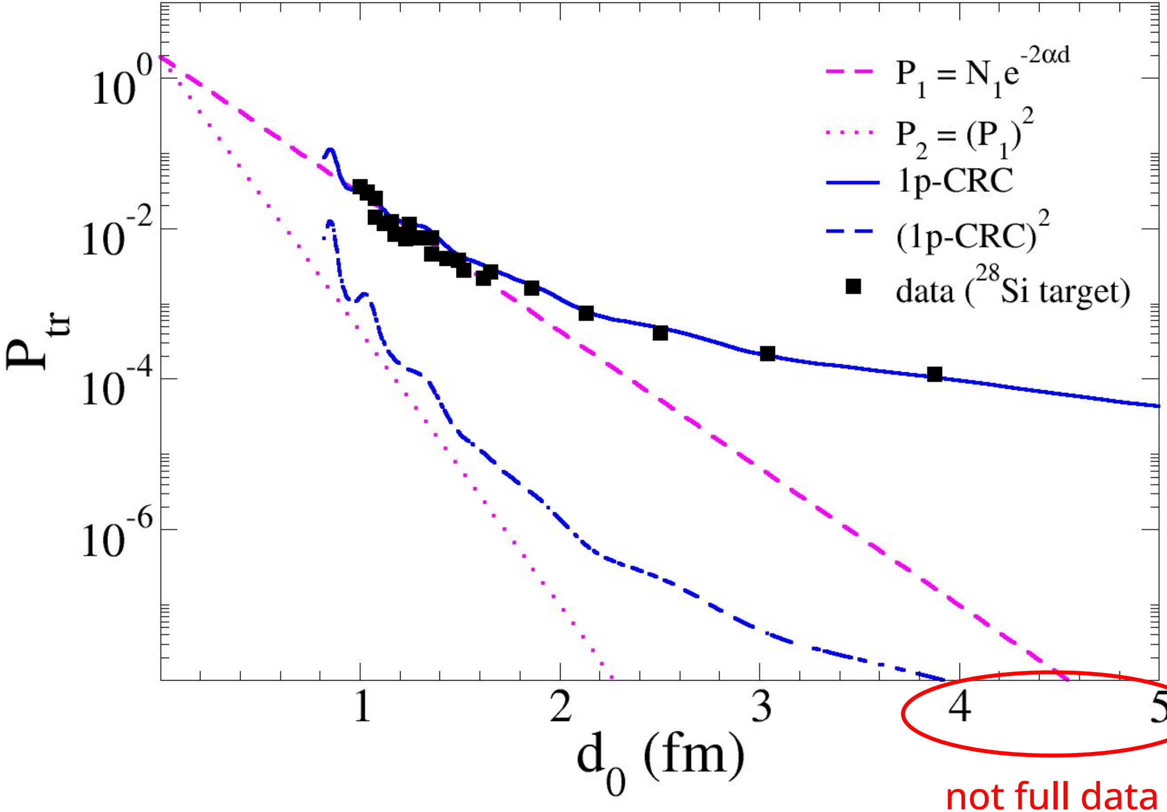
$^{28}Si(^{16}O,^{17}F)^{27}Al$



not full data

Transfer probabilities: results

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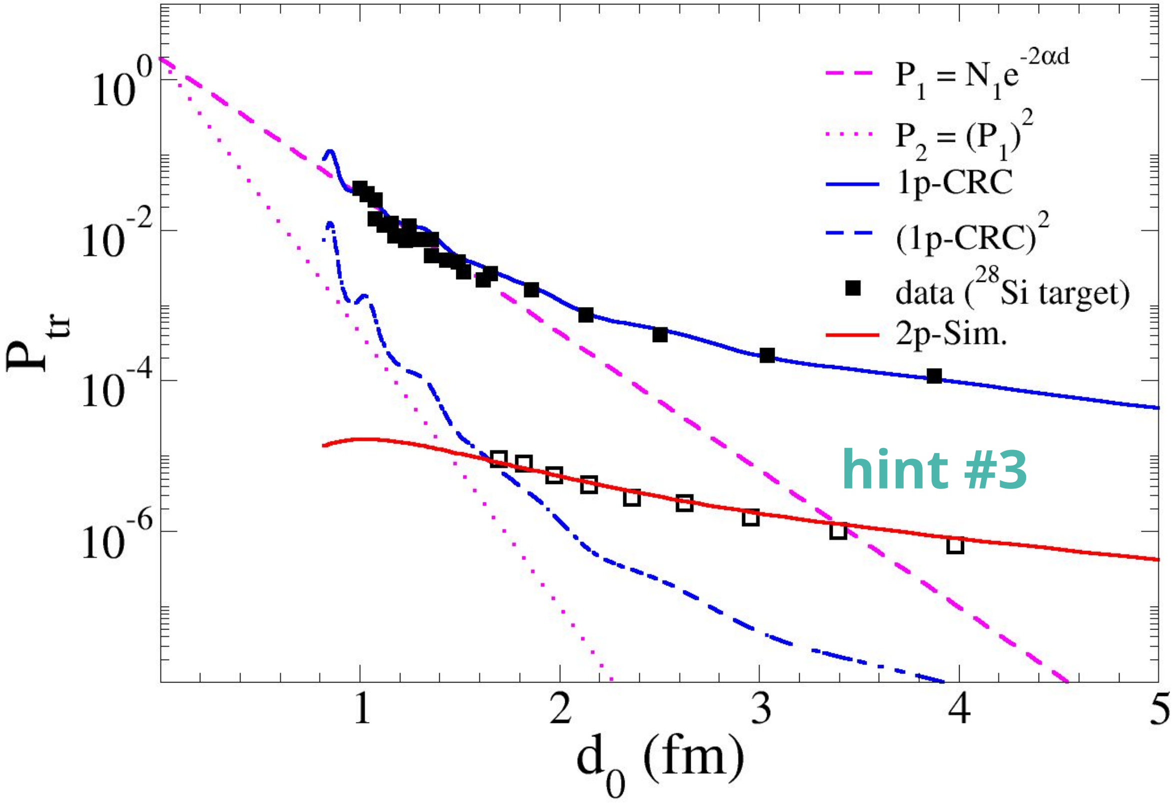
$^{28}Si(^{16}O,^{17}F)^{27}Al$

and

$^{28}Si(^{16}O,^{18}Ne)^{26}Mg$



hint #3

Caution with the concept of transfer probability

Physics Letters B 834 (2022) 137477

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Evidence of proton-proton correlations in the $^{116}Sn + ^{60}Ni$ transfer reactions

L. Corradi [a,*], S. Szilner [b,*], G. Pollarolo [c], T. Mijatović [b], D. Montanari [d], E. Fioretto [a], A. Goasduff [a], D. Jelavić Malenica [b], G. Montagnoli [d], A.M. Stefanini [a]

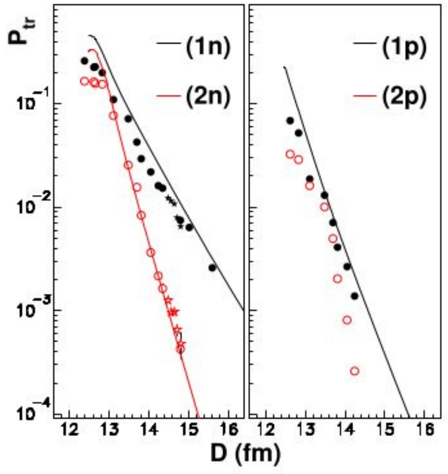
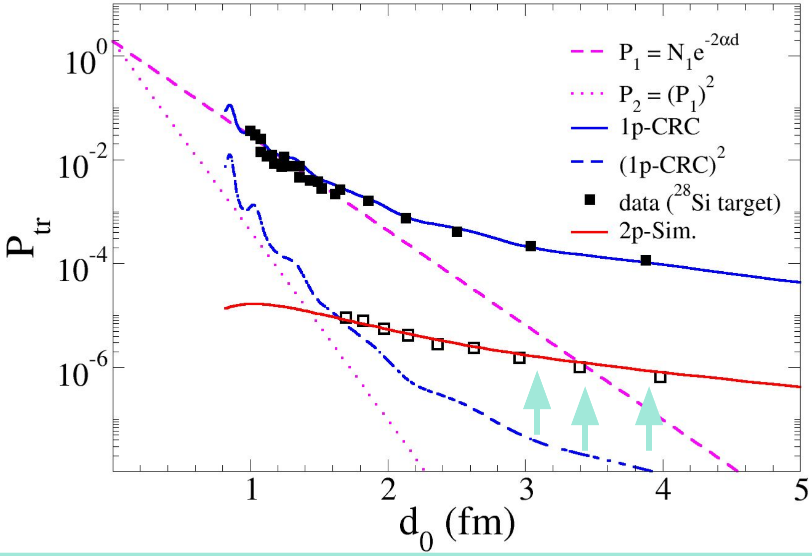


Fig. 4. Transfer probabilities (P_{tr}) as a function of the distance of closest approach (D) for the one- and two-neutron (as published in Refs. [8,9]), and one- and two-proton transfer channels. Solid lines are calculated transfer probabilities (see text).



keynotes:

1. measurements below the coulomb barrier
2. conclusions indicate that independent two-proton transfer underestimate experimental cross sections. Need to include *pp* correlation

Recent measurements…

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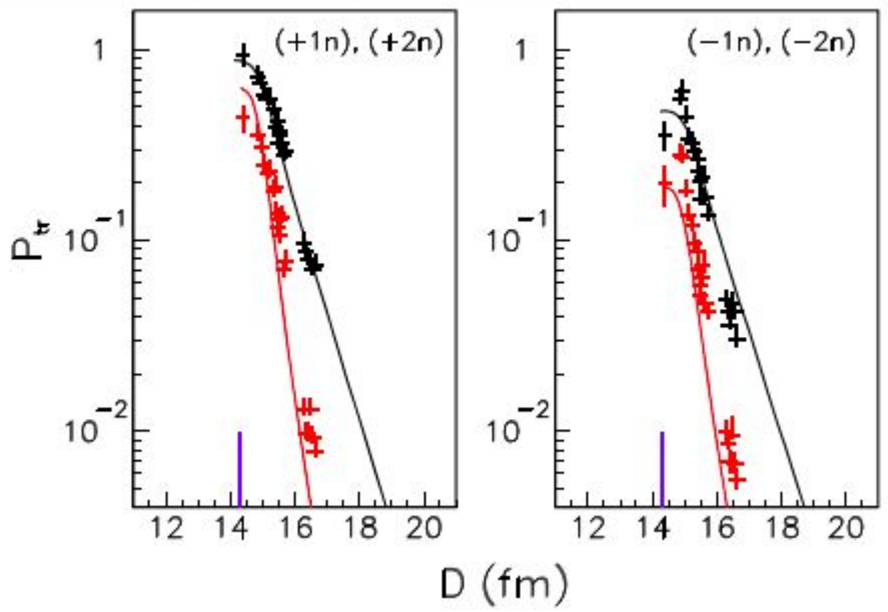
PHYSICAL REVIEW LETTERS 133, 202501 (2024)

Quest for Cooper Pair Transfer in Heavy-Ion Reactions: The ^{206}Pb + ^{118}Sn Case



The experimental two-neutron transfer cross sections indicate that in reactions between pair-vibrational (closed shell) and pair-rotational (open shell) nuclei, correlations manifest via pair-addition and pair-removal modes, which constitute one of the elementary modes of excitations in nuclei.

S. Szilner et al. PRL 133 (2024) 202501

Open questions

1. Is this a measure of *pp* correlation in transfer?
2. The 2-nucleon transfer is a four-body problem. Do we need to dive into the four-body formalism?
3. How do we compare *nn* and *pp* correlations in heavy-ion transfer reactions?

Recap and Perspectives

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1. Transfers induced by heavy ions offer unique scenario to treat nn, pp and pn pair transfers on the same theoretical footing
2. A multi-channel approach provides a robust framework for studies of two-nucleon transfer induced by heavy ions
3. 2p-pickup reaction in the ^{16}O + ^{28}Si: evidences of pp correlations
4. pn-pickup reaction under analysis

Thanks