7^{th} International Workshop of the Hellenic Institute of Nuclear Physics (HINP)

Recent results on the analysis of the $^{18}O+^{48}Ti$ collision at 275 MeV within the NUMEN project

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Outline

- Introduction
  - Neutrinoless double beta decay
  - The NUMEN project
  - A global approach in the $^{18}O+^{48}Ti$ collision at 275 MeV
- Experimental details - The MAGNEX facility
- Data reduction
  - $^{48}Ti(^{18}O,^{18}O)^{48}Ti$ elastic scattering reaction
  - $^{48}Ti(^{18}O,^{19}F)^{47}Sc$ and $^{48}Ti(^{18}O,^{17}O)^{49}Ti$ single-nucleon transfer reactions
  - $^{48}Ti(^{18}O,^{20}Ne)^{46}Ca$ two-proton transfer reaction
  - $^{48}Ti(^{18}O,^{18}Ne)^{48}Ca$ double charge exchange reaction
- Summary - Conclusions

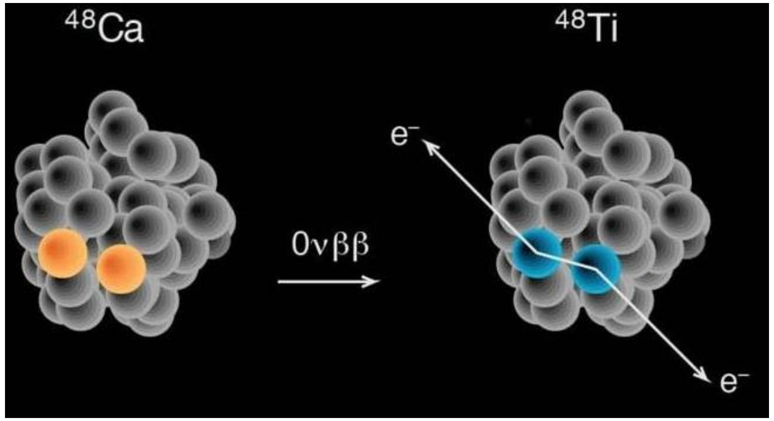
Neutrinoless double beta (0νββ) decay

Phase space factor: Motion of the two electrons (Atomic physics)

Contains the average neutrino mass

$$T_{1/2}^{-1} = G_{0\nu}\left|M_{0\nu\beta\beta}\right|^2 |f(m_i)|^2$$

0νββ decay rate



$${}^{A}_{Z}\mathrm{X}_{N} \longrightarrow {}^{\;\;A}_{Z+2}\mathrm{Y}_{N-2} + 2e^{-}$$

Nuclear Matrix Element (NME)

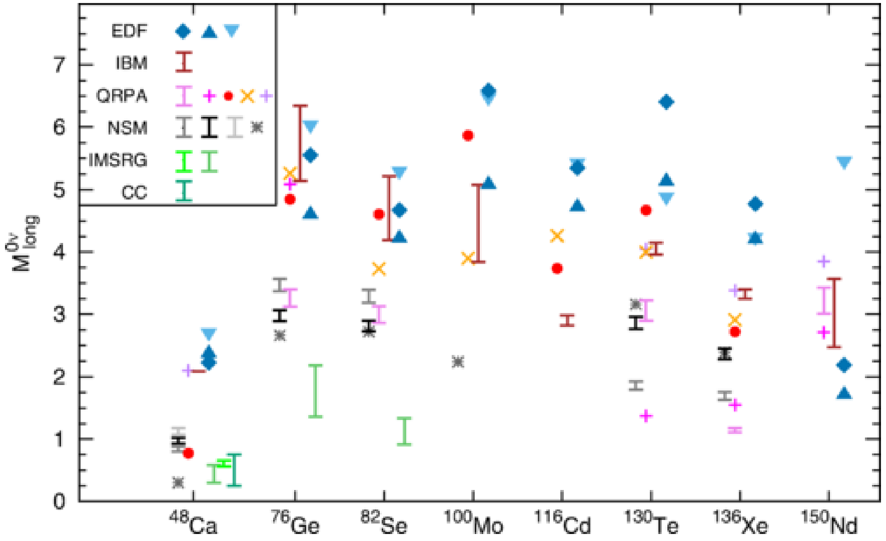
$$M_{0\nu\beta\beta} = \langle \Psi_f | \hat{O}^{0\nu\beta\beta} | \Psi_i \rangle$$

Nuclear physics enters the “game”

Accessible through theoretical calculations → Significant discrepancies between the various structure models!!

Talk by F. Cappuzzello

M. Agostini et al., Rev. Mod. Phys. 95, 025002 (2023)



A promising experimental tool:
Heavy-ion induced Double Charge Exchange (DCE) reactions

The NUMEN project

NUclear
Matrix
Elements for
Neutrinoless
double beta decay

NUMEN review article
F. Cappuzzello et al.,
EPJA 54, 72 (2018)

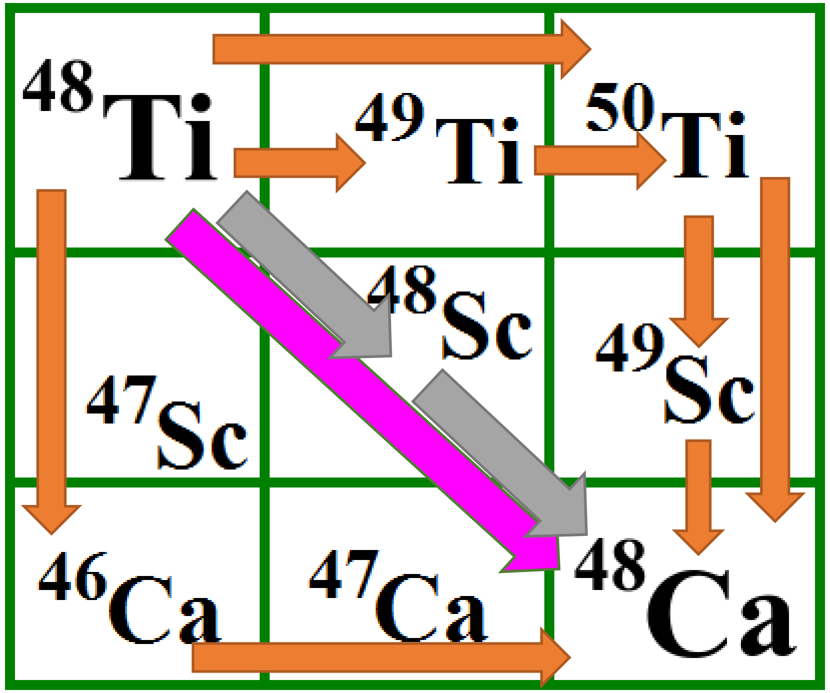
Talk by F. Cappuzzello

NUMEN review article
F. Cappuzzello et al.,
Prog. Part. Nucl. Phys. 128, 103999 (2023)

Access information on the Nuclear Matrix Elements (NMEs) of the $0\nu\beta\beta$ decay through the study of DCE reactions induced by heavy ions.

Transfer reactions: Competing processes leading to the same final states as DCE reaction.

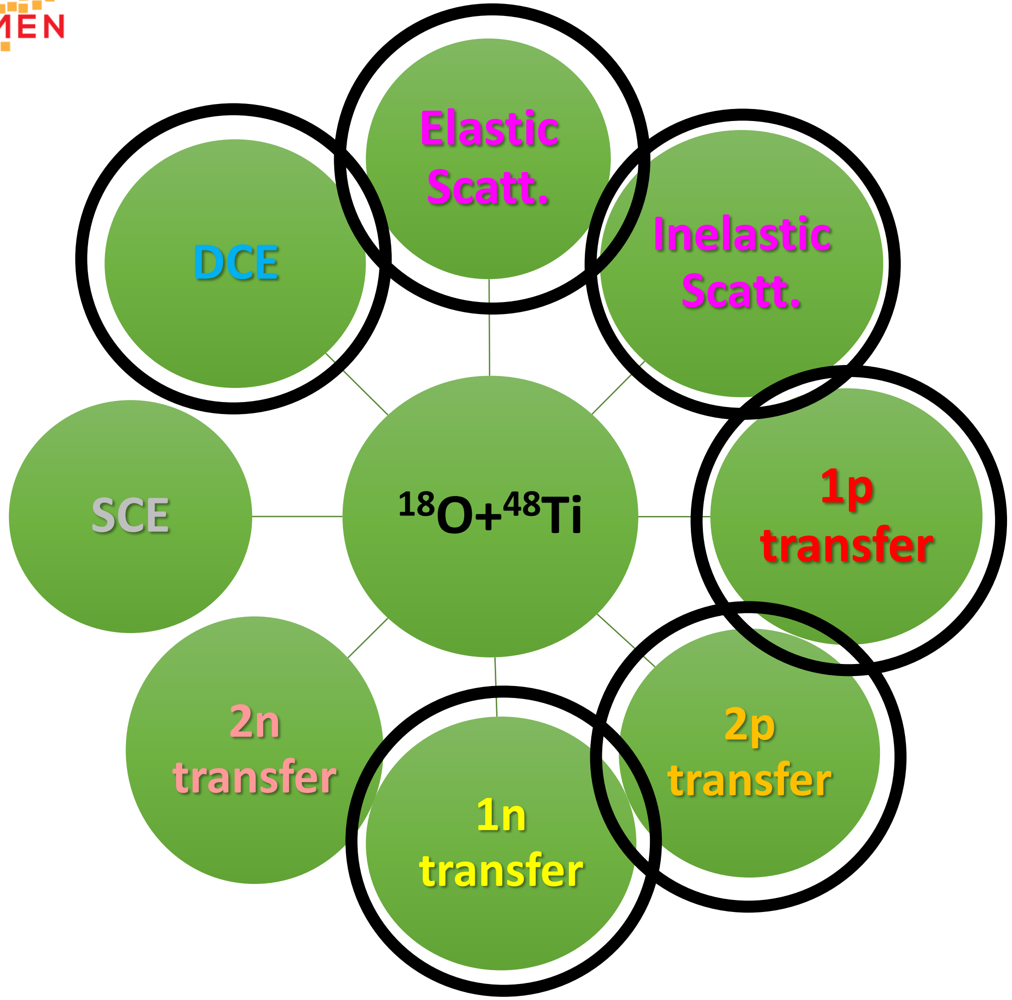
Measure the complete net of reaction channels that may contribute to the measured DCE cross-section.

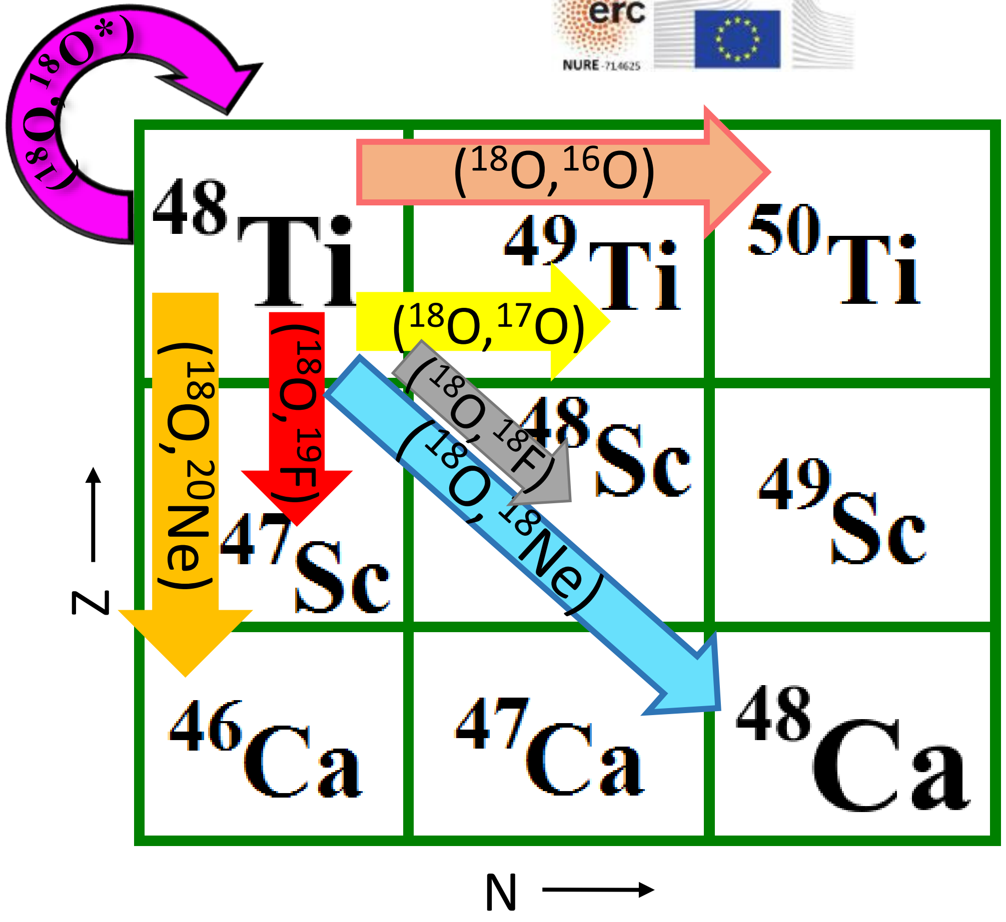


A global description of the $^{18}O+^{48}Ti$ collision @ 275 MeV

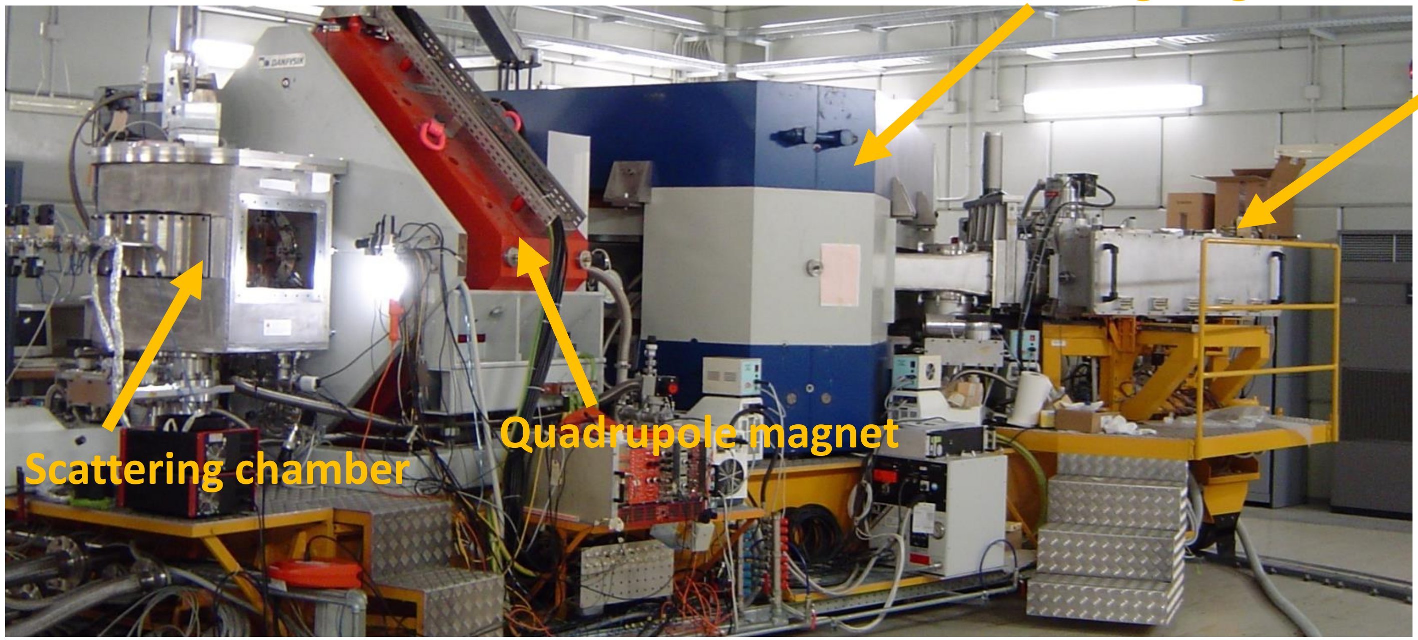
- Taking into consideration all the above, the study of the $^{18}O+^{48}Ti$ collision at the energy of 275 MeV was pursued by measuring the complete net of the available reaction channels as a part of NUMEN and NURE projects.

NURE: M. Cavallaro et al., PoS (BORMIO 2017), 015 (2017)





The MAGNEX large acceptance spectrometer



See talks by F. Cappuzzello, V. Soukeras, G. Souliotis and S. Koulouris

Possibility to measure at zero degree !

Measurements in a wide mass range (from protons up to ^{75}Zn)!!

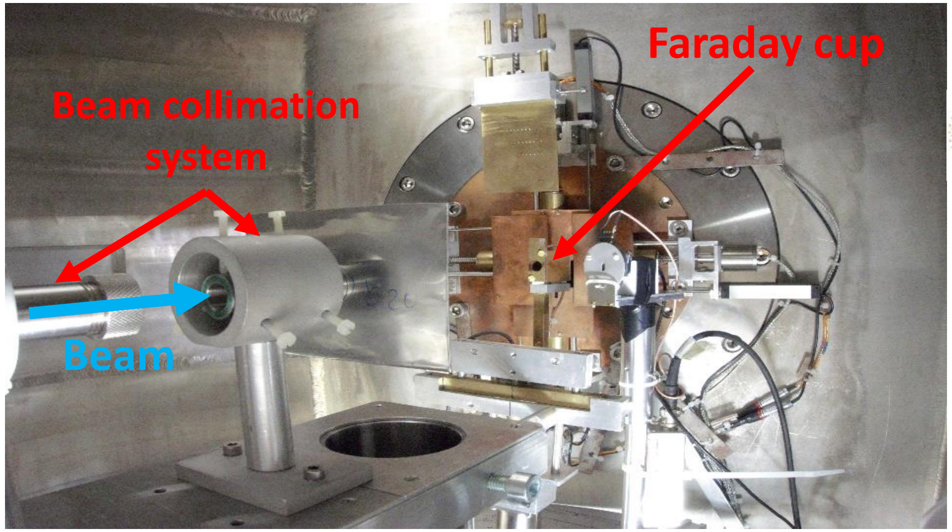
MAGNEX characteristics

Max. Magnetic rigidity	1.8 Tm
Solid angle	50 msr
Momentum acceptance	-14%, +10%
Covered angular range	-20°, +85°

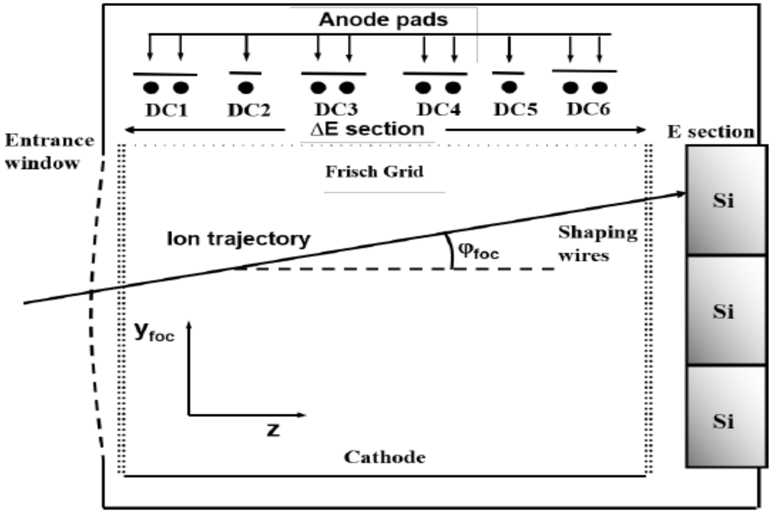
Achieved resolutions
Energy ΔE/E: 1/1000
Angular: 0.2°
Mass Δm/m: 1/300

Experimental Details

- Beam: $^{18}O^{8+}$ accelerated by SC cyclotron at 275 MeV.
- Target: TiO_2 evaporated onto a thin ^{27}Al foil.
- Background estimation: 2 additional runs with a WO_3 and an ^{27}Al target.
- Detection system: The reaction ejectiles were detected by the MAGNEX Focal Plane Detector (FPD).



Inner part of the scattering chamber



Lateral view of the MAGNEX FPD
D. Torresi et al., NIM A 989, 164918 (2021)

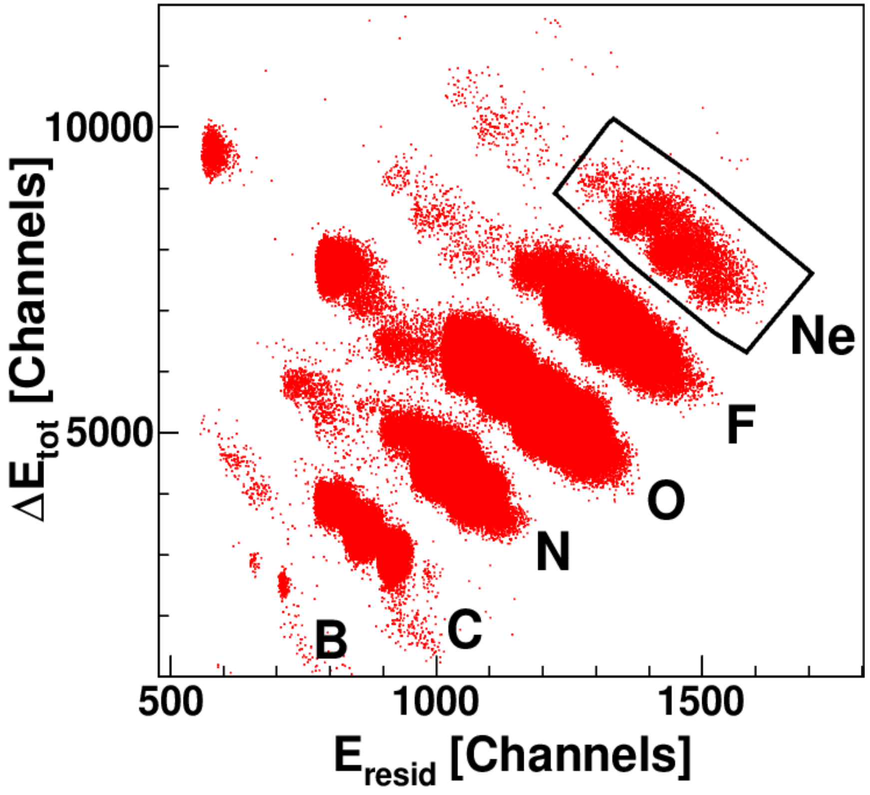
Focal Plane Detector

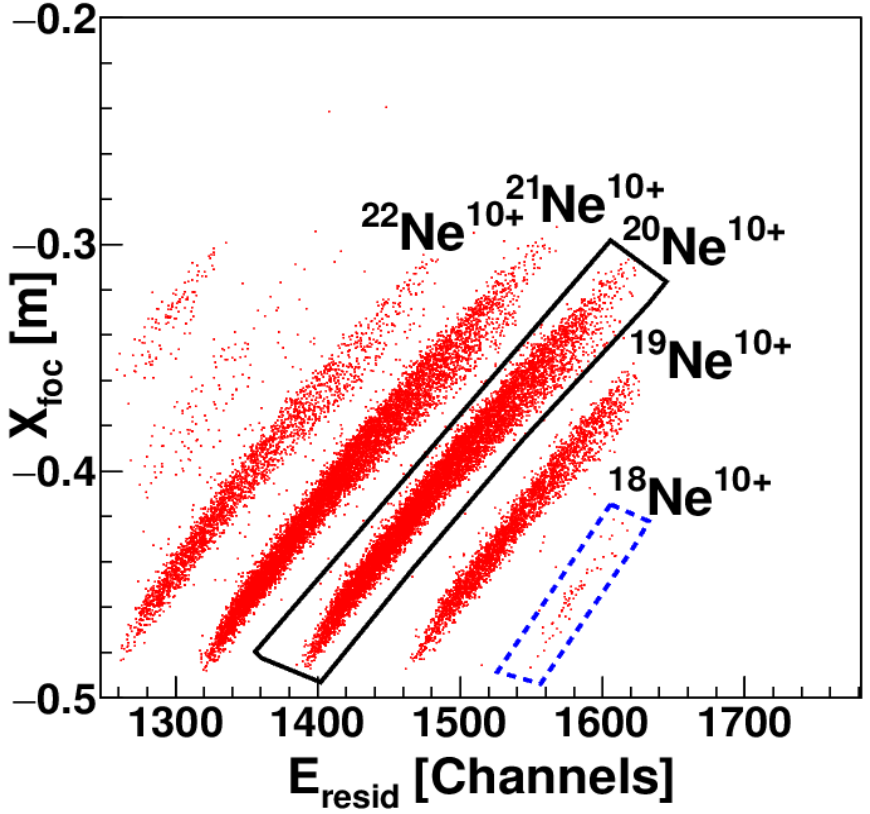
Ionization chamber → ➢Measure ions energy loss inside gas (ΔE)
➢Measure ions track X, Y coordinates

+

60 silicon detectors → ➢Measure ions residual energy (E_{resid})

Examples of particle identification spectra





(Bethe-Bloch formula) $-\frac{dE}{dx} \propto \frac{Z^2 M}{E}$

$$X_{foc} \propto \frac{\sqrt{m}}{q}\sqrt{E_{resid}}$$

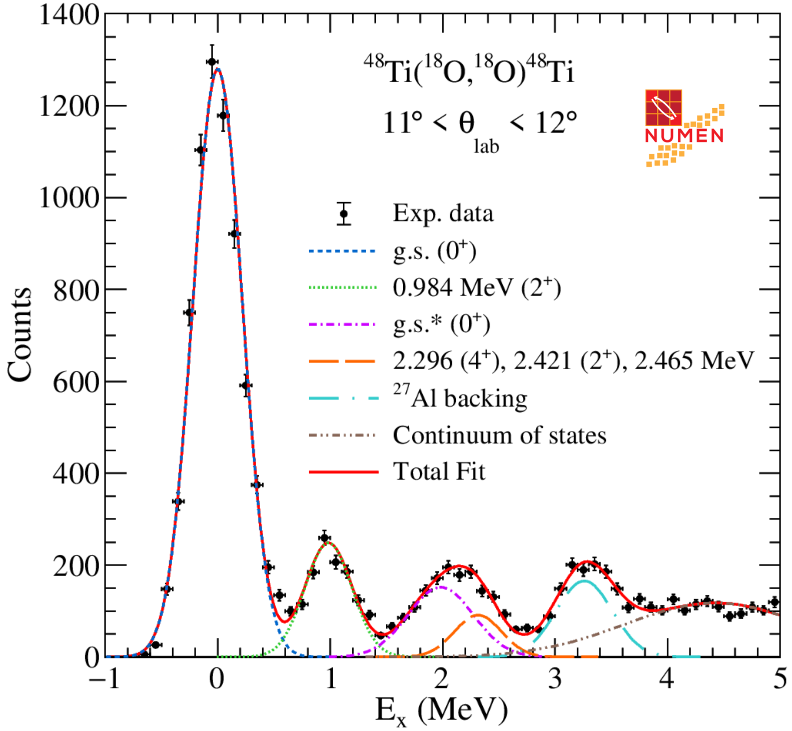
Elastic and inelastic scattering channels

$^{18}O+^{48}Ti$ →

- $^{19}F+^{47}Sc$ (one-proton pick-up)
- $^{17}O+^{49}Ti$ (one-neutron stripping)
- $^{20}Ne+^{46}Ca$ (two-proton pickup)
- $^{16}O+^{50}Ti$ (two-neutron stripping)
- $^{18}F+^{48}Sc$ (single charge exchange)
- $^{18}Ne+^{48}Ca$ (double charge exchange)

ISI: Key ingredient for the theoretical interpretation of all measured reaction channels !

Elastic and inelastic scattering channels



G. A. Brischetto, PhD Thesis UNICT 2023

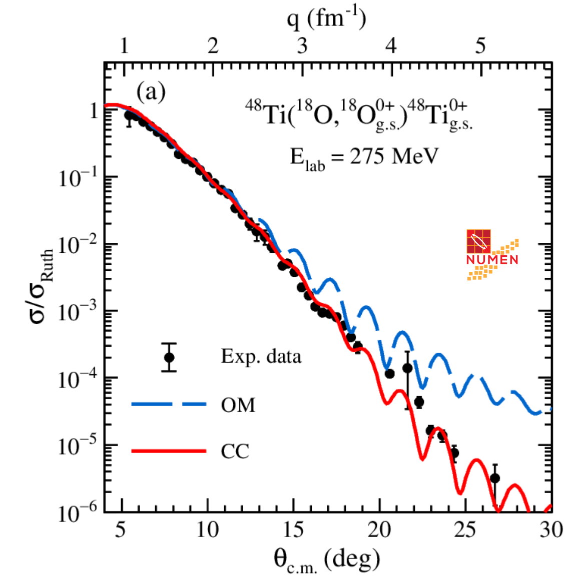
G. A. Brischetto, O. Sgouros, D. Carbone et al., PRC 109, 014604 (2024)

Optical Model

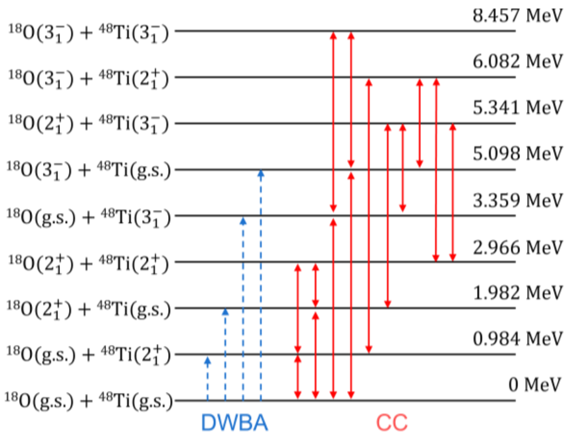
$$U_{nucl} = (N_R + iN_I)V_{SPP}$$

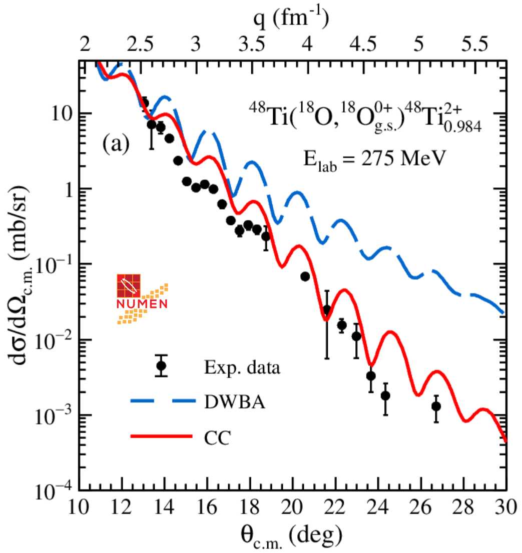
SPP: L. C. Chamon et al., PRC 66, 014610 (2002)

Calculation	N_R	N_I
OM/DWBA	1.0	0.78
CC	1.0	0.60

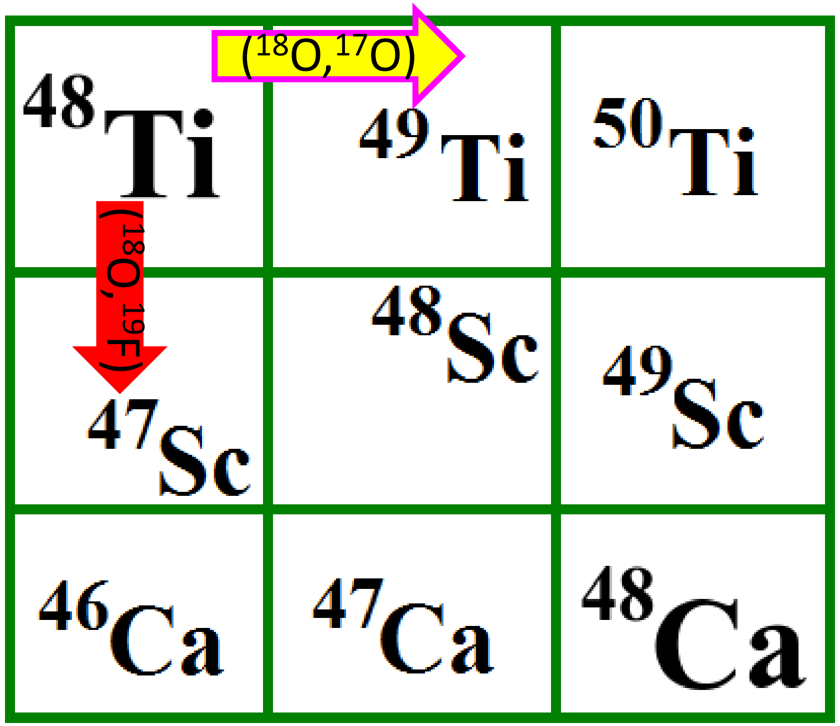


Coupling scheme





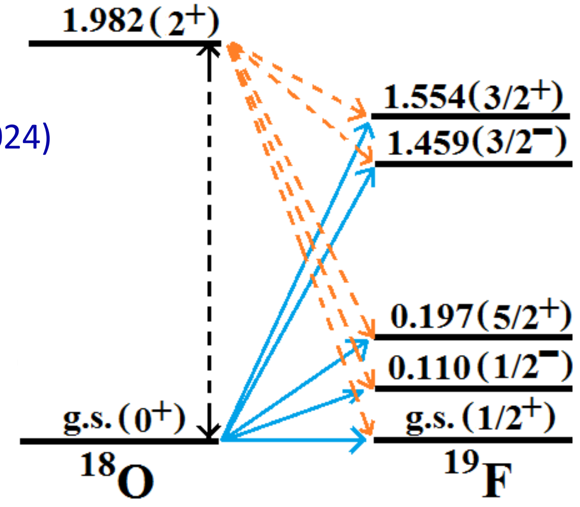
Single-nucleon transfer reactions



The Distorted-Wave Born Approximation ingredients

- Transfer proceeds in a single step from the ground state of the projectile (target) to a final state of the ejectile (residual) nucleus.

R. Ascuitto and J. S. Vaagen, EPJA 49, 3 (2024)



- Let us consider a reaction: $\alpha + A \rightarrow b + B$

$$\frac{d\sigma}{d\Omega} \propto |T^{DWBA}|^2 = \left| \int d\vec{r}_\alpha d\vec{r}_\beta \, x_\beta^{(-)*} \langle \phi_B \phi_b | V | \phi_A \phi_\alpha \rangle x_\alpha^{(+)} \right|^2$$

Distorted waves $x_{\alpha,\beta}$

- Describe the elastic scattering at the entrance(α) and exit(β) channel.
- Solutions of Schrödinger equation using the appropriate nucleus-nucleus potential.

↓

Constrained from the analysis of the elastic scattering data !

Overlap functions

$$\langle \phi_B | \phi_A \rangle \propto A_{\ell sj} \varphi_{\ell sj}^{Bx}$$

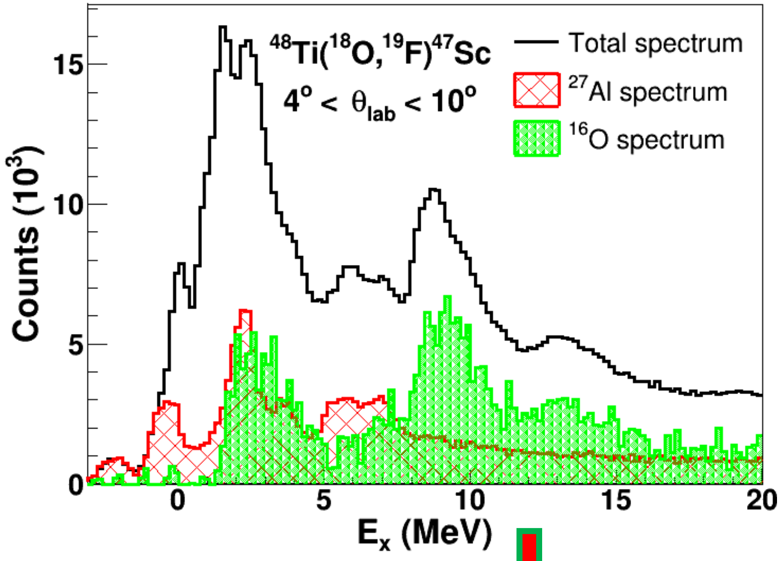
$$\langle \phi_b | \phi_a \rangle \propto B_{\ell sj} \varphi_{\ell sj}^{ax}$$

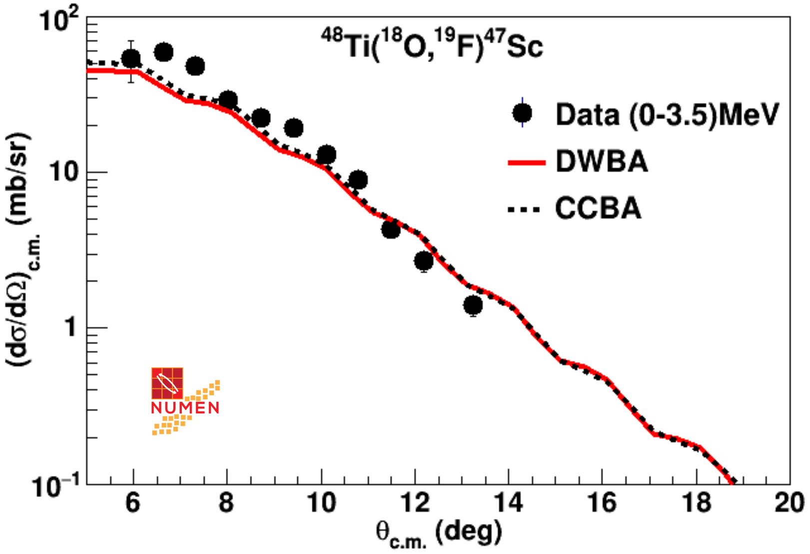
- $\varphi_{\ell sj}$ are single-particle solutions of a Woods-Saxon potential.
- Coefficients $A_{\ell sj}$ and $B_{\ell sj}$ are the spectroscopic amplitudes derived from large scale shell-model calculations.

see talk by A. Gargano

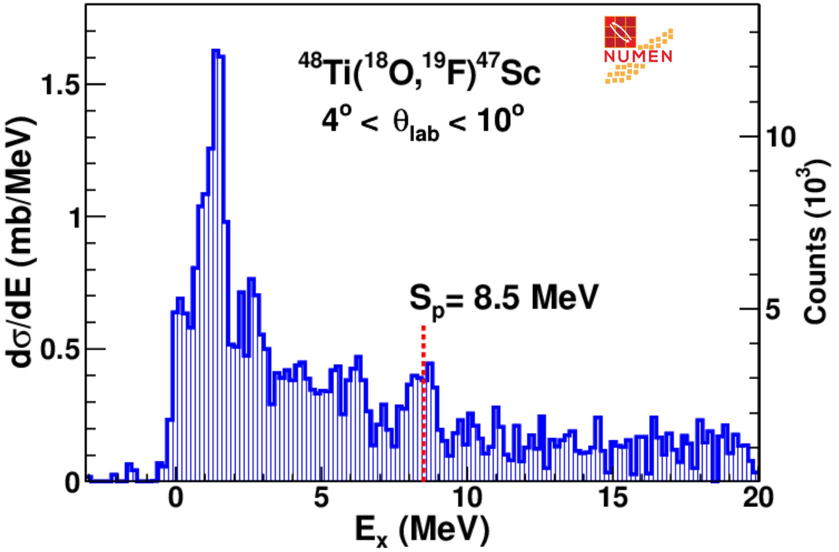
Overlaps	Interaction	Core	Nucleon orbitals
$\langle ^{19}F \| ^{18}O \rangle$	P-SD-MOD	^{4}He	1p, 1d, 2s
$\langle ^{17}O \| ^{18}O \rangle$			
$\langle ^{17}O \| ^{16}O \rangle$			
$\langle ^{47}Sc \| ^{48}Ti \rangle$	SDPF-MU	^{16}O	1d, 2s, 1f, 2p
$\langle ^{49}Ti \| ^{48}Ti \rangle$			
$\langle ^{28}Al \| ^{27}Al \rangle$			

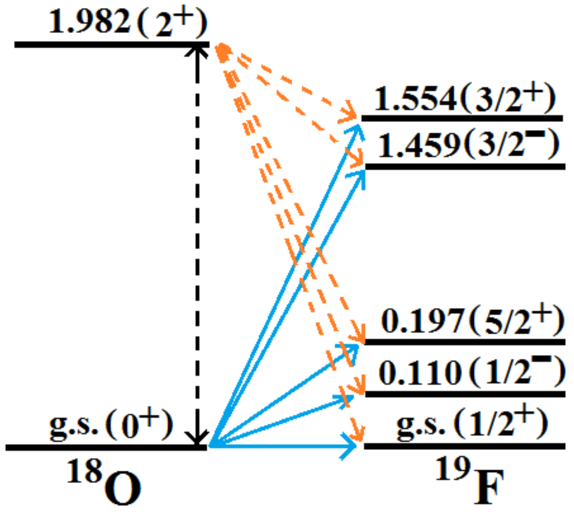
$^{48}Ti(^{18}O,^{19}F)^{47}Sc$ reaction



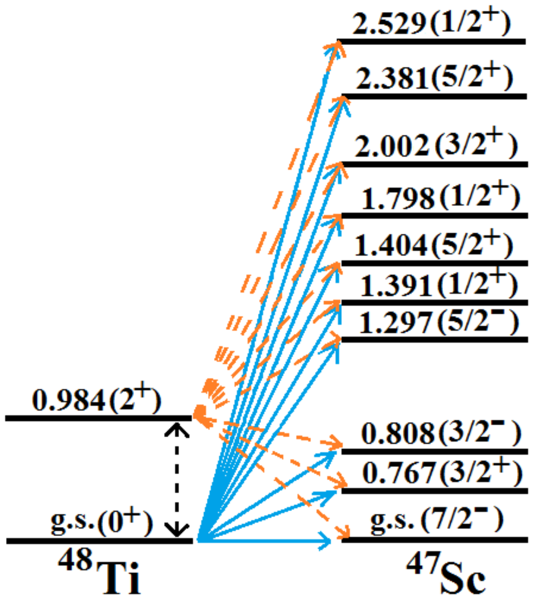


O. Sgouros et al., PRC 104, 034617 (2021)



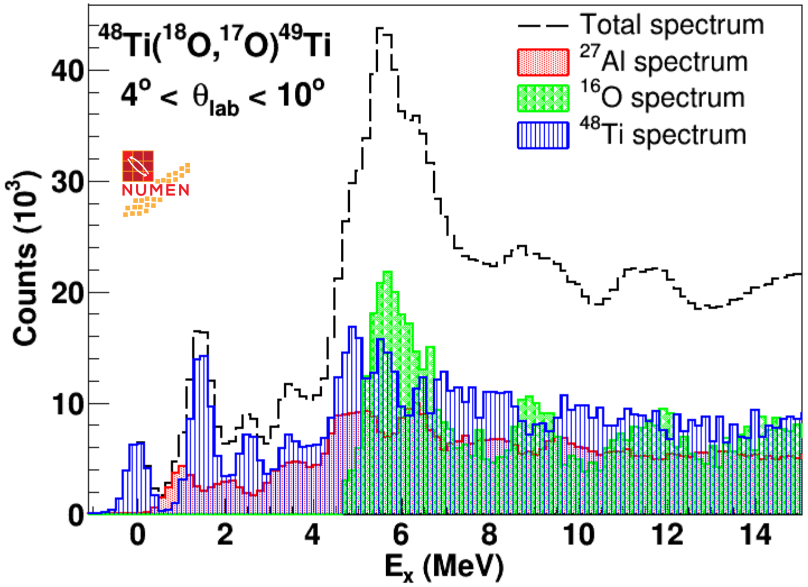


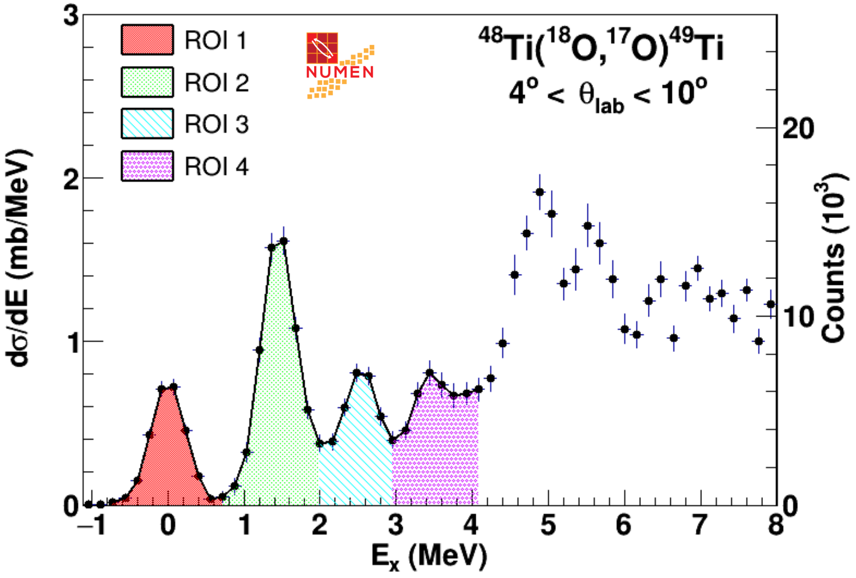
Projectile Overlaps

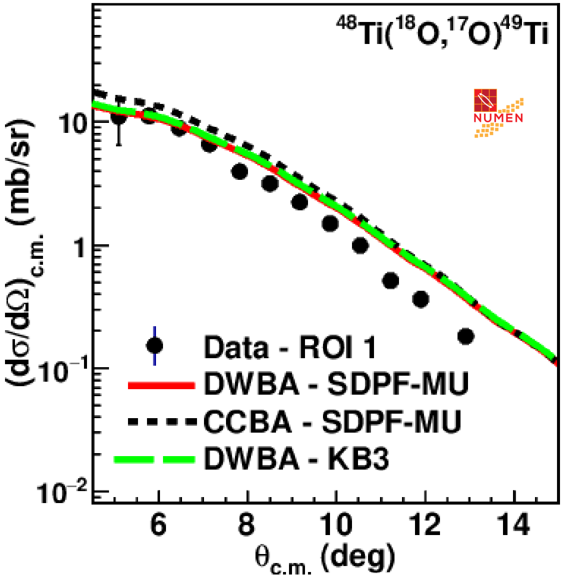


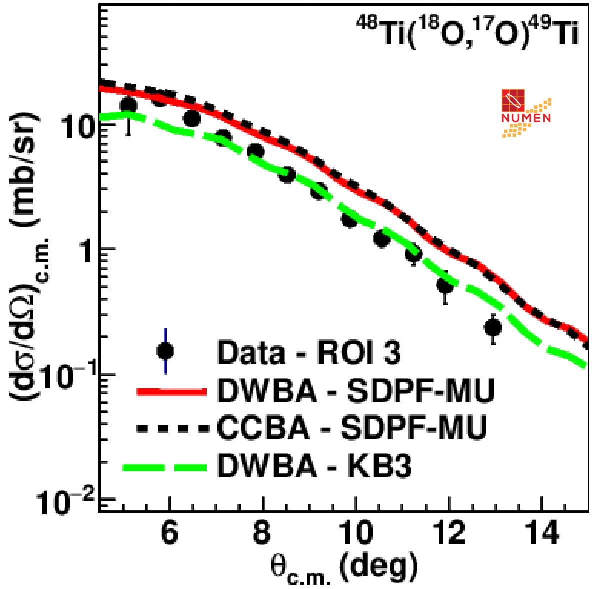
Target Overlaps

$^{48}Ti(^{18}O,^{17}O)^{49}Ti$ reaction







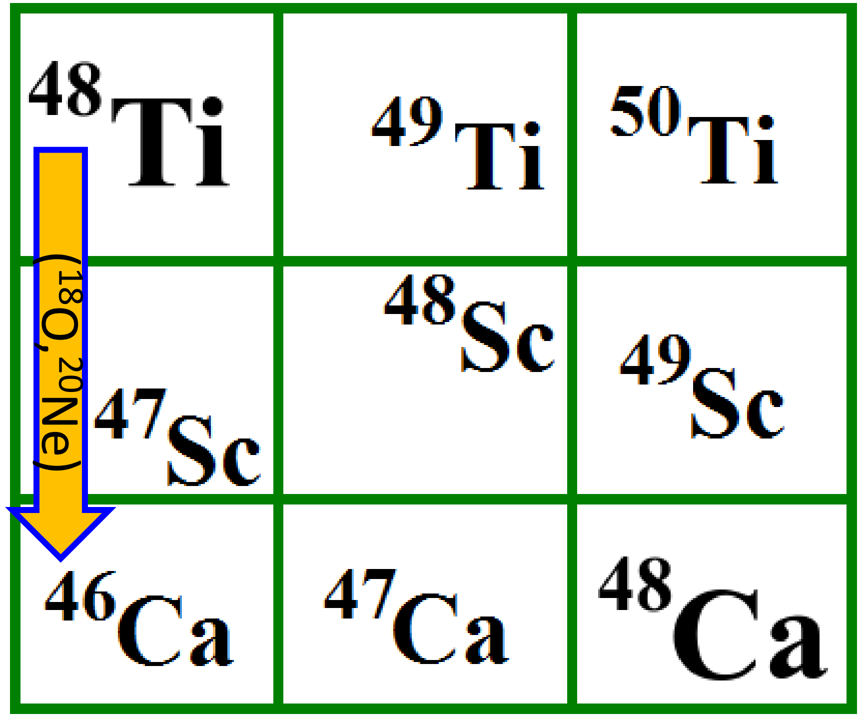


Small role of inelastic excitations !
Sensitivity on the adopted model space !

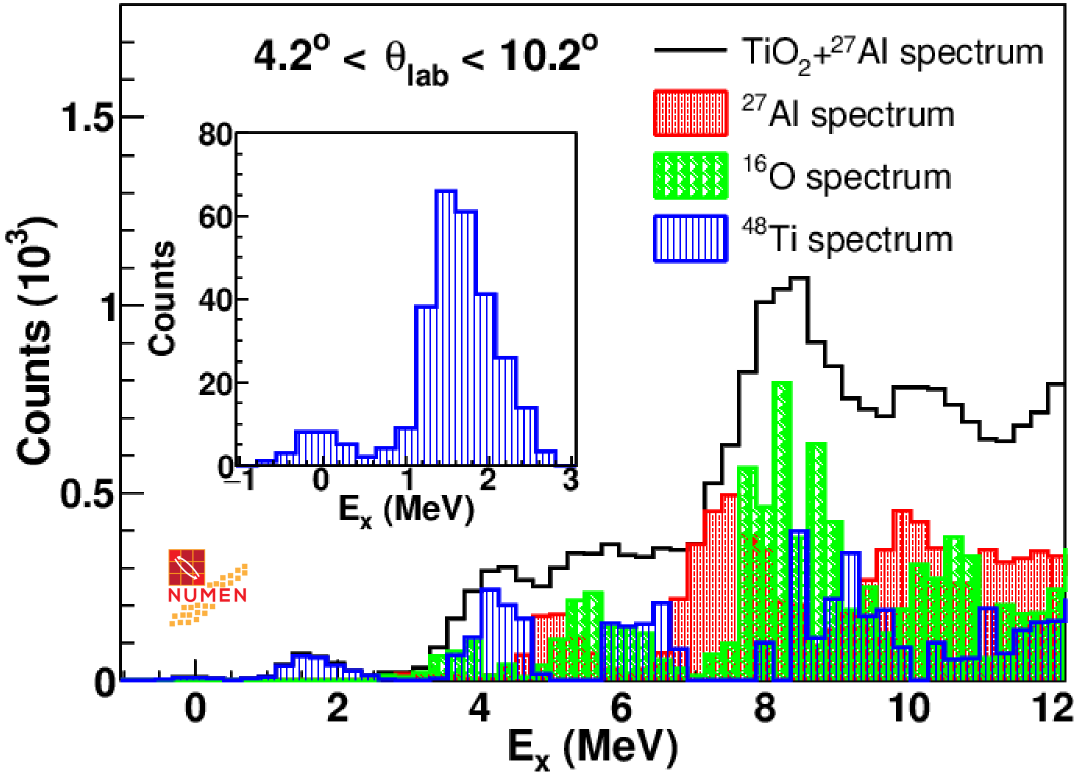
M. Cutuli, MSc Thesis
UNICT 2021

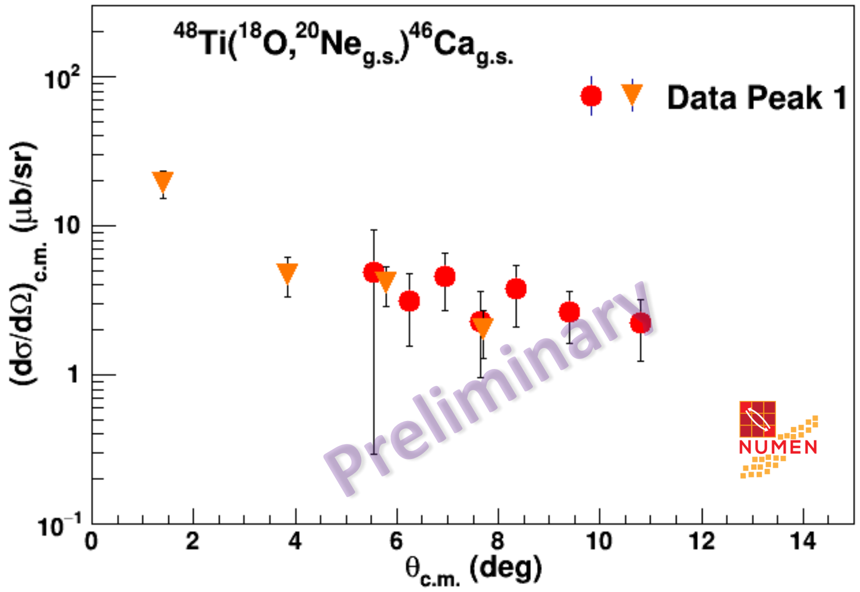
O. Sgouros, M. Cutuli et al.,
PRC 108, 044611 (2023)

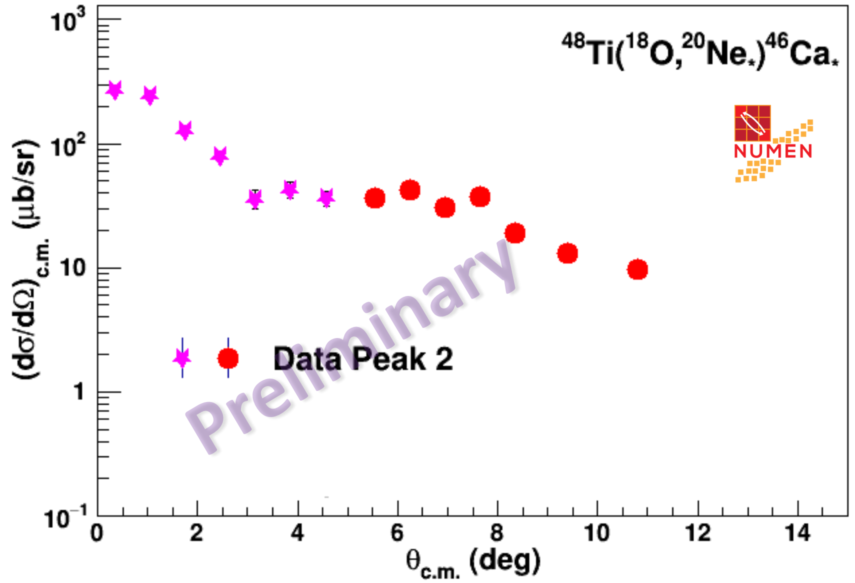
Two-proton transfer reaction



$^{48}Ti(^{18}O,^{20}Ne)^{46}Ca$ reaction – Differential cross-section determination

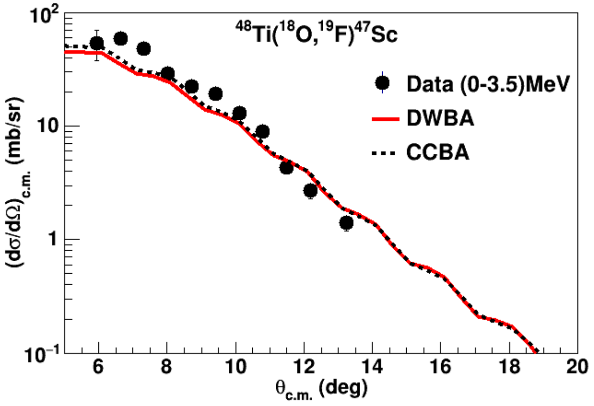




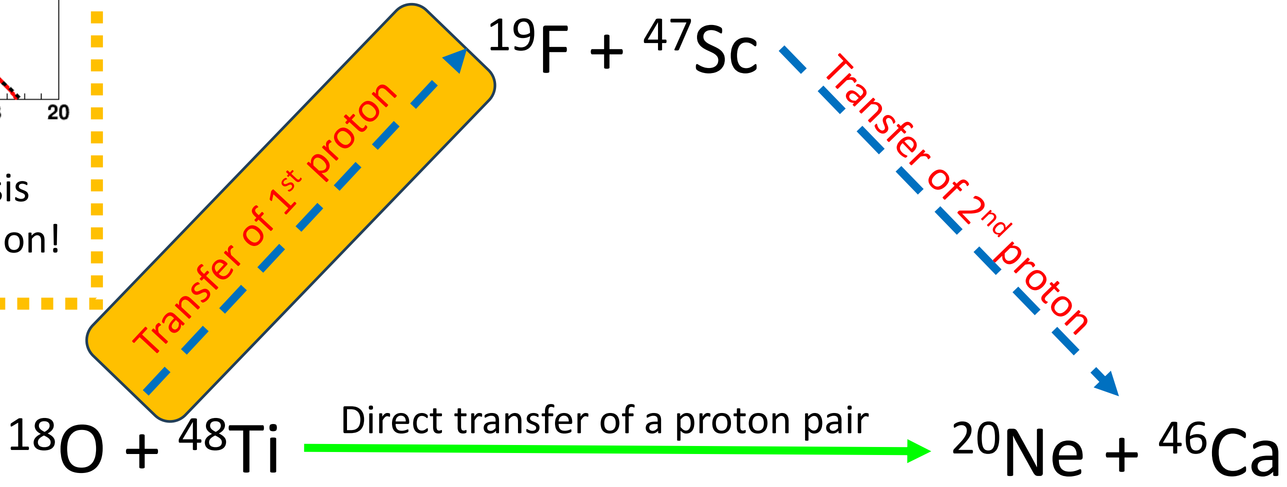


O. Sgouros, Il Nuovo Cimento 45C, 70 (2022)

$^{48}Ti(^{18}O,^{20}Ne)^{46}Ca$ reaction – Theoretical interpretation

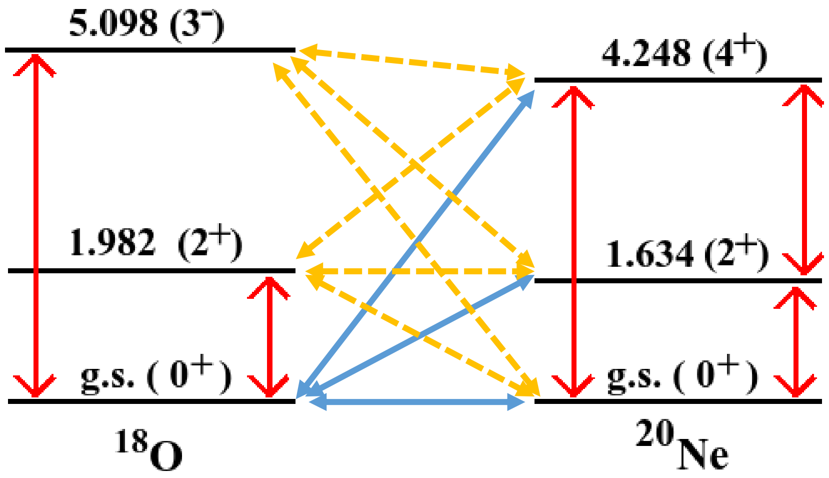


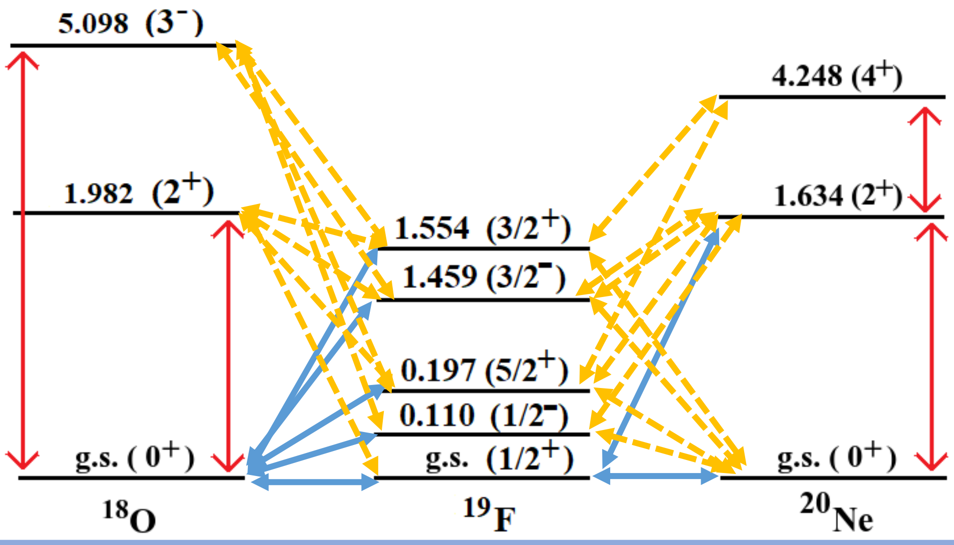
Constrained from the analysis of the $^{48}Ti(^{18}O,^{19}F)^{47}Sc$ reaction!



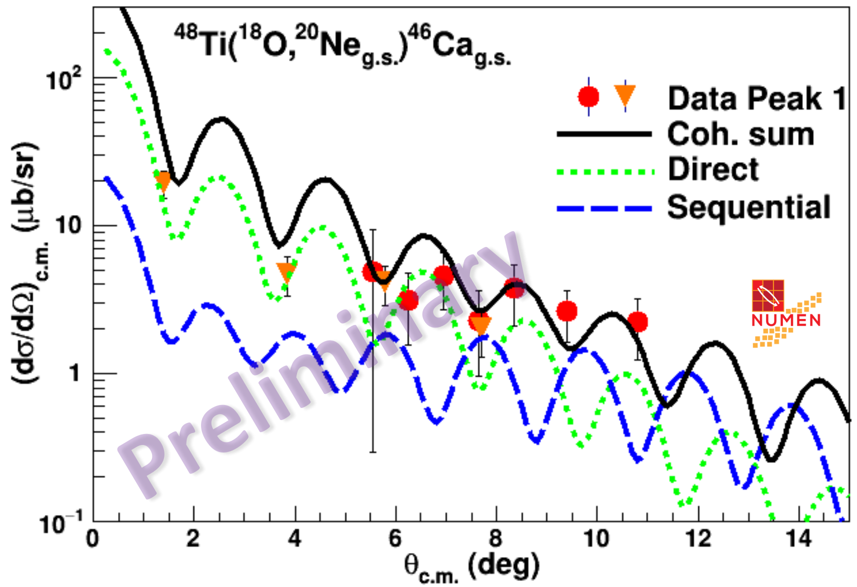
$^{48}Ti(^{18}O,^{20}Ne)^{46}Ca$ reaction – Theoretical interpretation

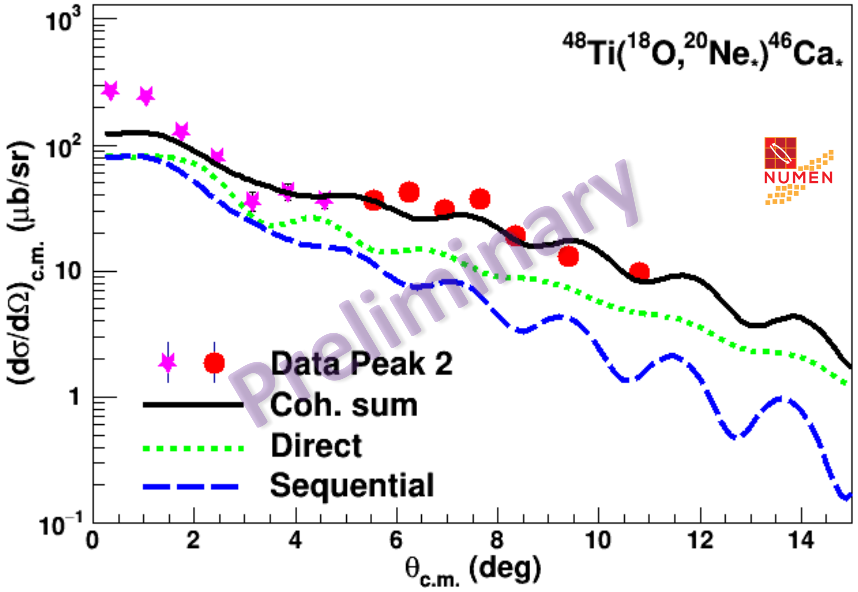
Projectile coupling scheme



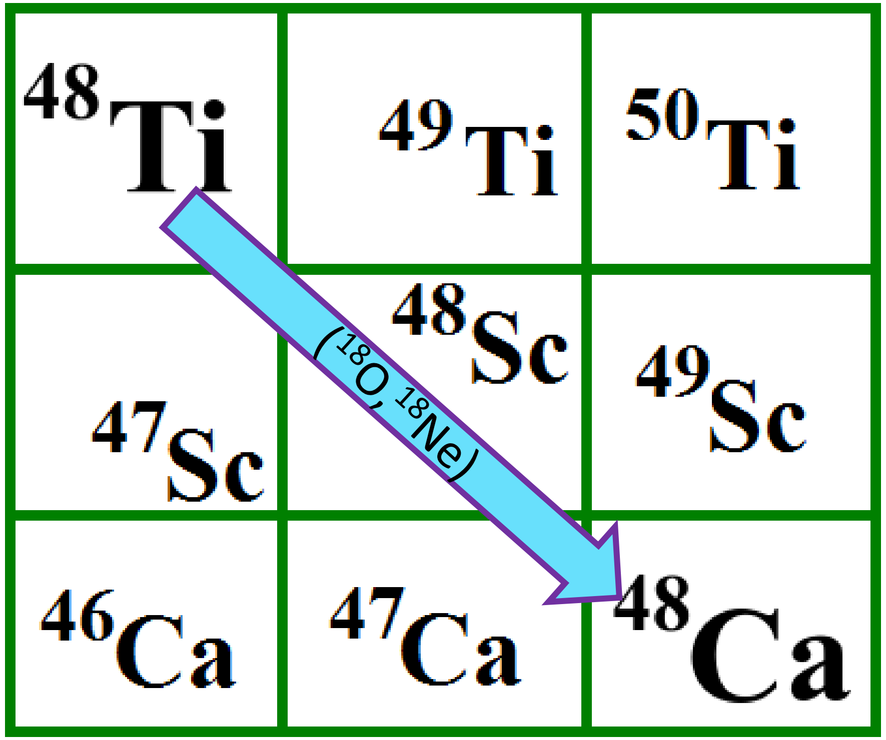


O. Sgouros et al., (in preparation)

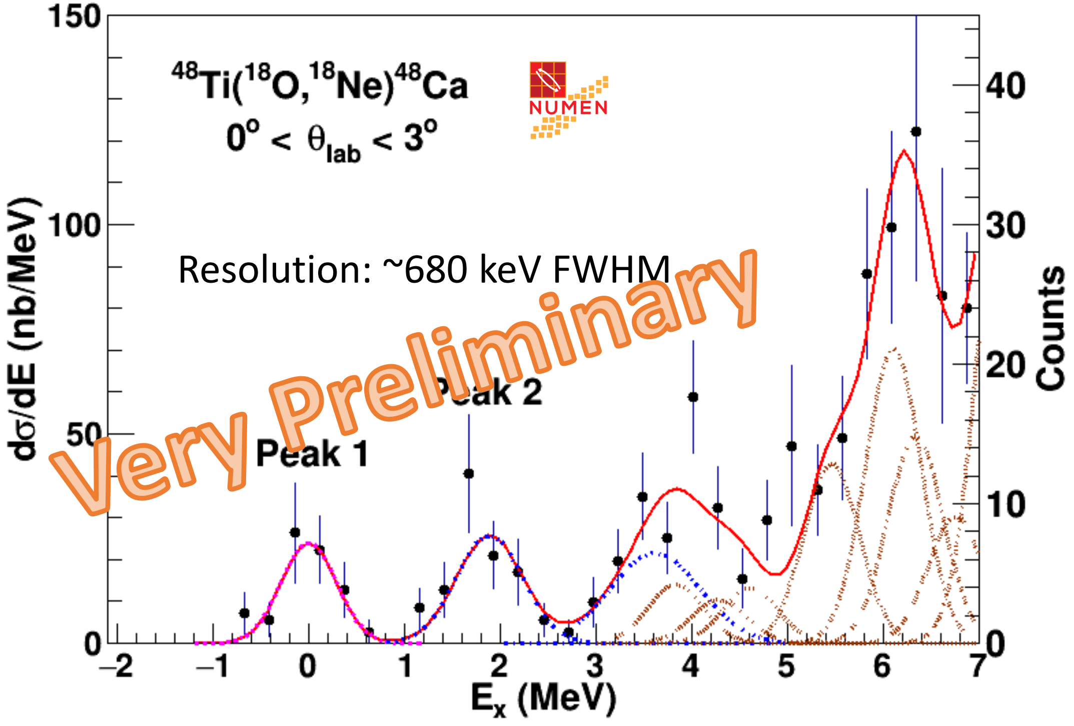


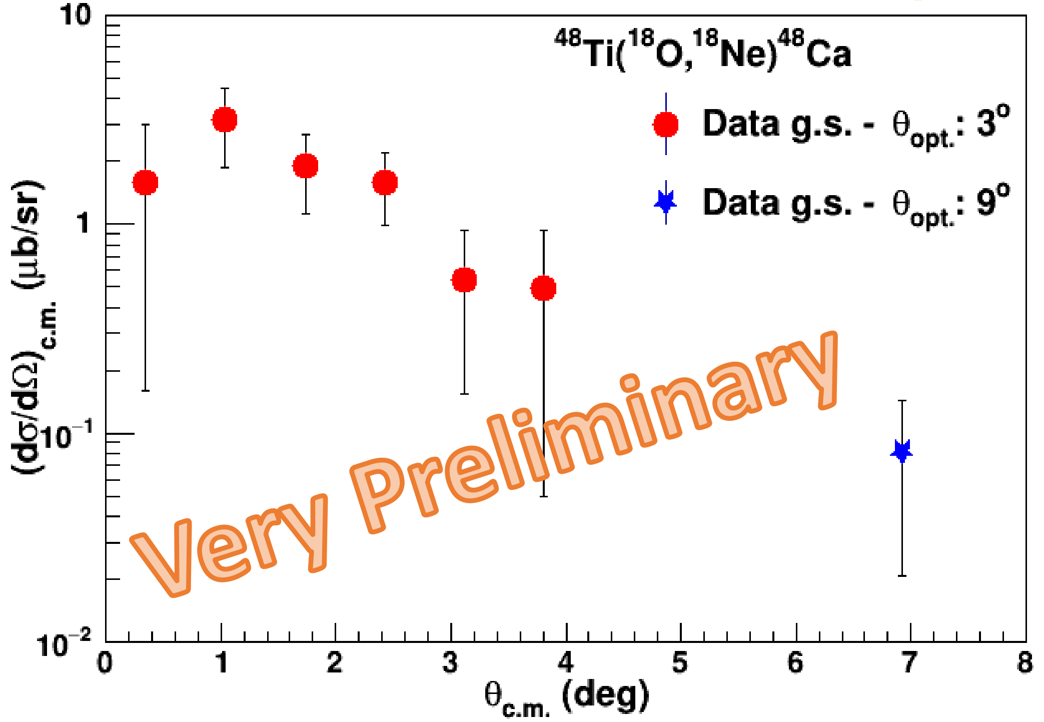


Double charge exchange reaction



$^{48}Ti(^{18}O,^{18}Ne)^{48}Ca$ reaction





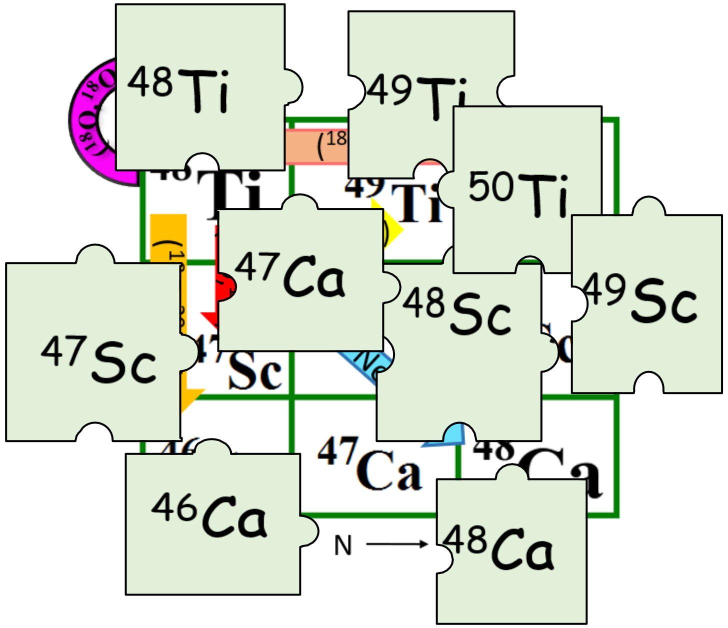
Peak label	Populated states	Integrated yield (Counts)	Int. cross-section (nb)
1	$^{18}Ne_{g.s.} + ^{48}Ca_{g.s.}$	24	20 ± 4
2	$^{18}Ne_{1.89} + ^{48}Ca_{g.s.}$	32	28 ± 5

Data @ $\theta_{opt.}$: 9deg
C. Garofalo, MSc Thesis UNICT
(in progress)

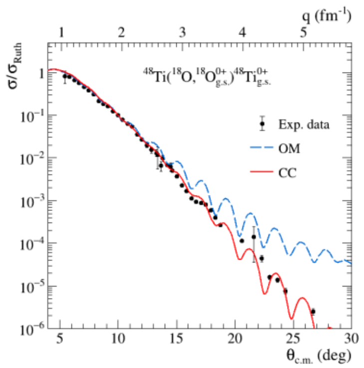
Summary - Conclusions

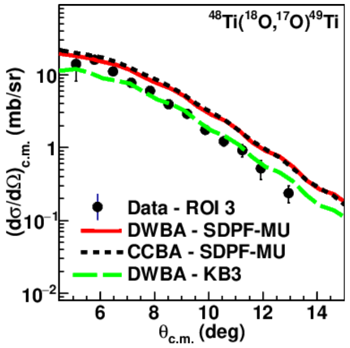
➢ NUMEN is an ambitious project aiming at accessing information on the NMEs of 0νββ decay through the study of heavy-ion induced double charge exchange reactions.

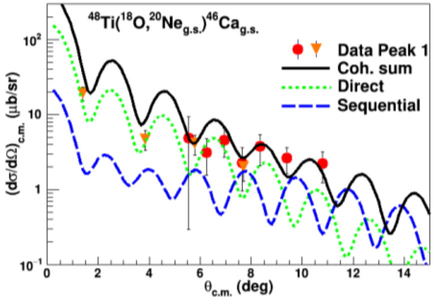
- A **multi-channel study** of the $^{18}O+^{48}Ti$ collision was performed by measuring the complete net of the available reaction channels.

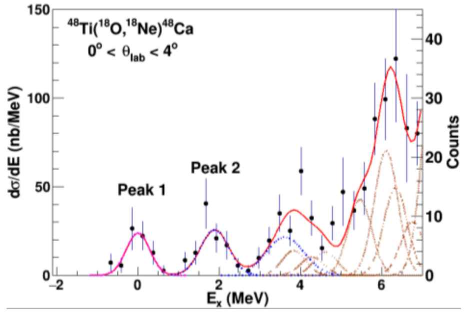


✓ Elastic Channel
✓ Single-nucleon transfer
✓ Two-proton transfer
✓ Double charge exchange channel









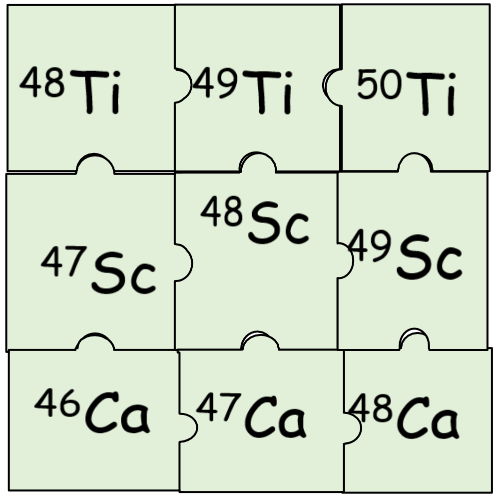
<u>Next steps</u>:

- **Completion of the analysis for the rest reaction channels.**
- **Estimation of contribution of multi-nucleon transfer on the DCE cross-section.**
- **Description of all data set under a unique coupled channels framework!**

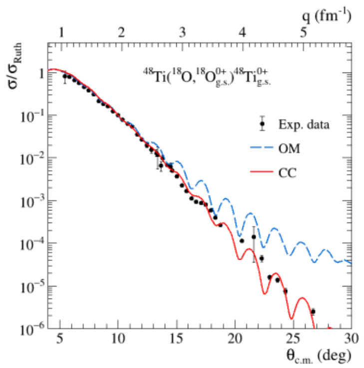
Summary - Conclusions

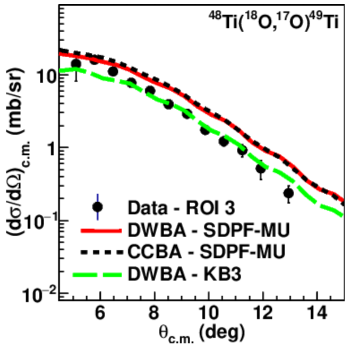
➢ NUMEN is an ambitious project aiming at accessing information on the NMEs of 0νββ decay through the study of heavy-ion induced double charge exchange reactions.

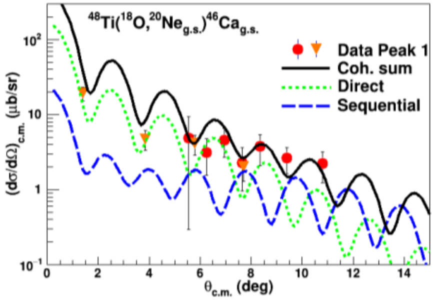
- A **multi-channel study** of the $^{18}O + ^{48}Ti$ collision was performed by measuring the complete net of the available reaction channels.

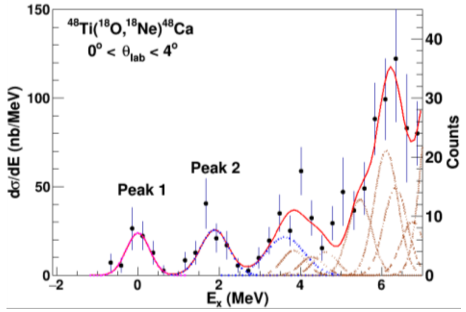


✓ Elastic Channel
✓ Single-nucleon transfer
✓ Two-proton transfer
✓ Double charge exchange channel









<u>Next steps</u>:

- **Completion of the analysis for the rest reaction channels.**
- **Estimation of contribution of multi-nucleon transfer on the DCE cross-section.**
- **Provide experimental constraints on the calculation of NMEs of 0νββ decay !**

The **NUMEN** collaboration

(**NU**clear **M**atrix **E**lements for **N**eutrinoless double beta decay)

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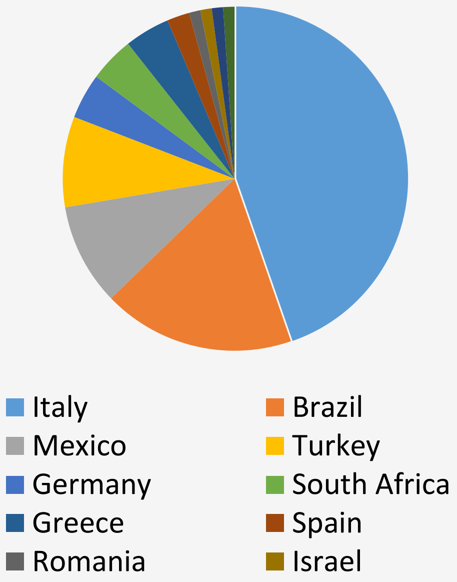



Thank you for your attention

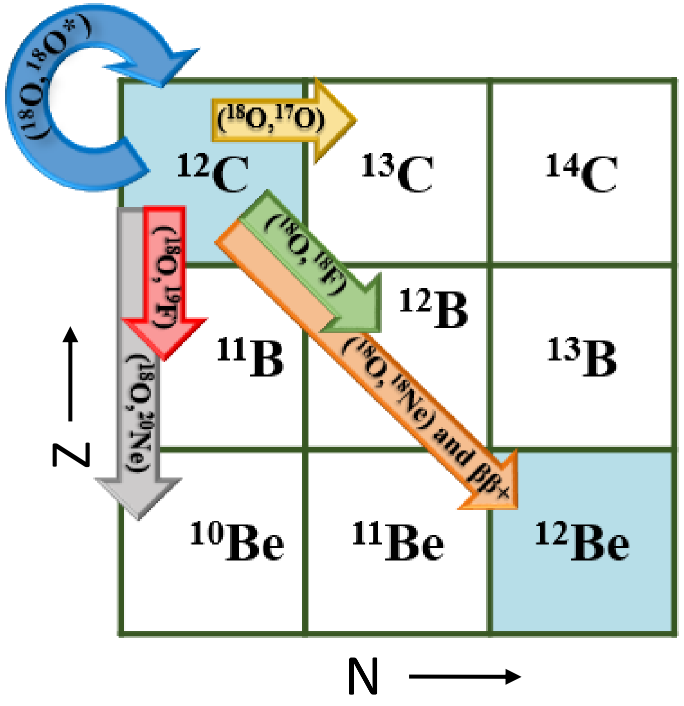
Backup Slides

The multi-channel approach within the NUMEN project

Measuring all the available reaction network under the same experimental conditions

Suppression of systematic errors in the data analysis

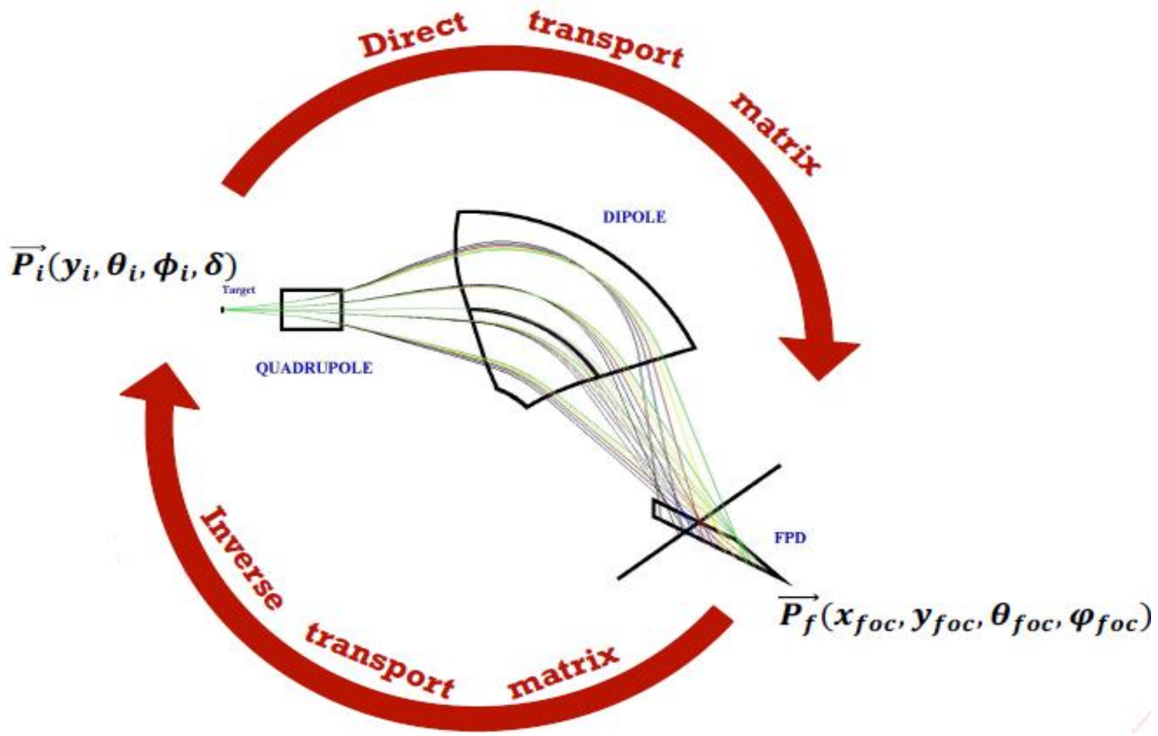
Provides the appropriate constraints in the adopted reaction and nuclear structure models



A. Spatafora et al., PRC 107, 024605 (2023)

Trajectory reconstruction

F. Cappuzzello et al., NIM A 638, 74 (2011)



Through a high order software trajectory reconstruction, the initial phase space parameters (E_{kin},θ_{lab}) at the target position are determined from the measured ones.

Measured parameters at the FPD

↓ Trajectory Reconstruction

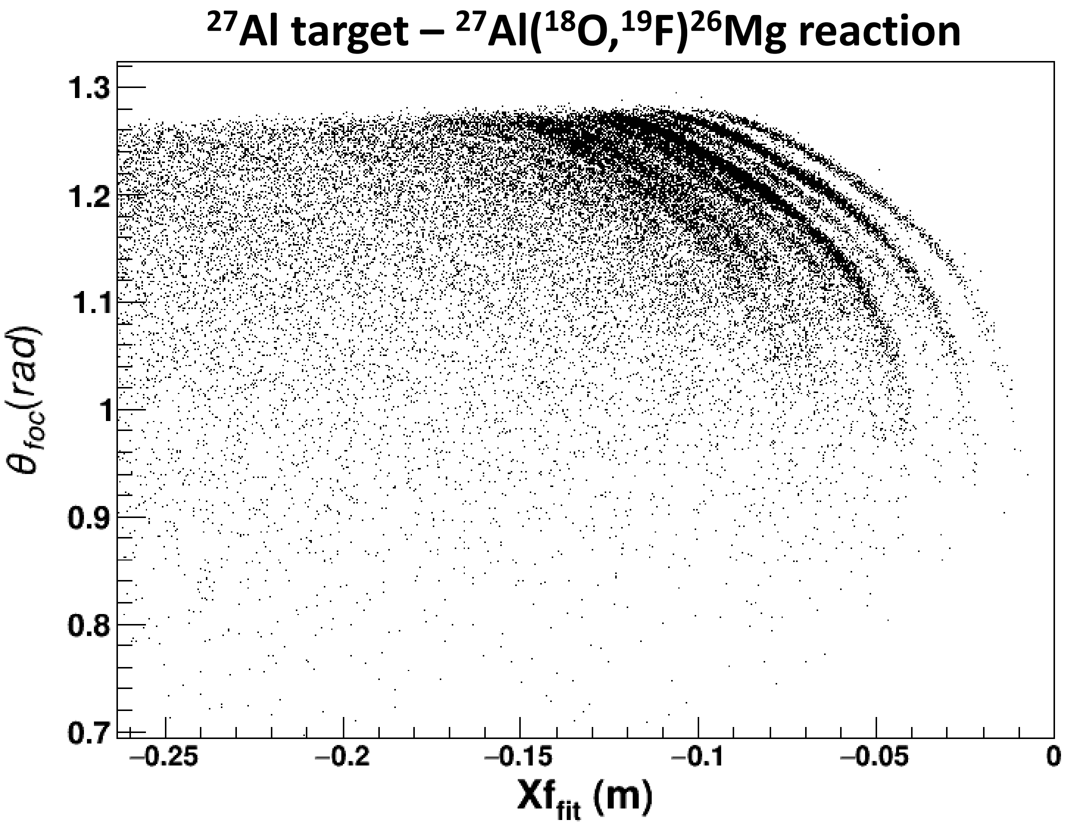
Momentum vector at target position

↓ Missing mass method [F. Cappuzzello et al., EPJA 52, 167 (2016)]

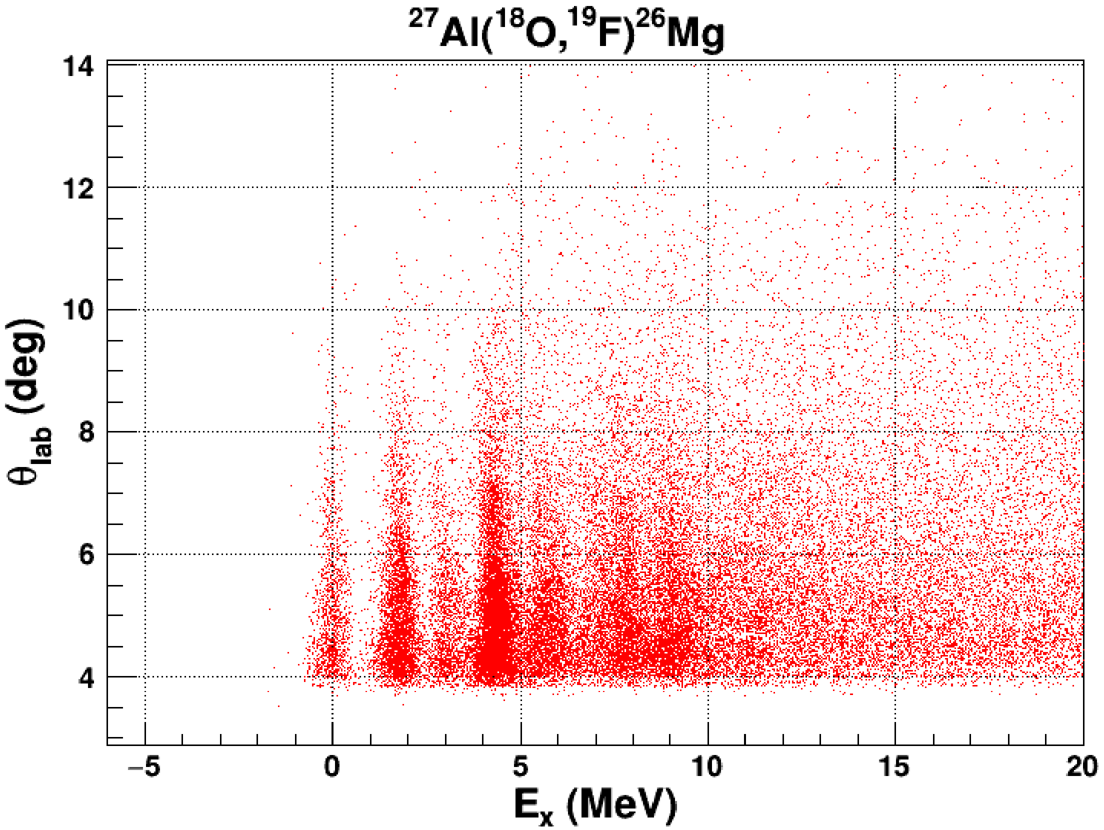
Excitation energy spectrum

Trajectory reconstruction

Final phase space (measured) parameters → Trajectory Reconstruction → Initial phase space parameters



θ_{foc}-X_{fit} correlation plot for the identified ^{19}F events measured at the Focal Plane Detector



Through a high order software ray reconstruction, the initial phase space parameters (E_{kin},θ_{lab}) at the target position are determined from the measured ones.