16th Varenna Conference on Nuclear Reaction Mechanisms

Global description in the $^{18}O+^{48}Ti$ collision within the NUMEN project

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University of Catania and INFN-LNS

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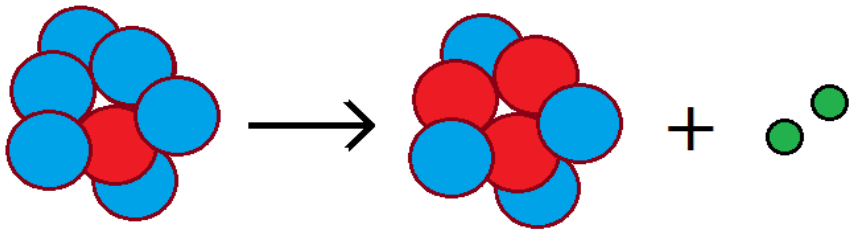
Outline

- 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
- Particle identification
- 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



$$ {}^{A}_{Z}X_{N} \longrightarrow {}^{A}_{Z+2}Y_{N-2} + 2e^{-} $$

E. Majorana, Il Nuovo Cimento 14, 171 (1937)

W. H. Furry, Phys. Rev. 56, 1184 (1939)

Decay rate of 0νββ decay

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

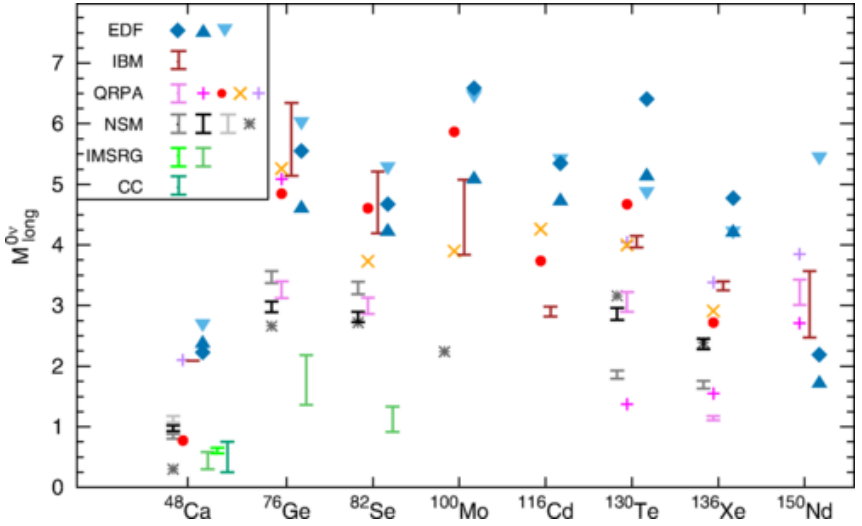
Accessible through experiment

$$ M_{0\nu\beta\beta} = \left\langle \phi_f \left| \hat{O}^{0\nu\beta\beta} \right| \phi_i \right\rangle $$

Nuclear Matrix Element (NME)

Accessible through theoretical calculations

Large discrepancies between the various structure models!!



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

Talk by M. Colonna

- Forbidden by the Standard model
- Not observed yet
- Prominent probe of neutrino nature and mass

The NUMEN project

NUclear
Matrix
Elements for
Neutrinoless
double beta decay

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

Access information on the Nuclear Matrix Elements (NMEs) of the 0νββ decay through the study of the Double Charge Exchange (DCE) reactions induced by heavy ions.

H. Lenske et al., Prog. Part. Nucl. Phys. 109, 103716 (2019)

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

0νββ decay

Mediated by weak interaction

$$M_{0\nu\beta\beta} = \langle \phi_f | \hat{O}^{0\nu\beta\beta} | \phi_i \rangle$$

DCE reaction

Mediated by strong interaction

$$M_{DCE} = \langle \phi_f | \hat{O}^{DCE} | \phi_i \rangle$$

So, why DCE reactions?

Talks by H. Lenske and M. Colonna

Important analogies between the two processes

Both processes probe the same initial and final state wave functions

The transition operators "O" have a similar mathematical structure

The NUMEN project

NUclear
Matrix
Elements for
Neutrinoless
double beta decay

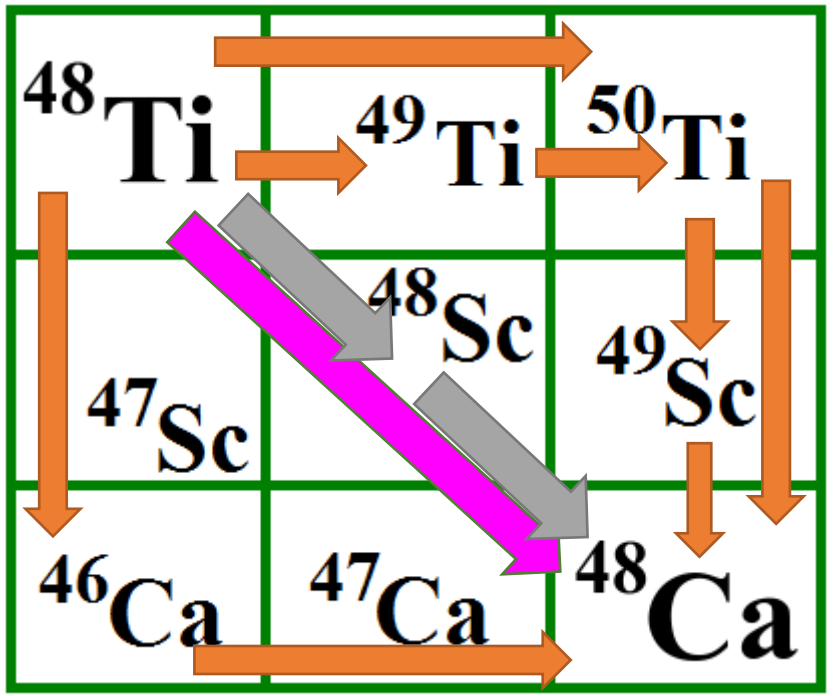
F. Cappuzzello et al., EPJA 54, 72 (2018)

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

Access information on the Nuclear Matrix Elements (NMEs) of the 0νββ decay through the study of the Double Charge Exchange (DCE) reactions induced by heavy ions.

<u>Transfer reactions:</u> 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.



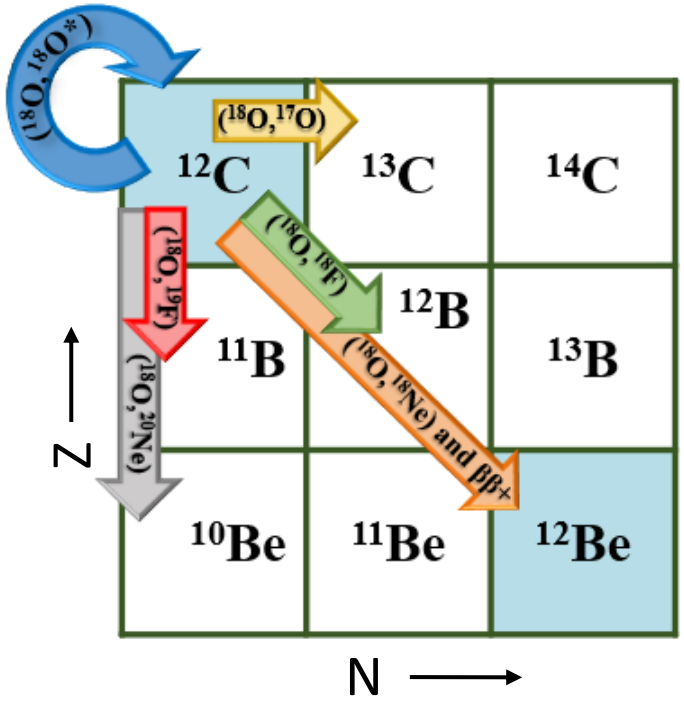
The multi-channel approach within the NUMEN project

Talk by
A. Spatafora

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

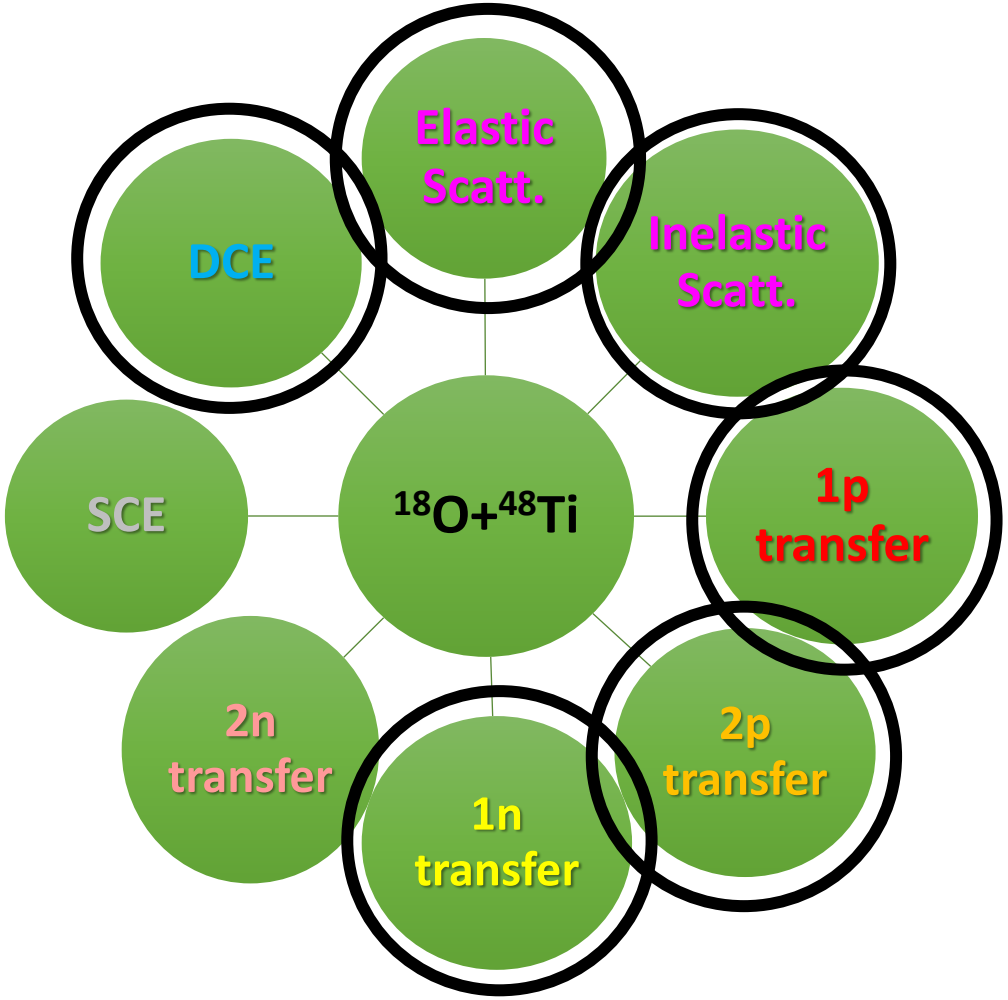


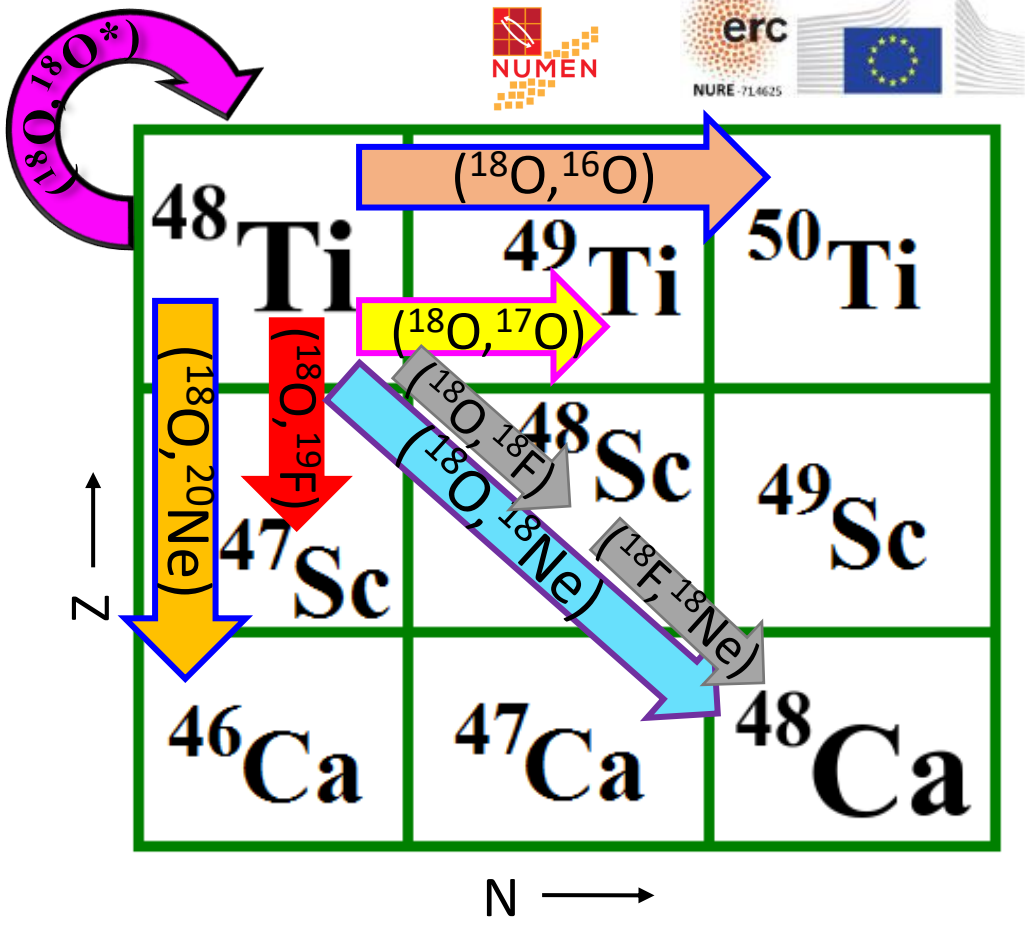
A. Spatafora et al., PRC 107, 024605 (2023)

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

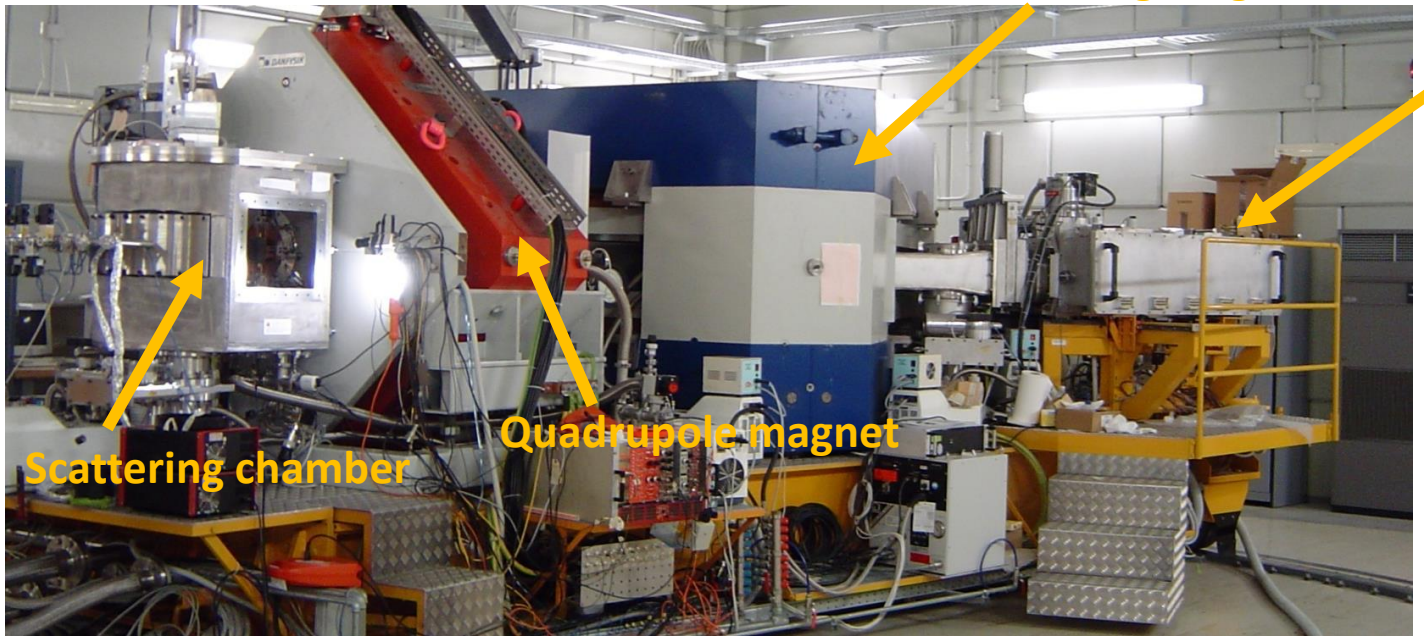
- Taking into consideration all the above, the study of the $^{18}O+^{48}Ti$ collision at the energy of 275 MeV was pursued by measuring the complete net of the available reaction channels as a part of NUMEN and NURE projects.

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





The MAGNEX large acceptance spectrometer



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

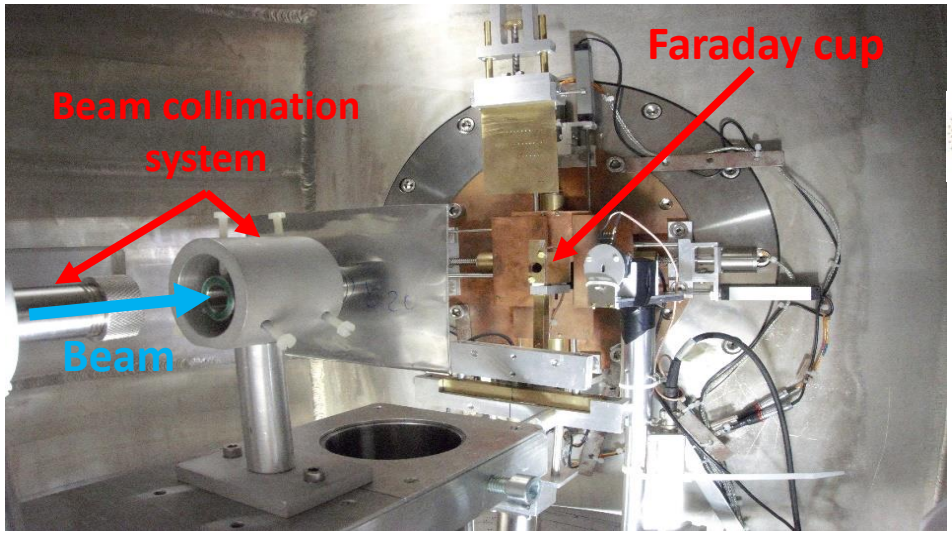
MAGNEX characteristics

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

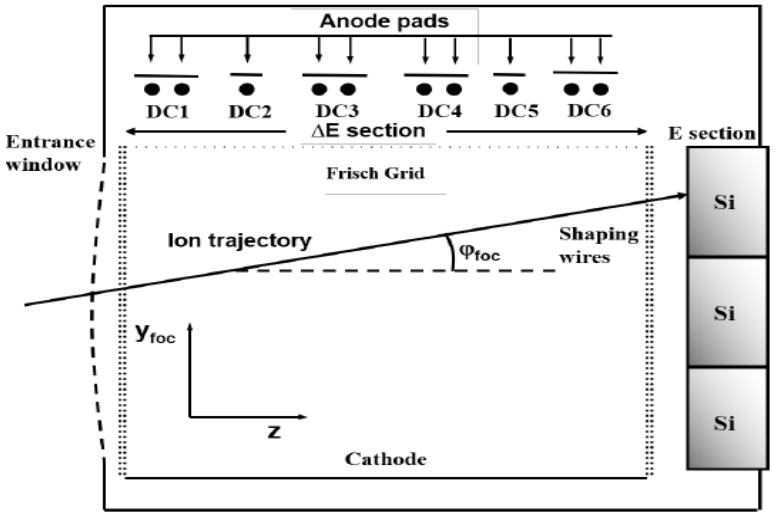
Achieved resolutions
Energy ΔE/E: 1/1000
Angular: 0.2°
Mass Δm/m: 1/300

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)

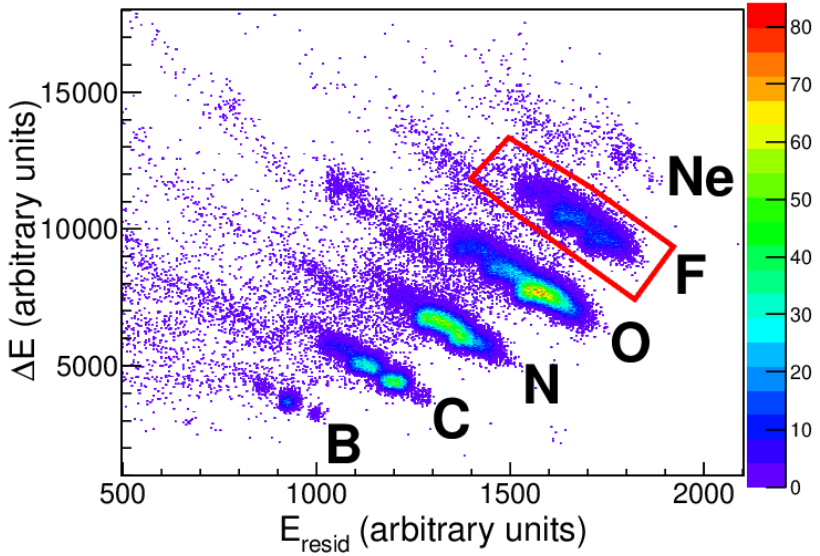
Focal Plane Detector

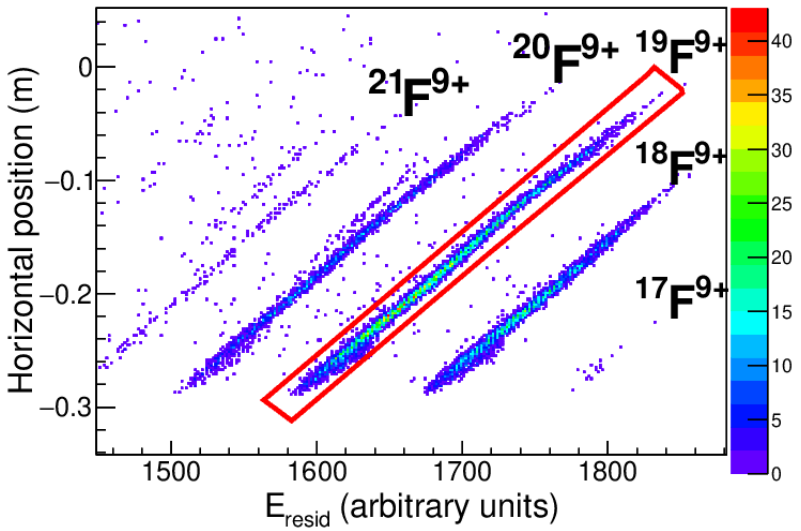
Ionization chamber → ➢Measure ions energy loss inside gas (ΔE)
➢Measure ions track X, Y coordinates

\+

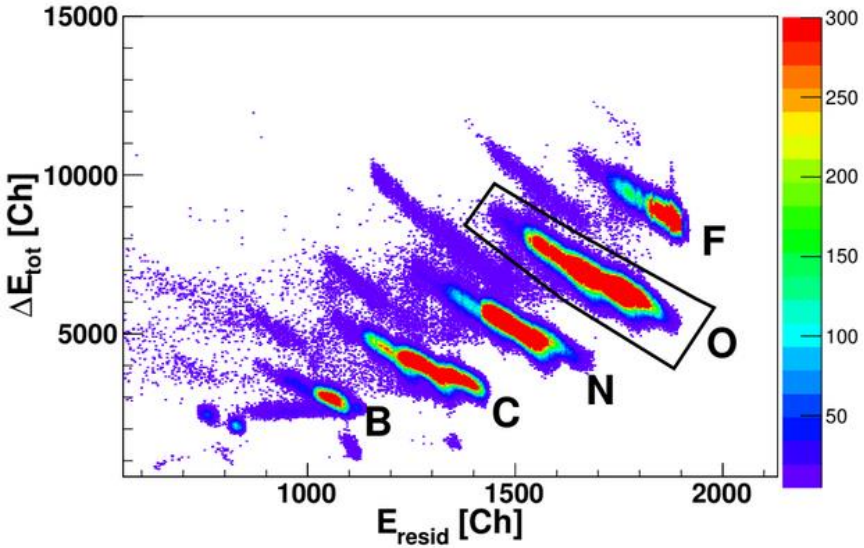
60 silicon detectors → ➢Measure ions residual energy (E_{resid})

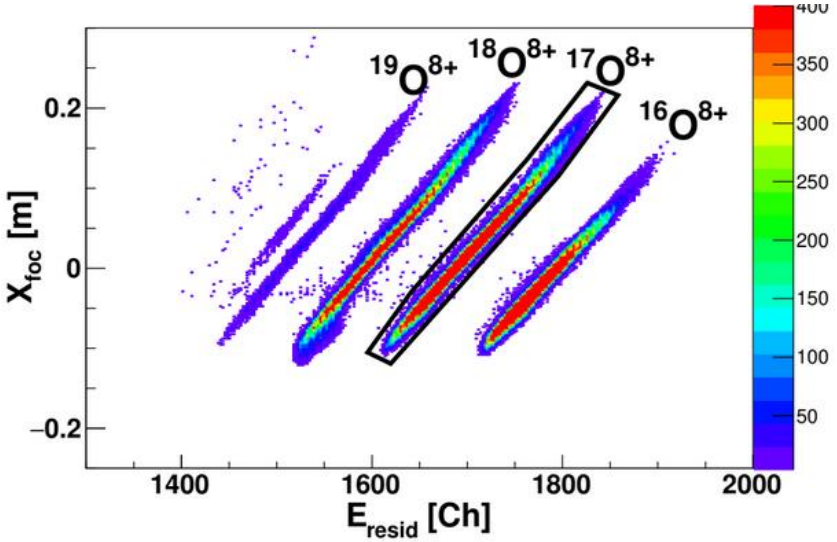
Examples of particle identification spectra





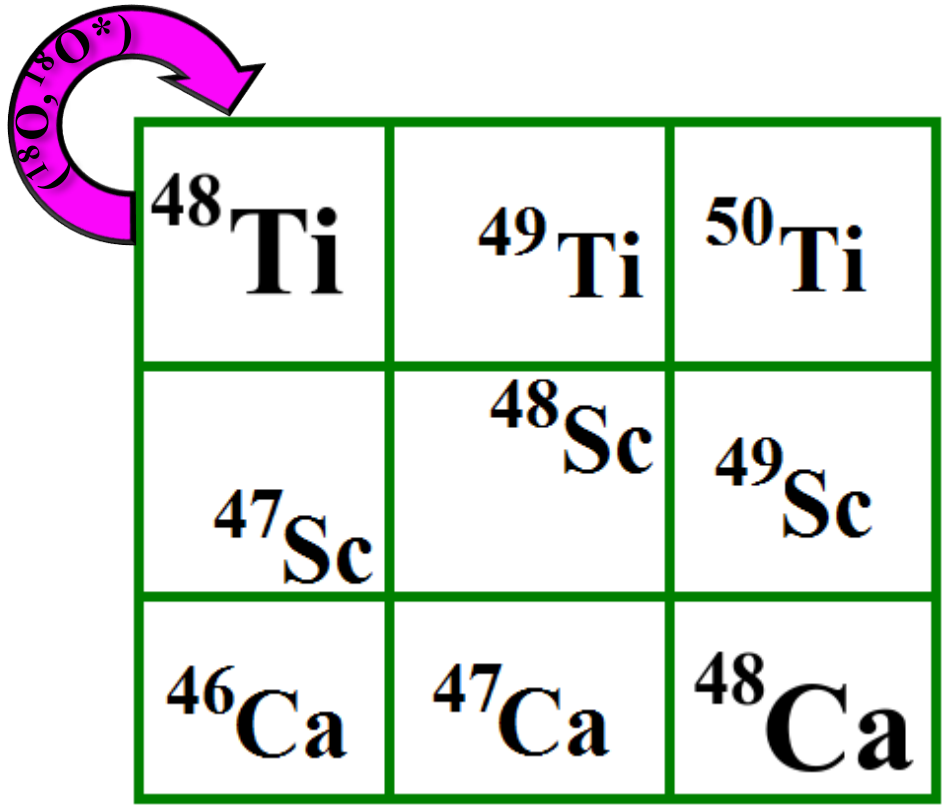
One-proton transfer channel
$^{48}Ti(^{18}O,^{19}F)^{47}Sc$



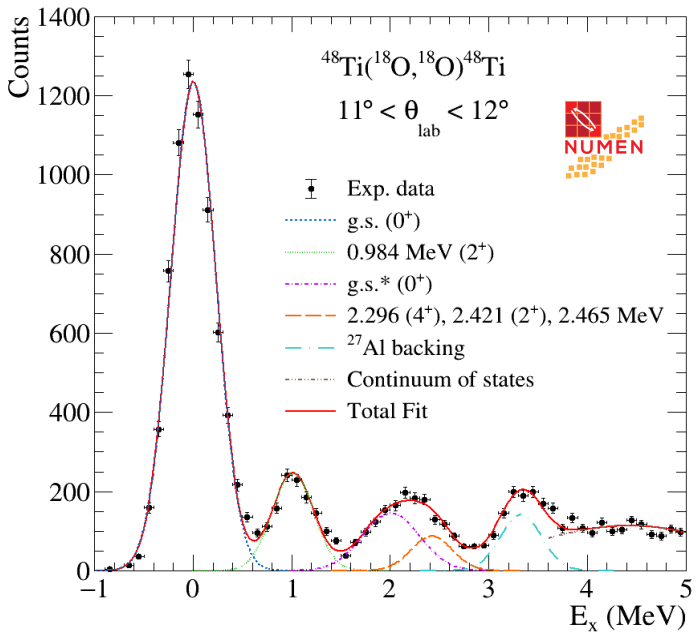


One-neutron transfer channel
$^{48}Ti(^{18}O,^{17}O)^{49}Ti$

Elastic and inelastic scattering channels



Elastic and inelastic scattering channels



Energy resolution ≈ 500 keV (FWHM)

G. A. Brischetto, PhD Thesis
UNICT 2023

G. A. Brischetto et al. (in preparation)

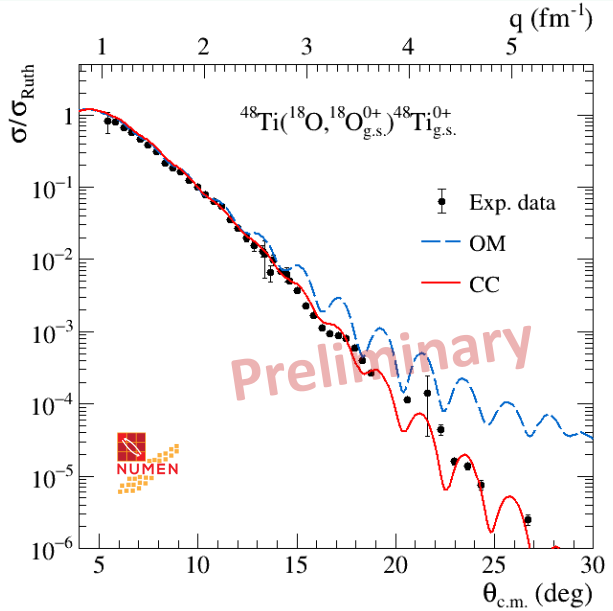
Optical Model

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

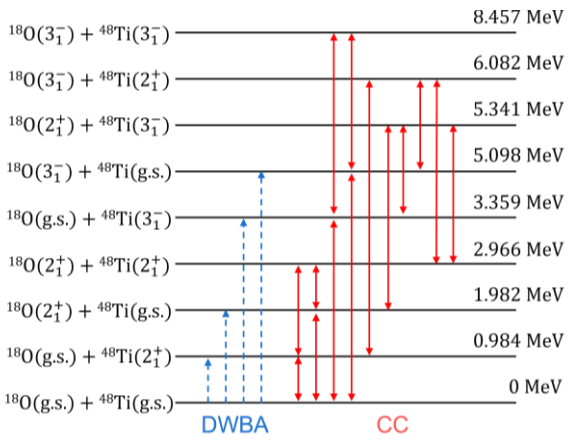
SPP: L. C. Chamon et al.,

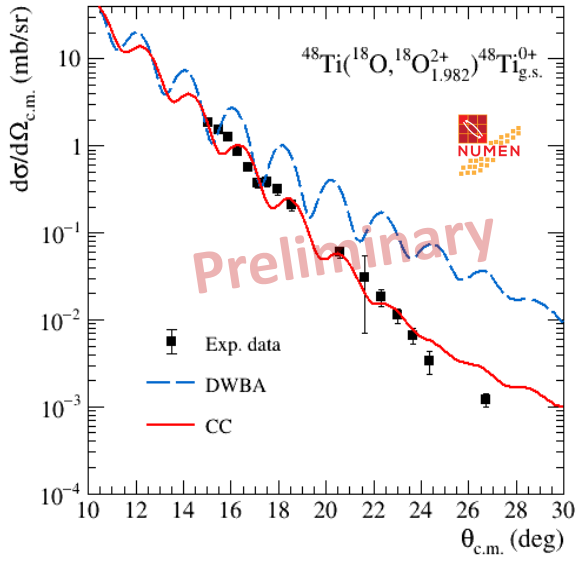
PRC 66 (2002) 014610

Calculation	N_R	N_I
OM/DWBA	1.0	0.78
CC	1.0	0.60

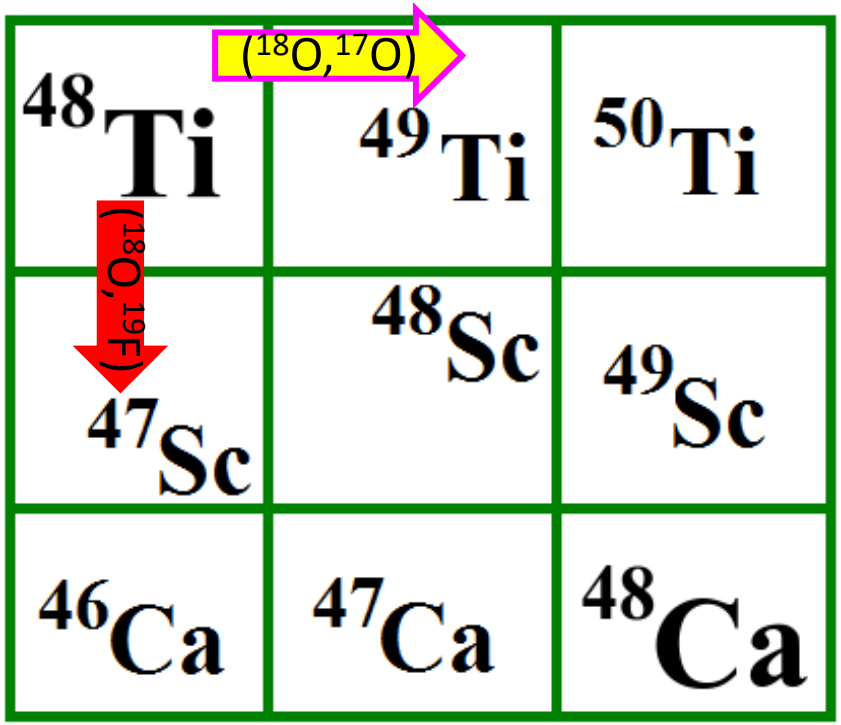


Coupling scheme

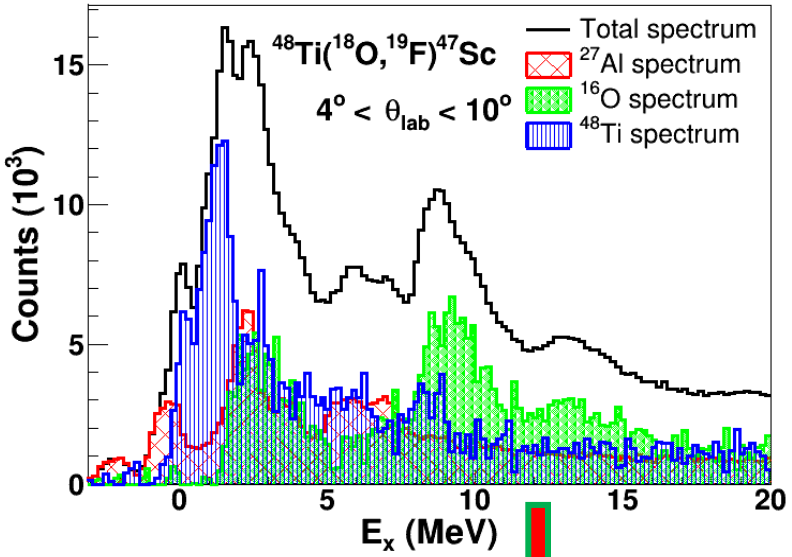


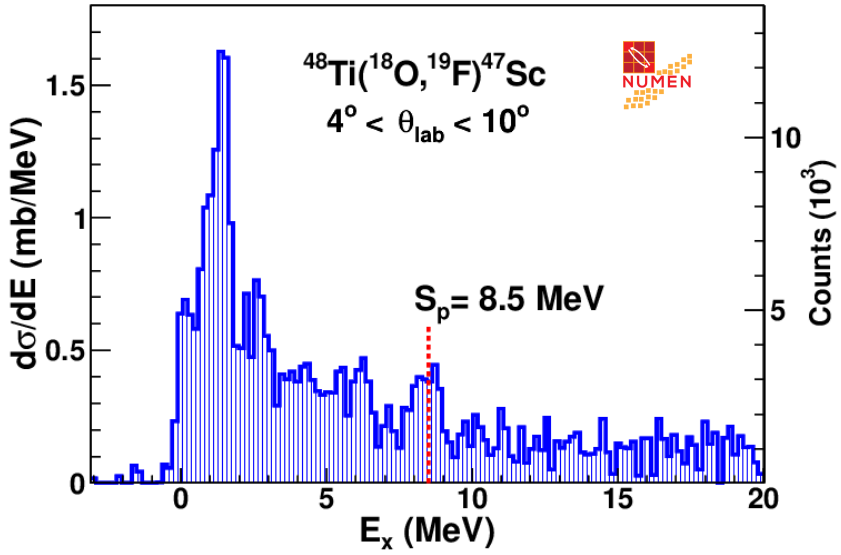


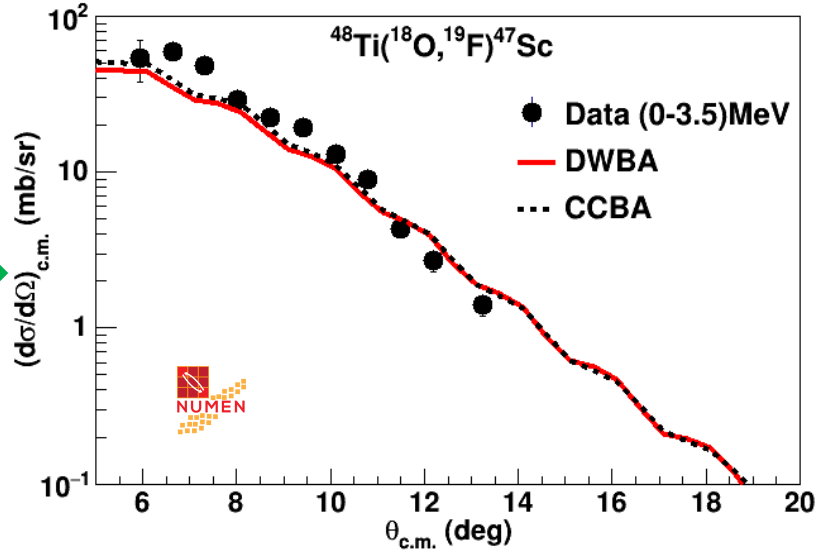
Single-nucleon transfer reactions



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





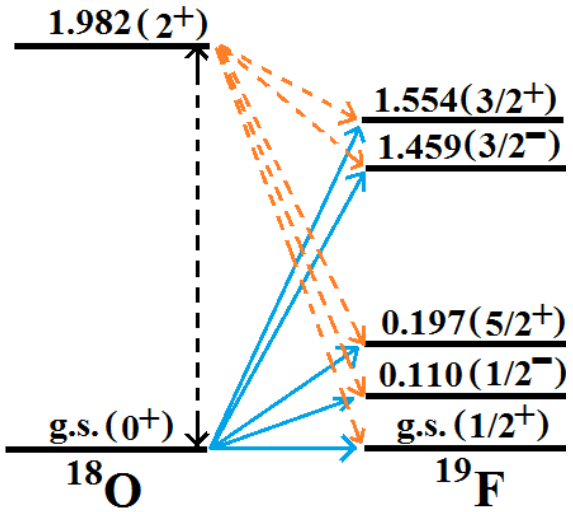


DWBA/CCBA ingredients

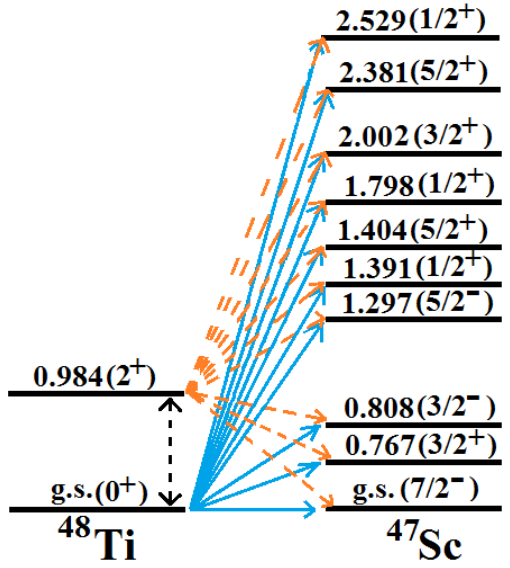
Overlaps	Interaction	Core	Nucleon orbitals
$<^{19}F\|^{18}O>$	P-SD-MOD	^{4}He	1p, 1d, 2s
$<^{47}Sc\|^{48}Ti>$	SDPF-MU	^{16}O	1d,2s,1f,2p

ISI: Constrained from the analysis of the elastic scattering!

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

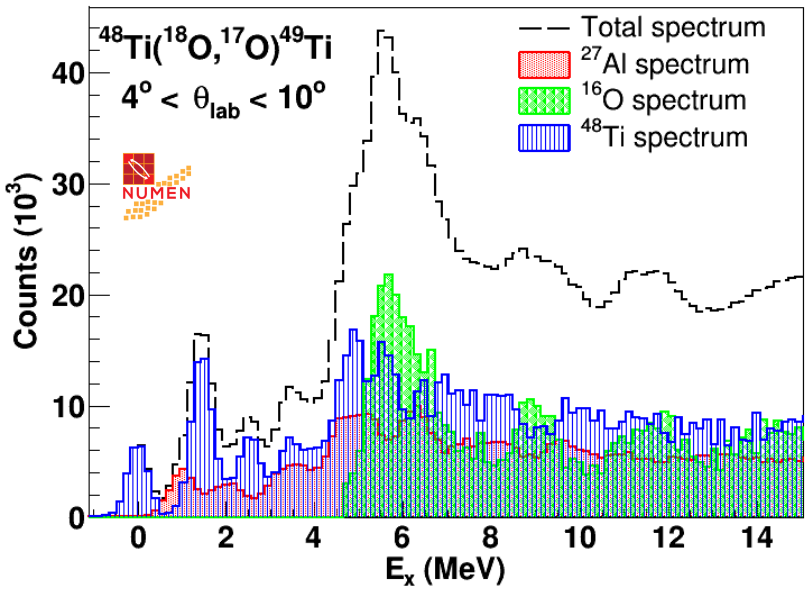


Projectile Overlaps



Target Overlaps

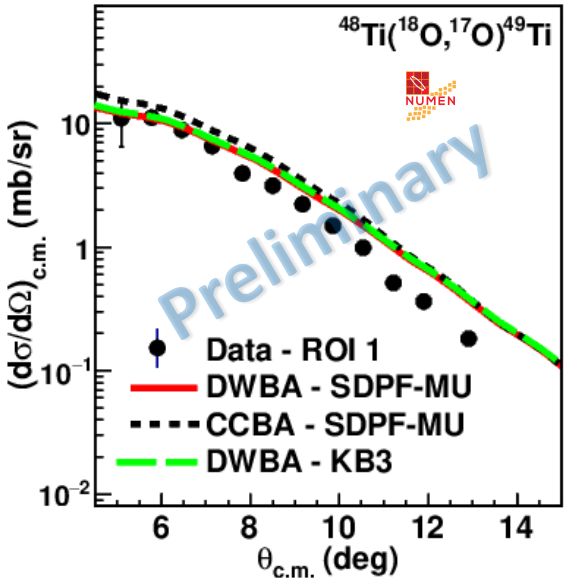
^{48}Ti(^{18}O,^{17}O)^{49}Ti reaction

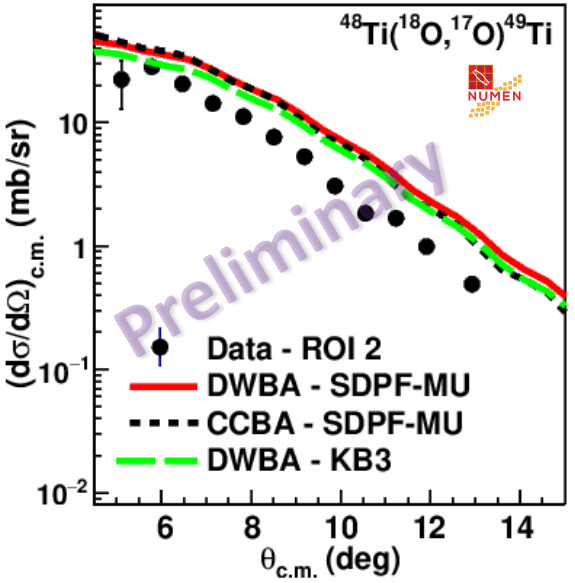


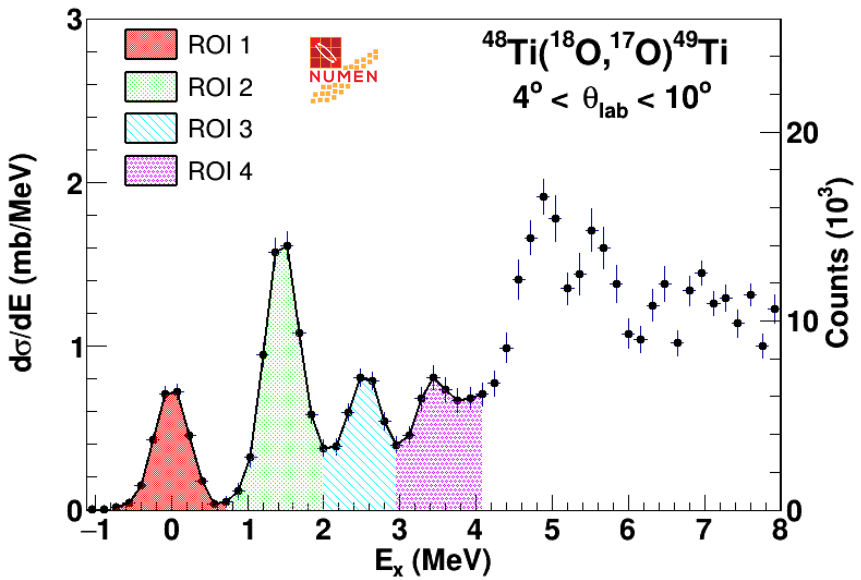
DWBA/CCBA ingredients

Overlaps	Interaction	Core	Nucleon orbitals
$<^{17}O\|^{18}O>$	P-SD-MOD	^{4}He	1p, 1d, 2s
$<^{49}Ti\|^{48}Ti>$	SDPF-MU	^{16}O	1d,2s,1f,2p
$<^{49}Ti\|^{48}Ti>$	KB3	^{40}Ca	1f,2p

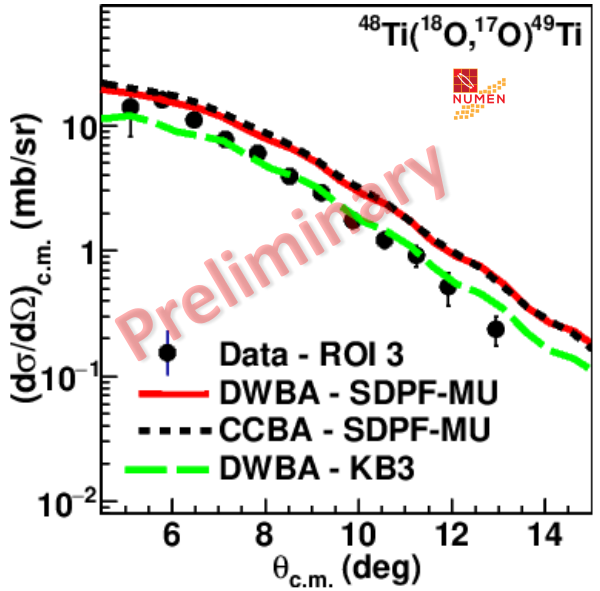
ISI: Constrained from the analysis of the elastic scattering!

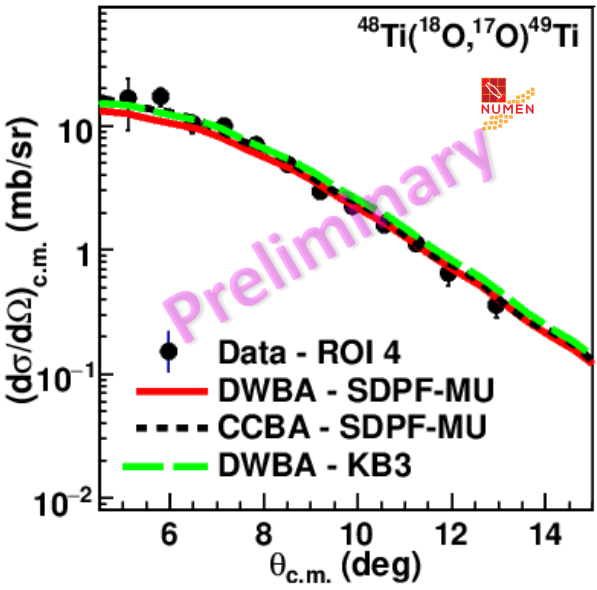




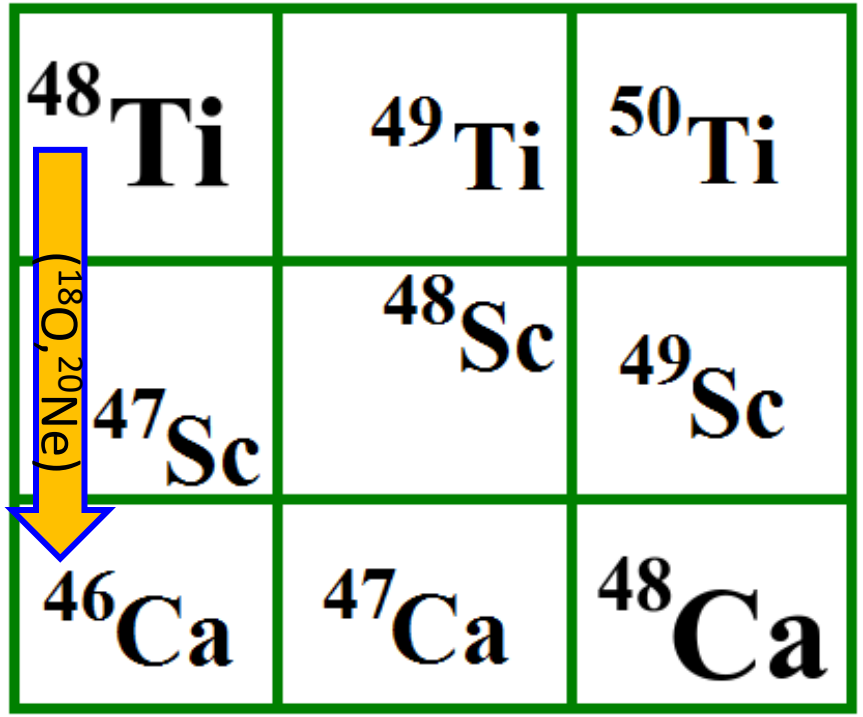


O. Sgouros et al. (in preparation)

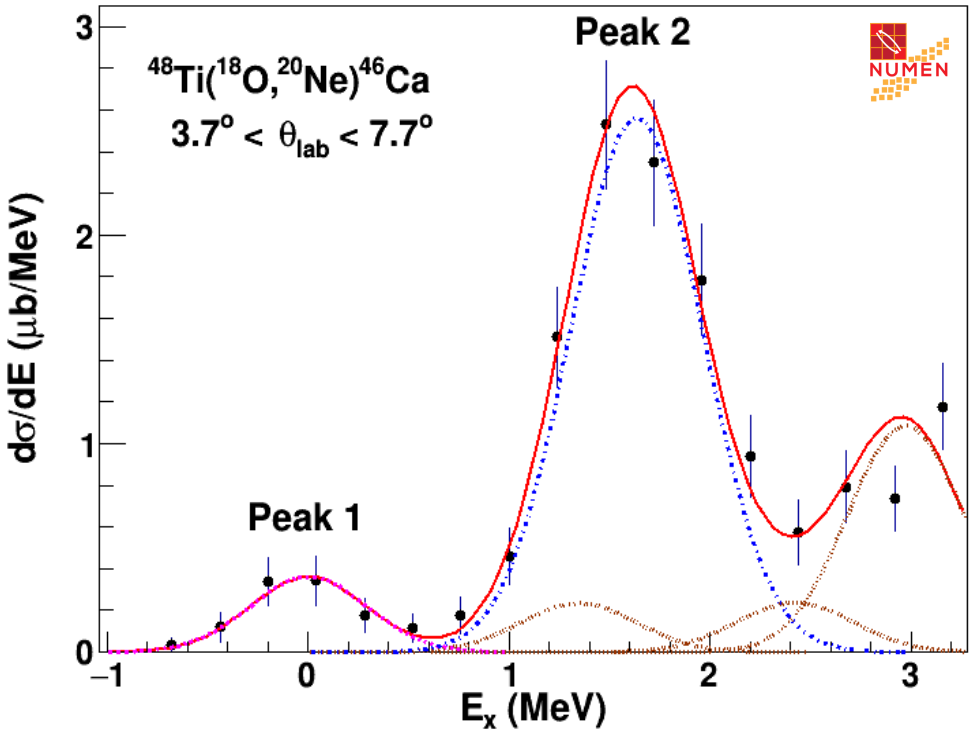




Two-proton transfer reaction



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



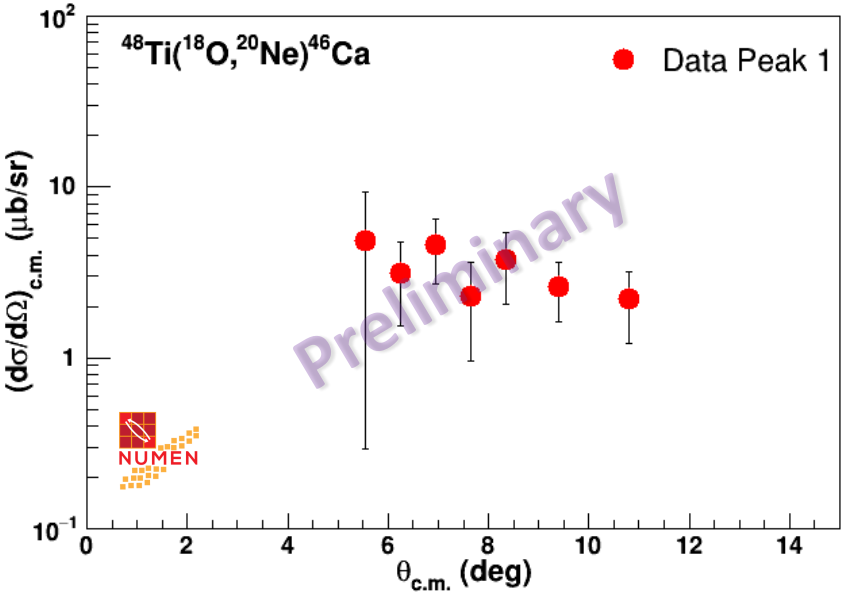
O. Sgouros, Il Nuovo Cimento 45C, 70 (2022)

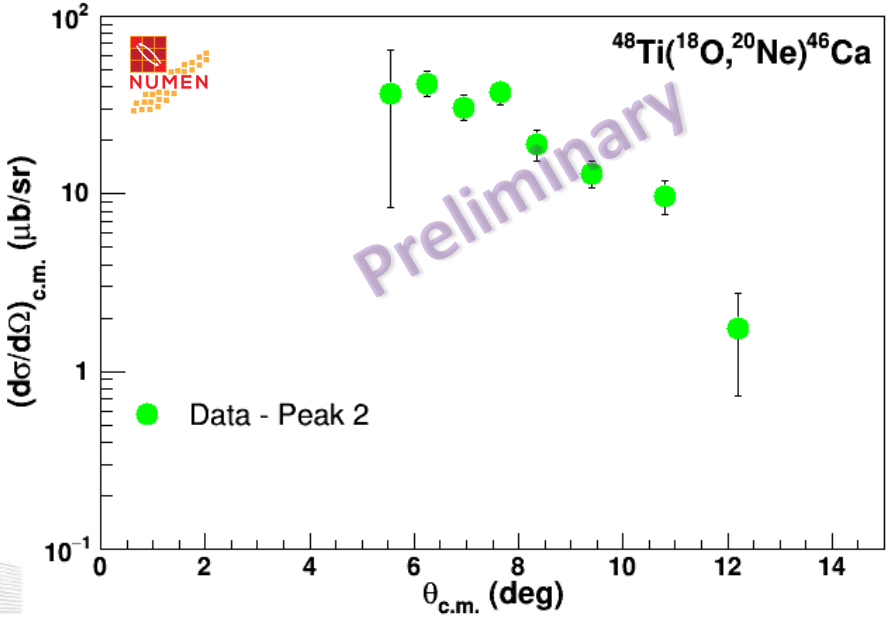
^{20}Ne states

Energy (MeV)	Spin (J^p)
0.0	0^+
1.634	2^+
4.247	4^+

^{46}Ca states

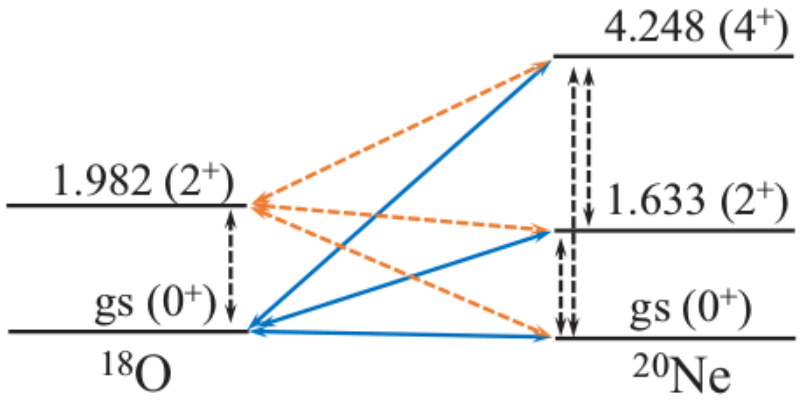
Energy (MeV)	Spin (J^p)
0.0	0^+
1.346	2^+
2.423	0^+
2.575	4^+
2.974	6^+



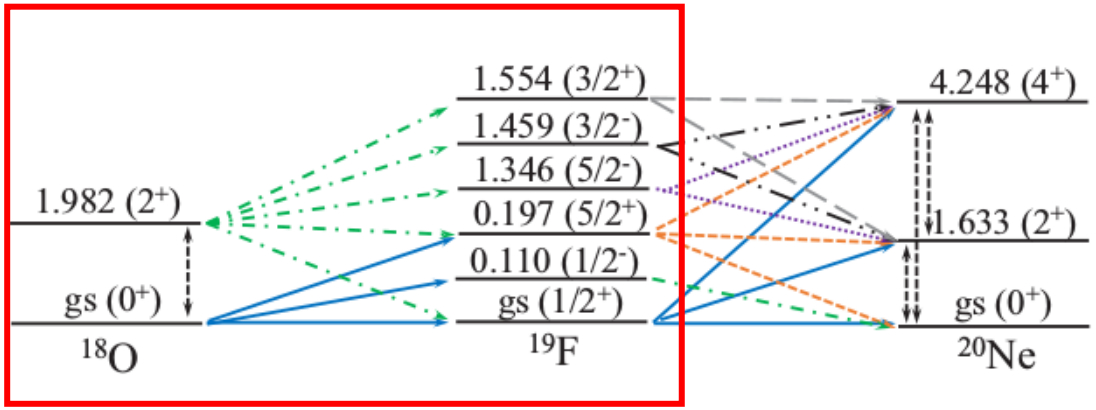


$^{48}Ti(^{18}O,^{20}Ne)^{46}Ca$ reaction – Theoretical interpretation

Projectile overlaps



Direct transfer of 2 protons

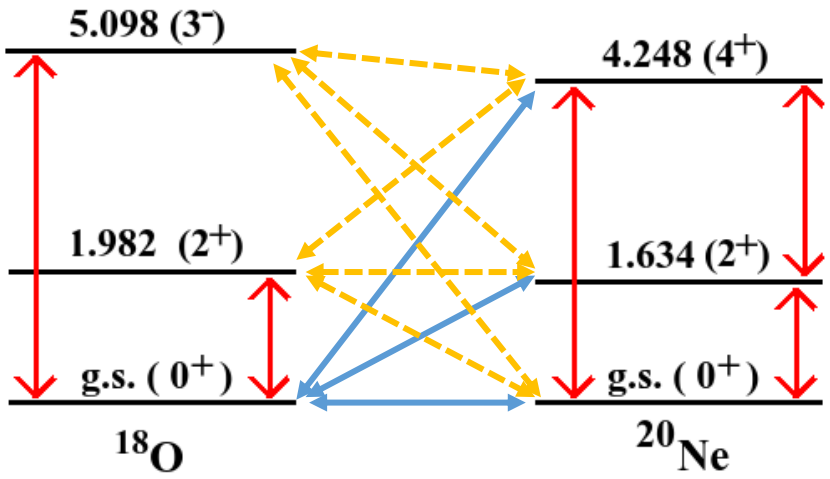


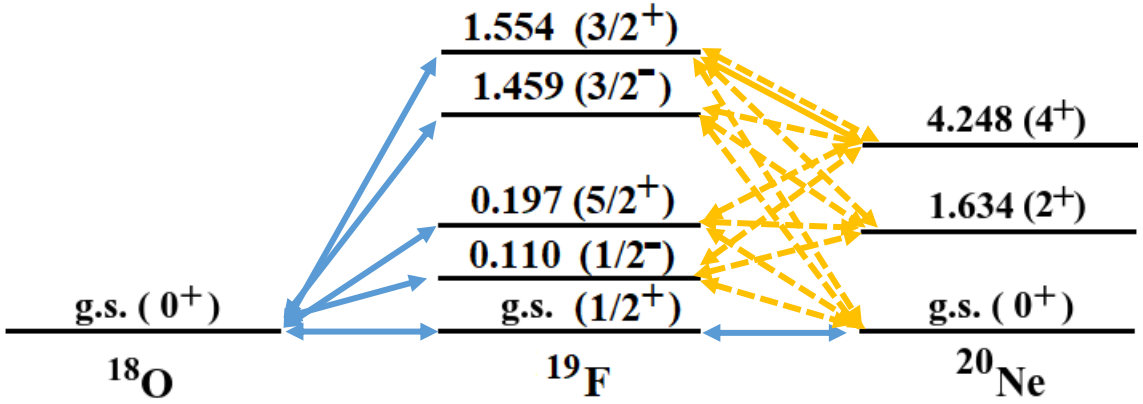
Sequential transfer of protons

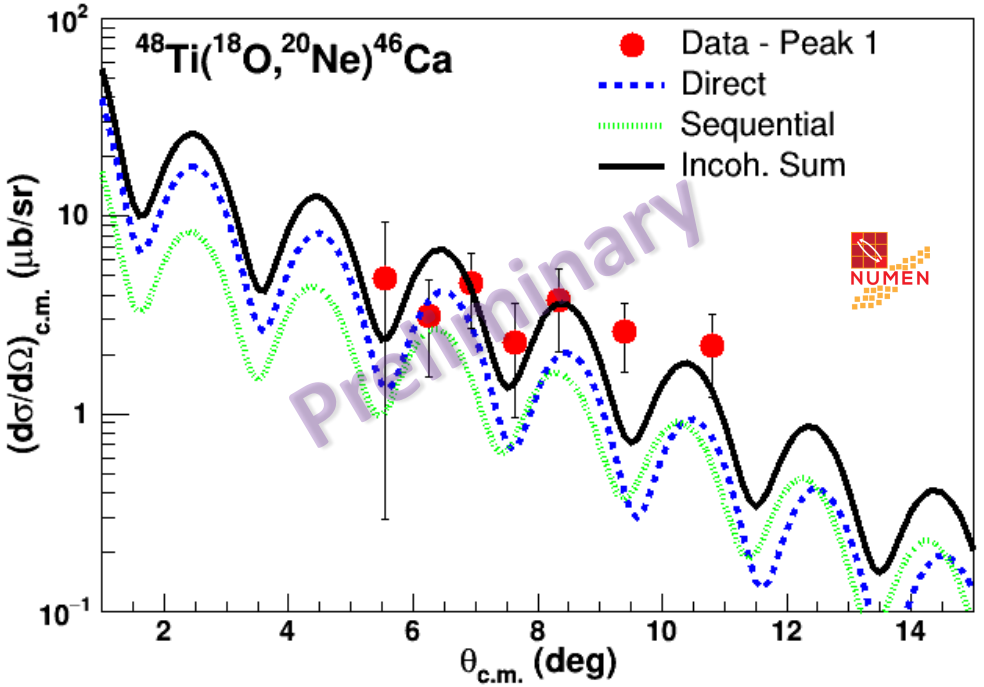
Experimentally constraint from the analysis of one-proton transfer reaction!!

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

Preliminary coupling scheme

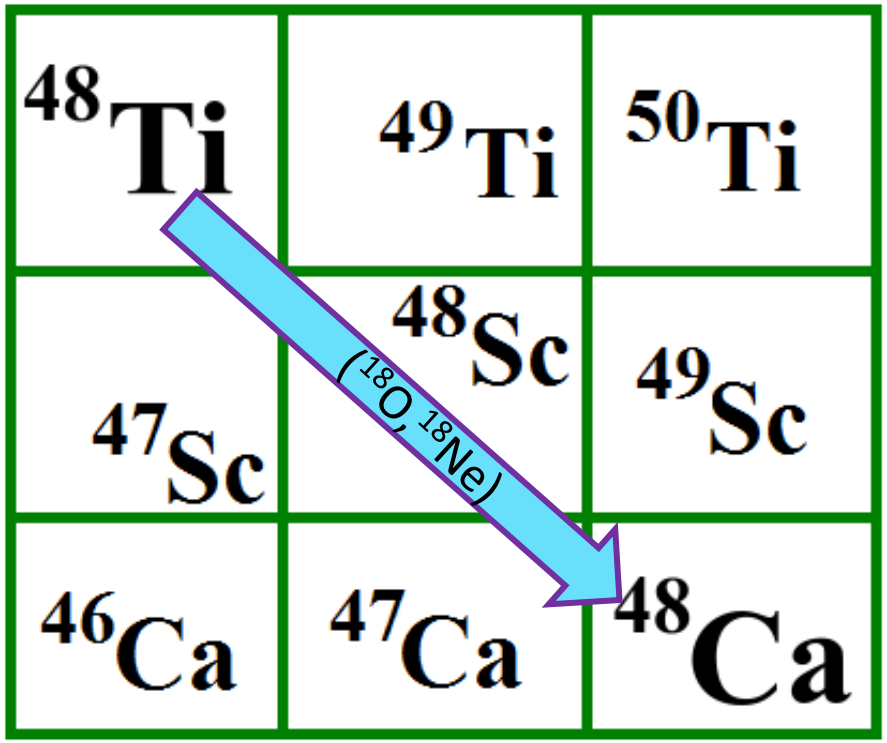




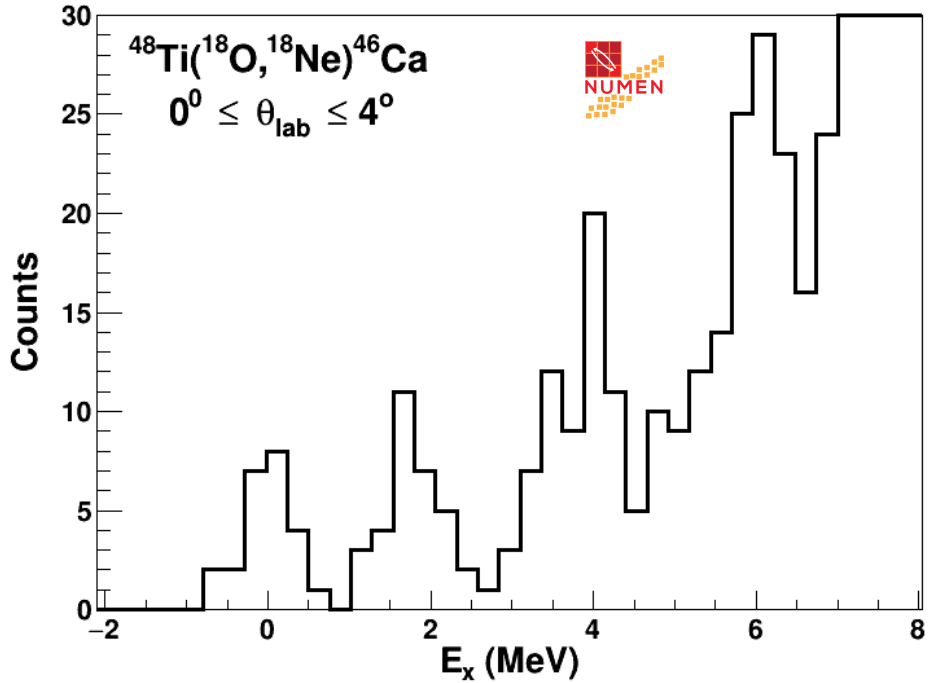


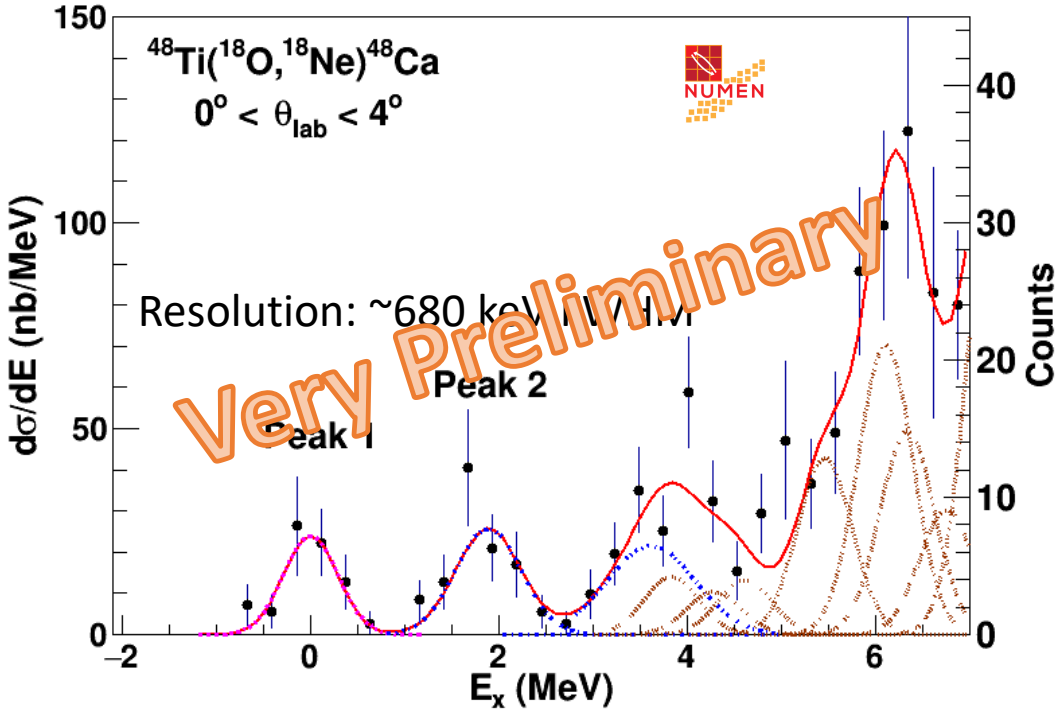
Calculations were performed according to the prescription reported in **PRC 103, 054604 (2021)** - J. L. Ferreira: Private communication

Double charge exchange reaction



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





^{18}Ne states

Energy (MeV)	Spin (J^p)
0.0	0^+
1.887	2^+
3.376	4^+

^{48}Ca states

Energy (MeV)	Spin (J^p)
0.0	0^+
3.832	2^+
4.284	0^+

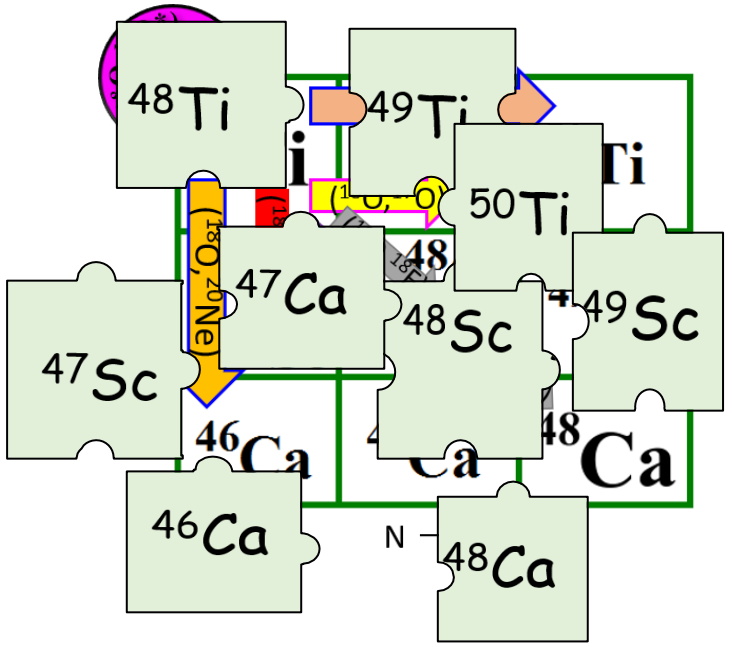
Peak label	Integrated yield (Counts)	Int. cross section (nb)
1	4	20 ± 4
2	32	28 ± 5

Very Preliminary

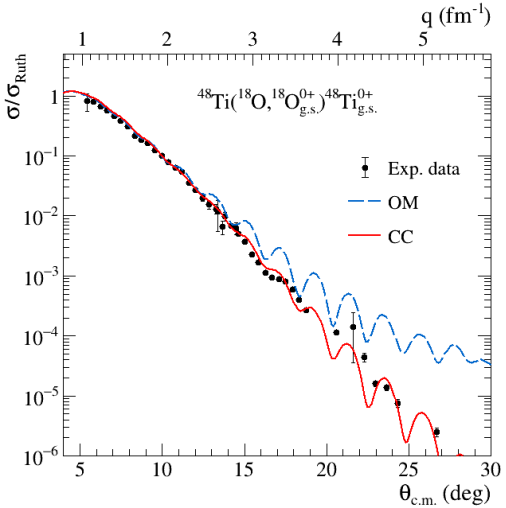
Summary - Conclusions

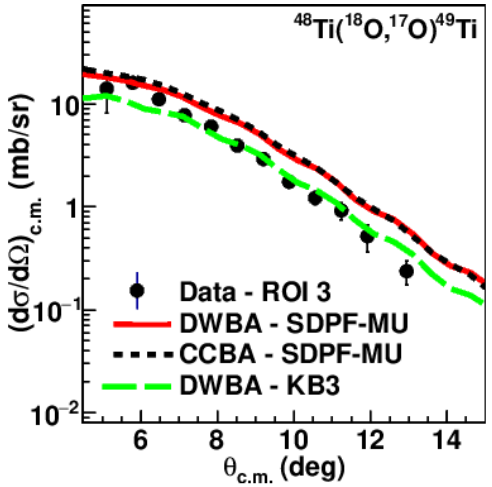
- NUMEN is an ambitious project aiming at accessing information on the NMEs of 0νββ decay through the study of heavy-ion induced double charge exchange reactions.

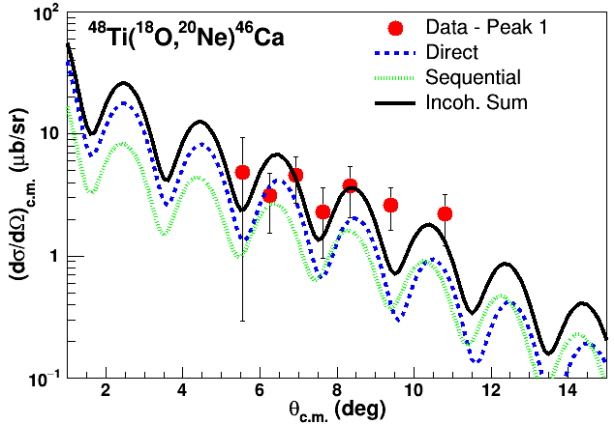
- A **multi-channel study** of the $^{18}O+^{48}Ti$ collision was performed by measuring the complete net of the available reaction channels:
  - ✓ Elastic Channel
  - ✓ Single-nucleon transfer
  - ✓ Two-proton transfer
  - ✓ Double charge exchange channel

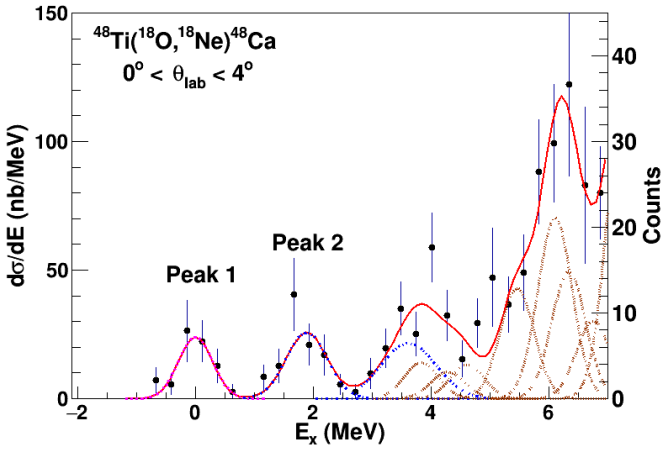


Next step: Completion of the analysis for the rest reaction channels and description of all data set under a unique coupled channels framework!





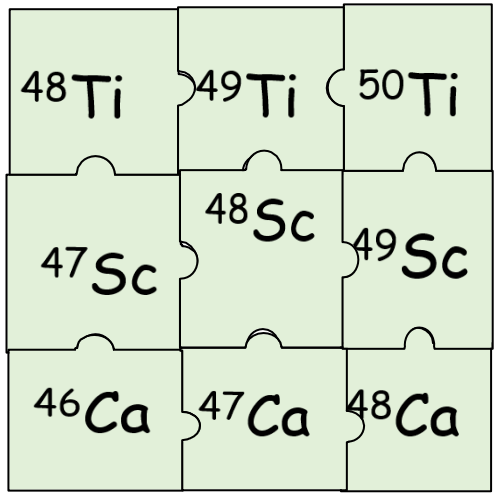




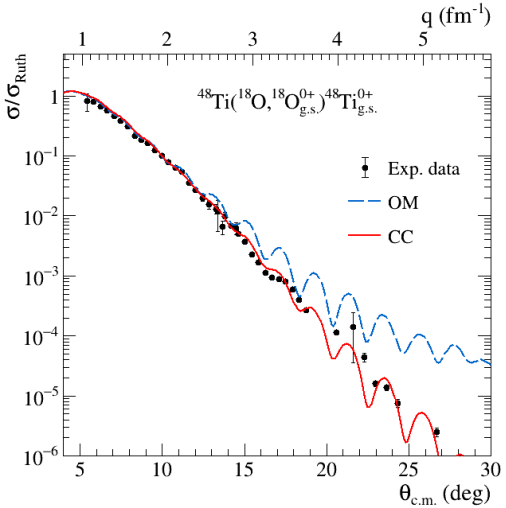
Summary - Conclusions

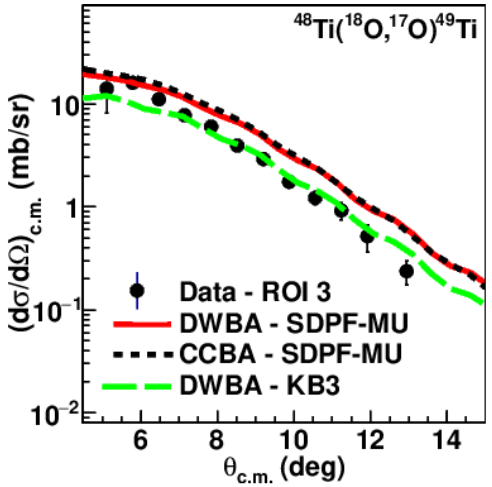
- NUMEN is an ambitious project aiming at accessing information on the NMEs of 0νββ decay through the study of heavy-ion induced double charge exchange reactions.

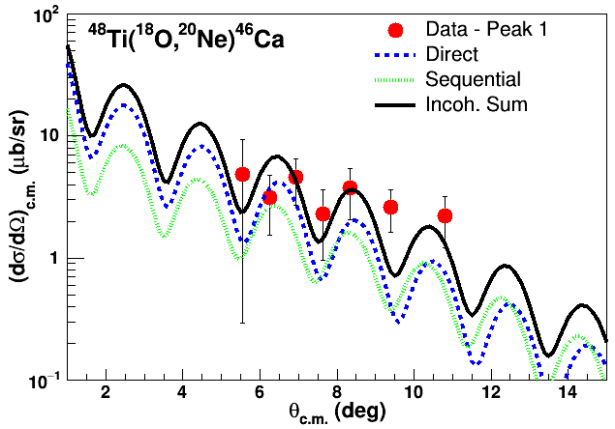
- A **multi-channel study** of the $^{18}O+^{48}Ti$ collision was performed by measuring the complete net of the available reaction channels:
  - ✓ Elastic Channel
  - ✓ Single-nucleon transfer
  - ✓ Two-proton transfer
  - ✓ Double charge exchange channel

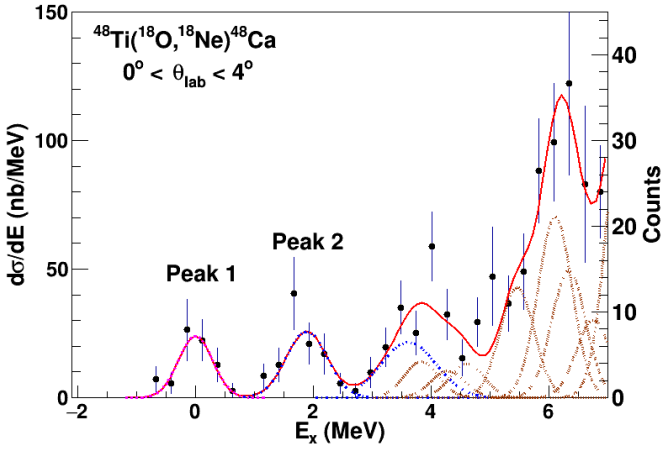


Next step: Completion of the analysis for the rest reaction channels and description of all data set under a unique coupled channels framework!









Thank you for your attention