Study of the one-proton transfer reaction in the $^{18}O + ^{48}Ti$ collision at 275 MeV

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for the NUMEN collaboration

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Outline

- Introduction
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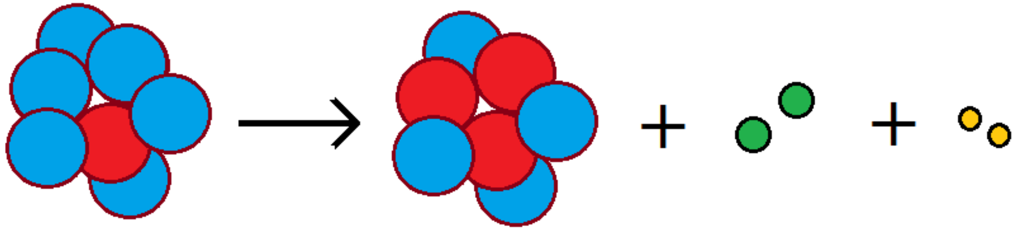
  - The NUMEN project
- Experimental Setup - The MAGNEX facility
- Particle Identification
- Data reduction
  - $^{27}Al(^{18}O,^{19}F)^{26}Mg$ reaction
  - $^{16}O(^{18}O,^{19}F)^{15}N$ reaction
  - $^{48}Ti(^{18}O,^{19}F)^{47}Sc$ reaction
- Data Interpretation ⟶ Distorted-Wave and Coupled-Channels Born Approximation
- Conclusions

Double beta decay

Two-neutrino double beta decay

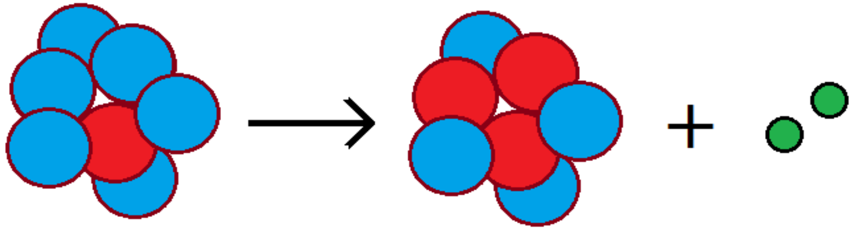
$${}^{A}_{Z}X_{N} \longrightarrow {}^{A}_{Z+2}Y_{N+2} + 2e^{+} + 2\overline{\nu}_{e}$$



- Predicted by the Standard model
- Experimentally observed for 11 nuclei with $T_{1/2}$ ranging between (10^{18}-10^{24}) yr

Neutrino-less double beta (0νββ) decay

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



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

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

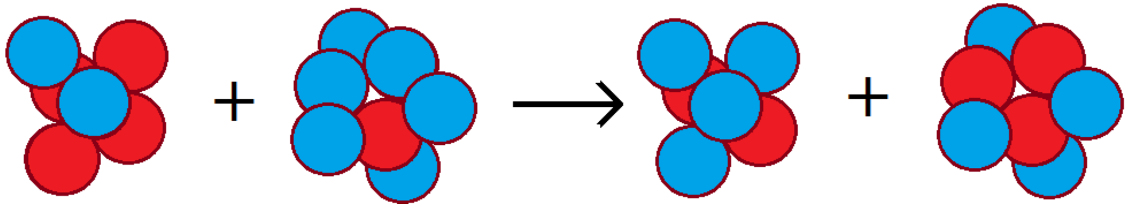
Accessible through experiment

Nuclear Matrix Elements (NMEs)

Double charge exchange reactions and 0νββ decay

DCE reaction

$$ {}^{A_1}_{Z_1}C_{N_1} + {}^{A}_{Z}X_{N} \longrightarrow {}^{A_1}_{Z_1-2}D_{N_1+2} + {}^{A}_{Z+2}Y_{N-2} $$

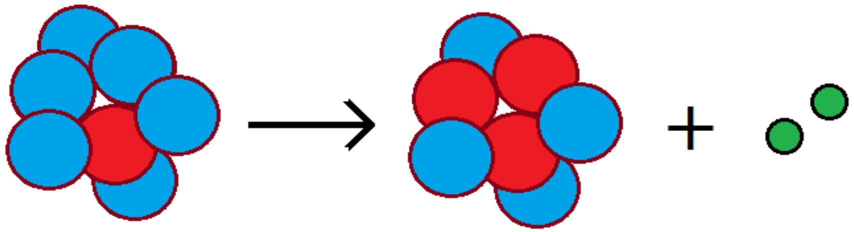


DCE reactions are mediated by the strong Interaction

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

0νββ decay

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



0νββ decay is mediated by the weak interaction

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

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 DCE may provide an important piece of information on 0νββ decay NMEs

The NUMEN project

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

NUMEN experimental campaign aims at accessing information on the Nuclear Matrix Elements (NMEs) of the neutrino-less double beta (0νββ) decay through the study of the Double Charge Exchange (DCE) reactions induced by heavy ions.

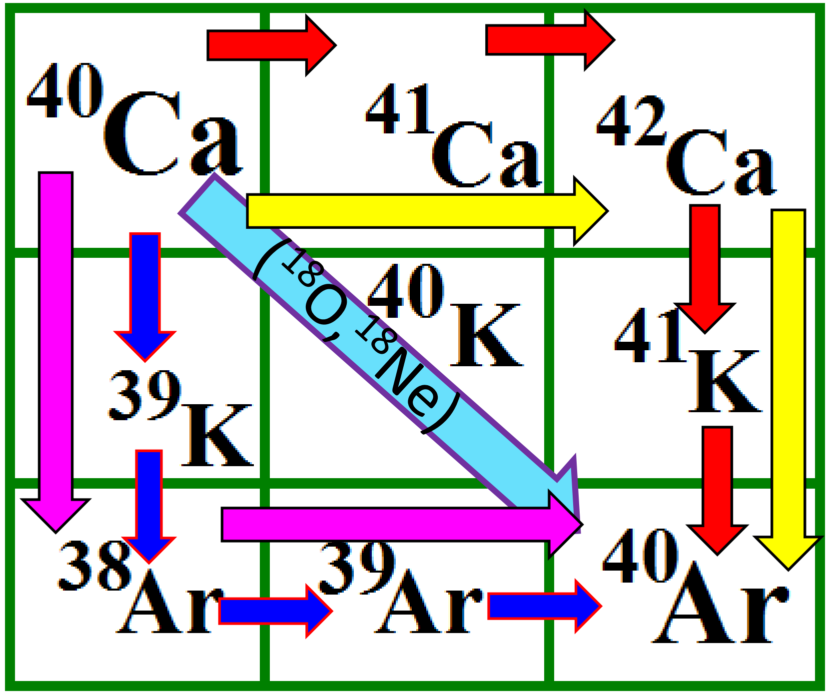
$$\frac{d\sigma^{DCE}}{d\Omega} \propto \left|T^{DCE}\right|^2 = \left|\left\langle \chi_\beta \phi_b \phi_B \left|\hat{O}\right| \phi_a \phi_A \chi_\alpha \right\rangle\right|^2$$

The complete description of the reaction dynamics and nuclear structure of the involved nuclei is imperative.

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

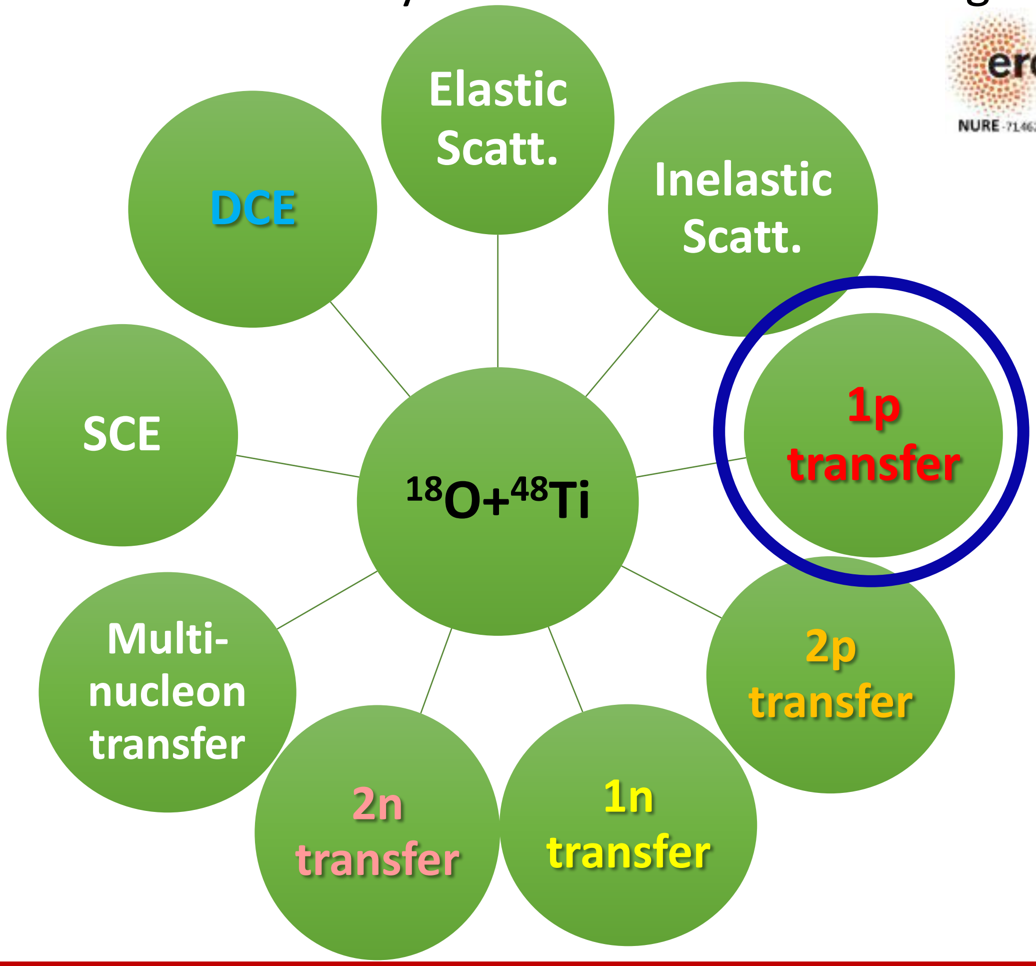
- Feasibility test: The $^{40}Ca(^{18}O,^{18}Ne)^{40}Ar$ reaction

F. Cappuzzello et al., EPJA 51, 145 (2015)

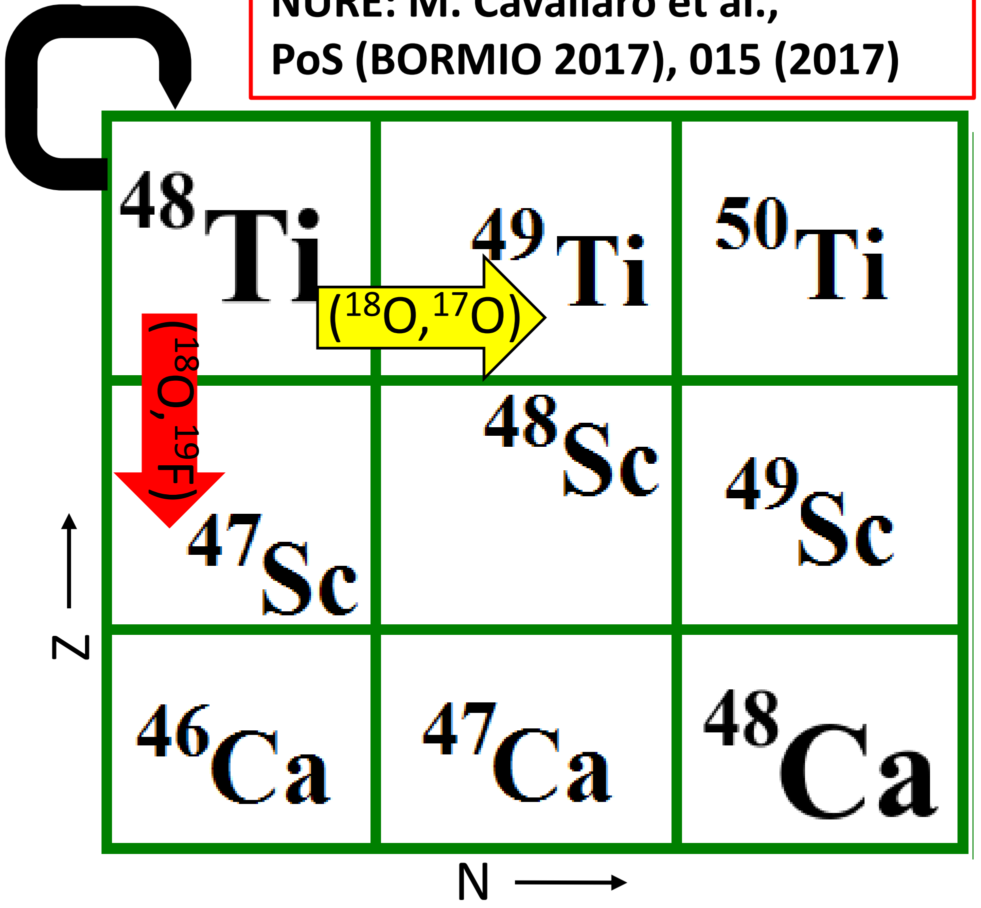


Study of the $^{18}O+^{48}Ti$ reaction @ 275 MeV

- Taking into consideration all the above, the study of the $^{18}O+^{48}Ti$ reaction at the energy of 275 MeV was persued by measuring the complete net of the available reaction channels as a part of NUMEN and NURE projects.
- Transfer reactions provide the ground for testing the nuclear structure models and validate the Optical Potential suggested from the analysis of the elastic scattering.



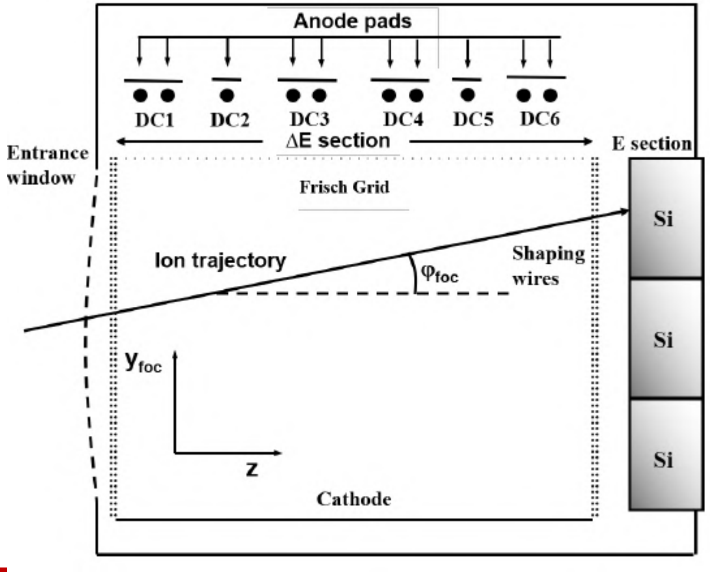
NURE: M. Cavallaro et al., PoS (BORMIO 2017), 015 (2017)



Experimental Setup – The MAGNEX facility

A photo of the MAGNEX facility

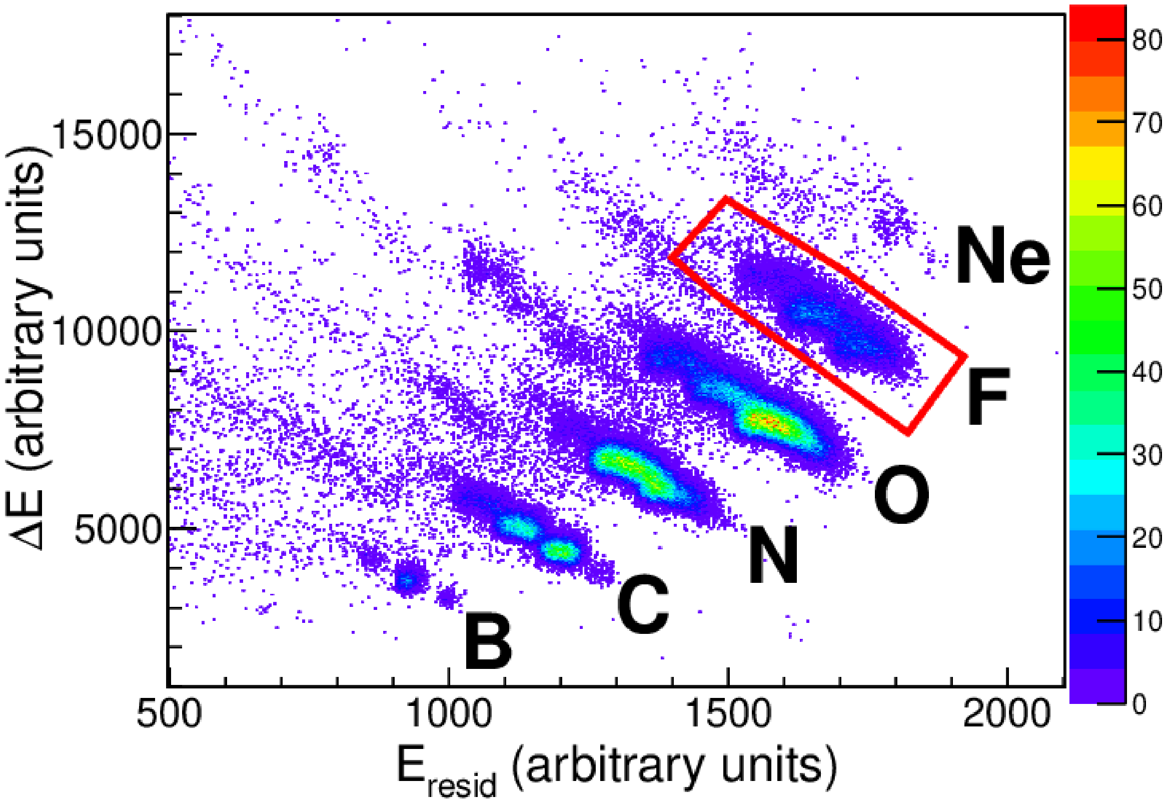
- Beam: $^{18}O^{8+}$ accelerated by SC cyclotron at 275 MeV.
- Target: TiO_2 evaporated onto a thin ^{27}Al foil.
- Background estimation: 2 additional runs with a WO_3 and an ^{27}Al target.
- Detection system: The reaction ejectiles were detected by the MAGNEX Focal Plane Detector (FPD).

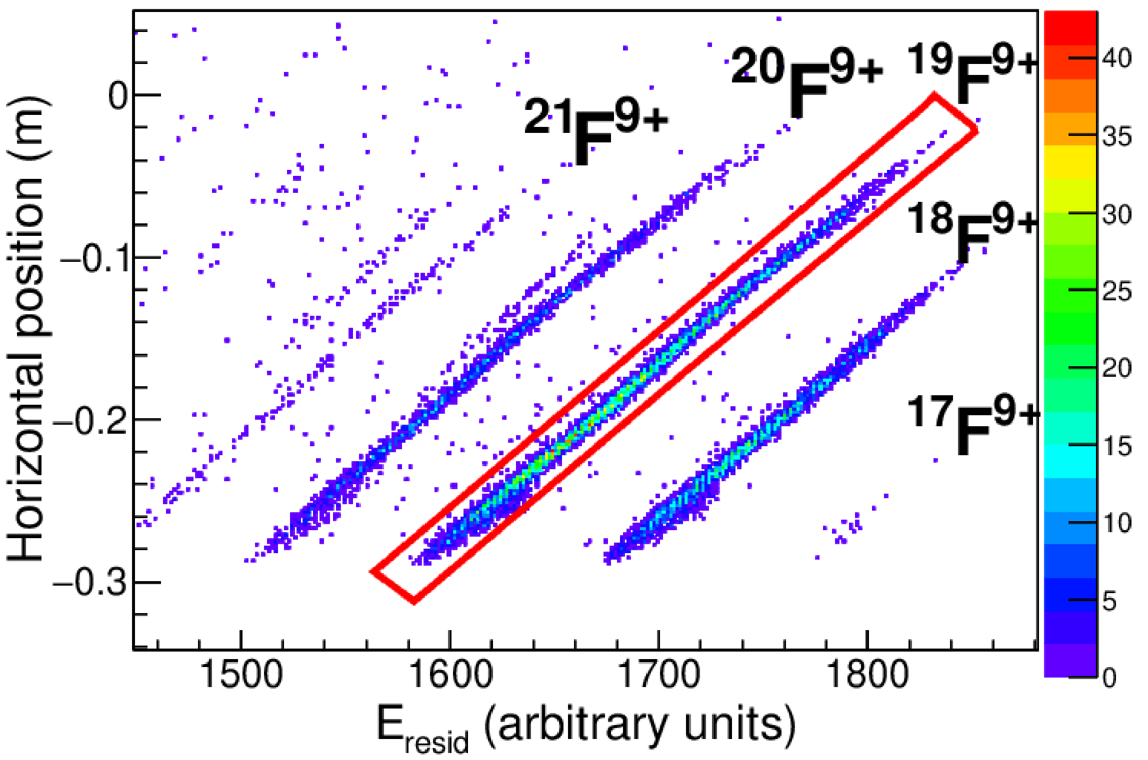


Lateral view of the MAGNEX FPD
D. Torresi et al., NIM A 989, 164918 (2021)

Talks of
Manuela Cavallaro
Francesco Cappuzzello
Vasilis Soukeras
Stergios Koulouris

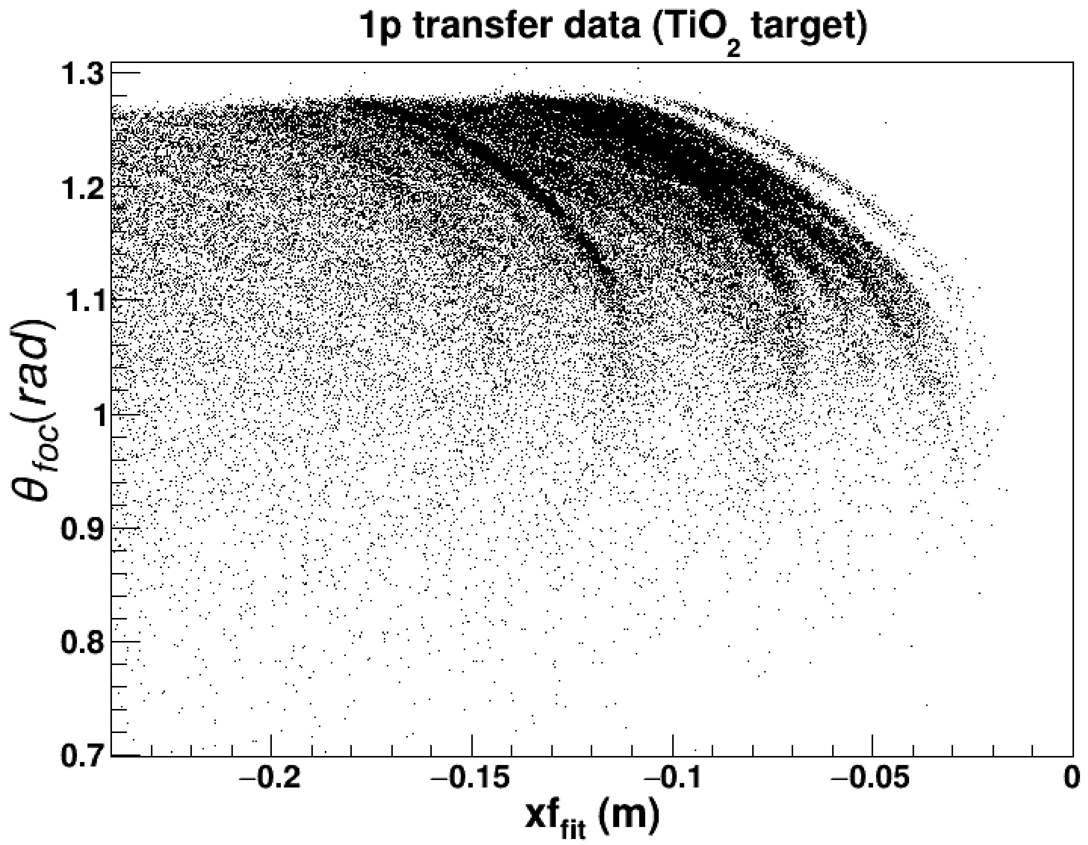
Identification of ^{19}F ejectiles

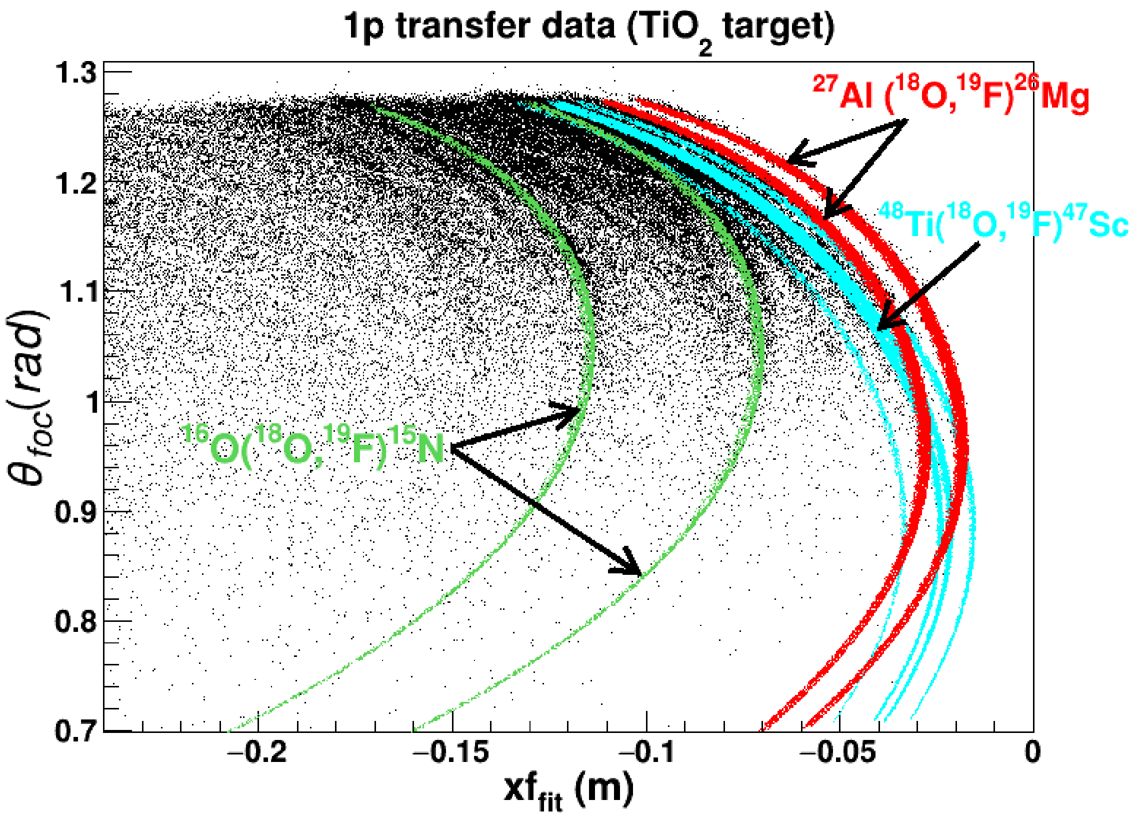




The particle identification was performed following the prescription reported in Nucl. Instrum. Meth. A 621, 419 (2010)

Background identification





Background events due to the presence of ^{27}Al and **oxygen** in the target were identified in the spectra.

Kinematic simulations were performed with COSY INFINITY code using a realistic description of magnetic fields and MAGNEX geometry.

Strategy of the data analysis

- Step 1: Analysis of the 1p-transfer data obtained with ^{27}Al target.

$^{27}Al(^{18}O,^{19}F)^{26}Mg$

- Step 2: Analysis of the 1p-transfer data obtained with (WO_3 + ^{27}Al) target.

$^{16}O(^{18}O,^{19}F)^{15}N$

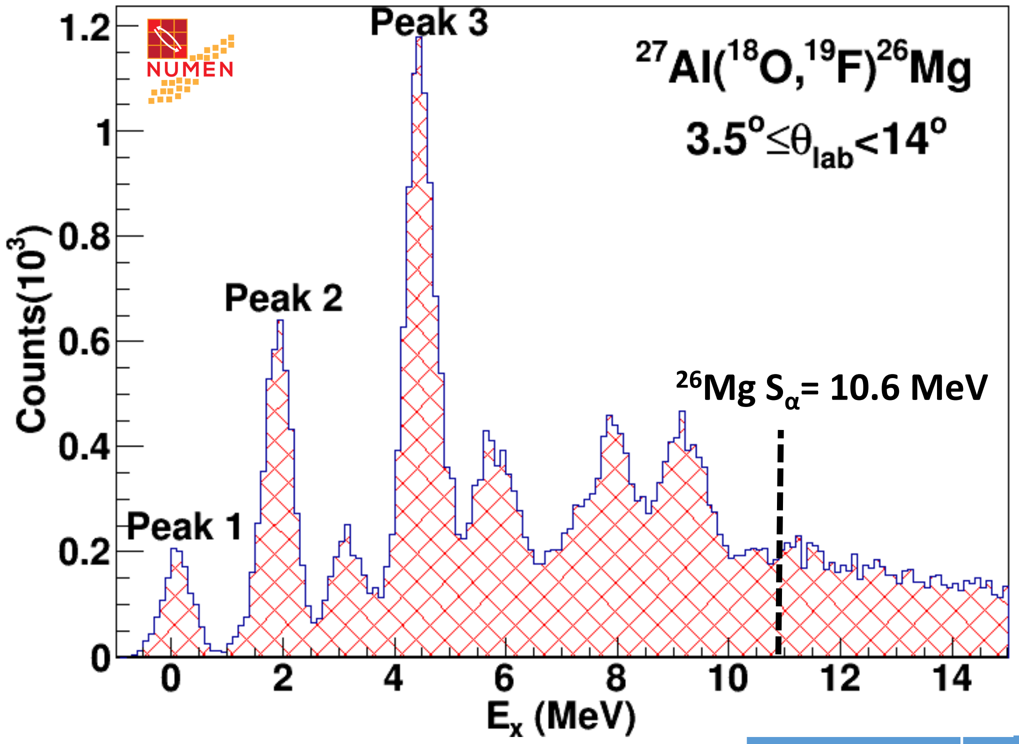
Determination of the excitation energy spectrum corresponding to the reaction on oxygen, after subtracting the contribution due to the presence of ^{27}Al in the target.

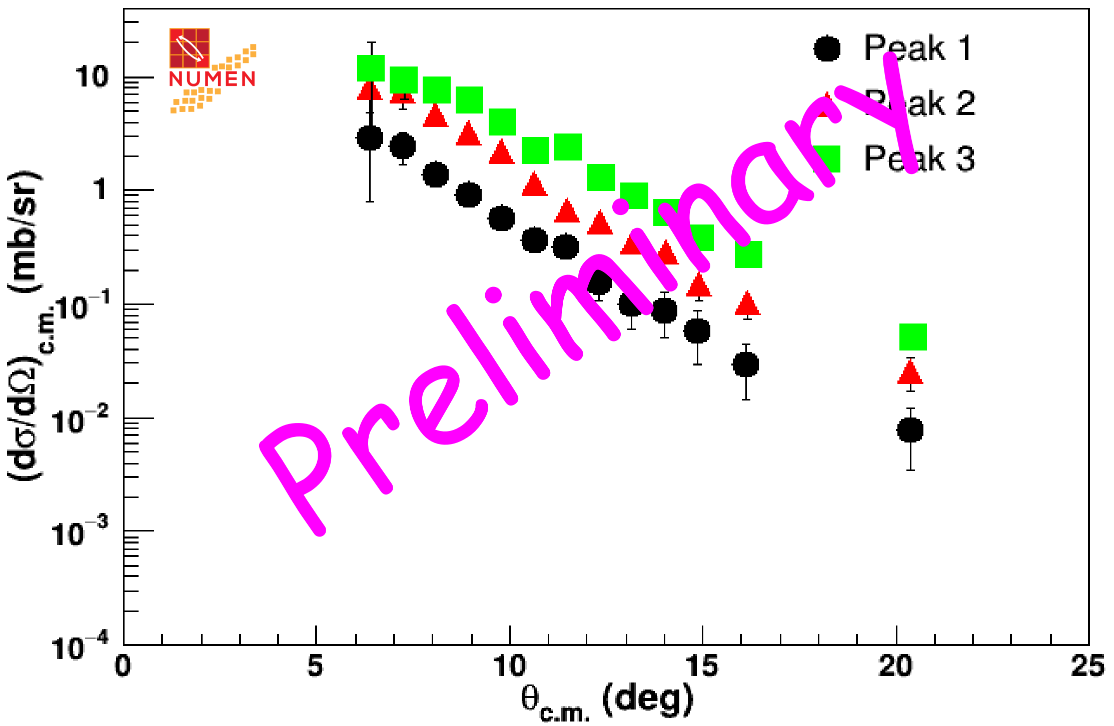
- Step 3: Analysis of the 1p-transfer data obtained with (TiO_2 + ^{27}Al) target.

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

- **Final Goal**: Determination of the excitation energy spectrum corresponding to the reaction on titanium, after subtracting the contribution due to the presence of **^{27}Al** and **oxygen** in the target.

$^{27}Al(^{18}O,^{19}F)^{26}Mg$ - Determination of the absolute differential cross sections





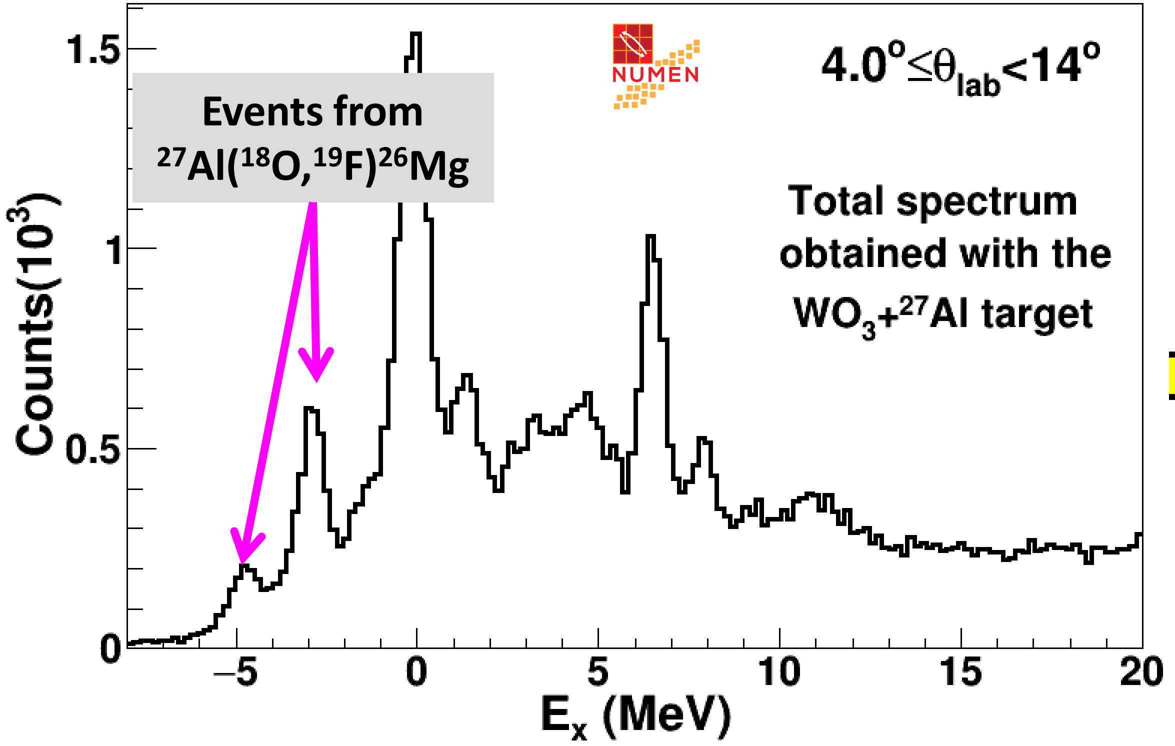
Nucleus	E_x (MeV)	J^π
^{19}F	0.000	$1/2^+$
	0.110	$1/2^-$
	0.197	$5/2^+$
	1.459	$3/2^-$
	1.554	$3/2^+$

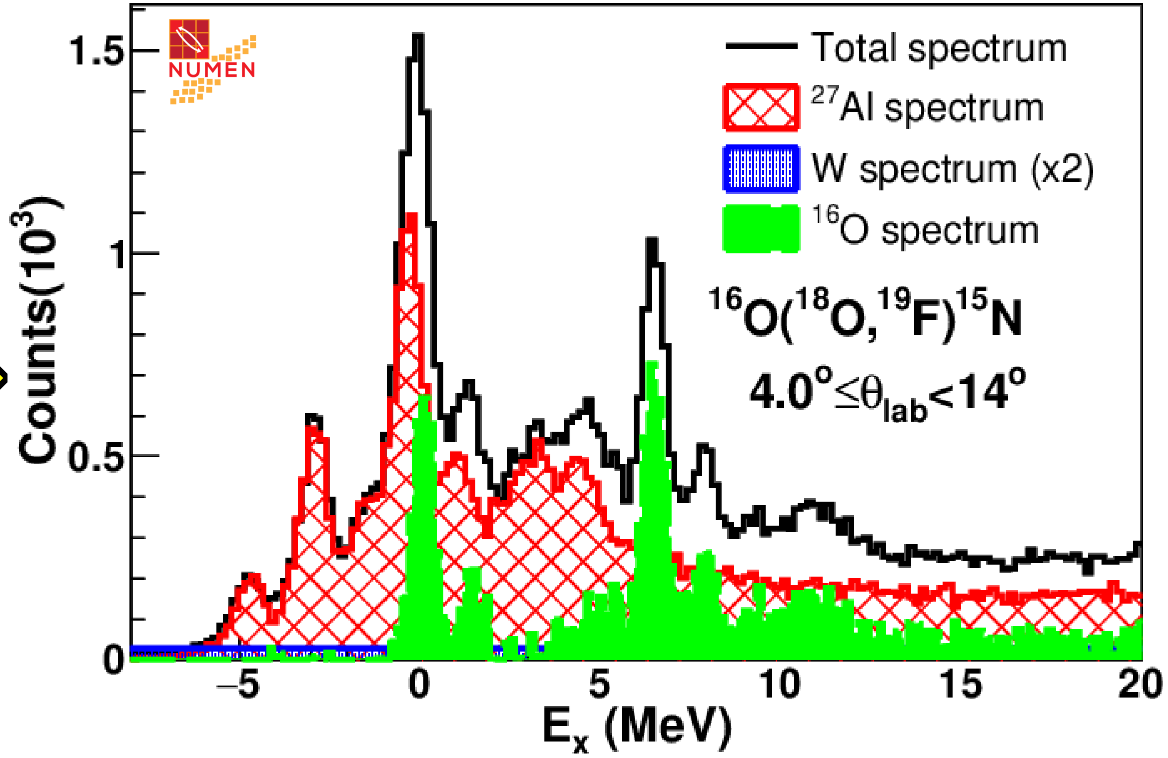
Nucleus	E_x (MeV)	J^π
^{26}Mg	0.000	0^+
	1.809	2^+
	2.938	2^+
	4.319	4^+
	4.333	2^+
	4.350	3^+

Peak label	Counts	Absolute cross section (μb)
1	1321	130±4
2	4261	424±6
3	8742	809±9

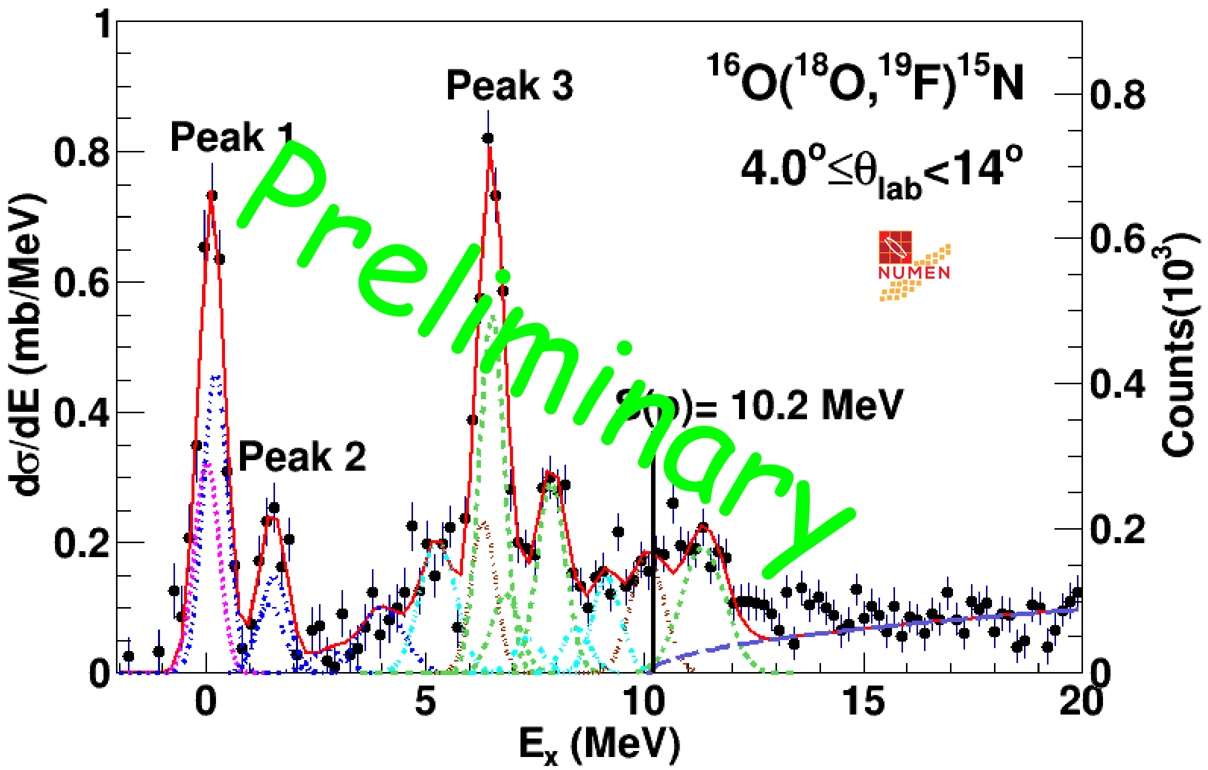
WO_3+^{27}Al target

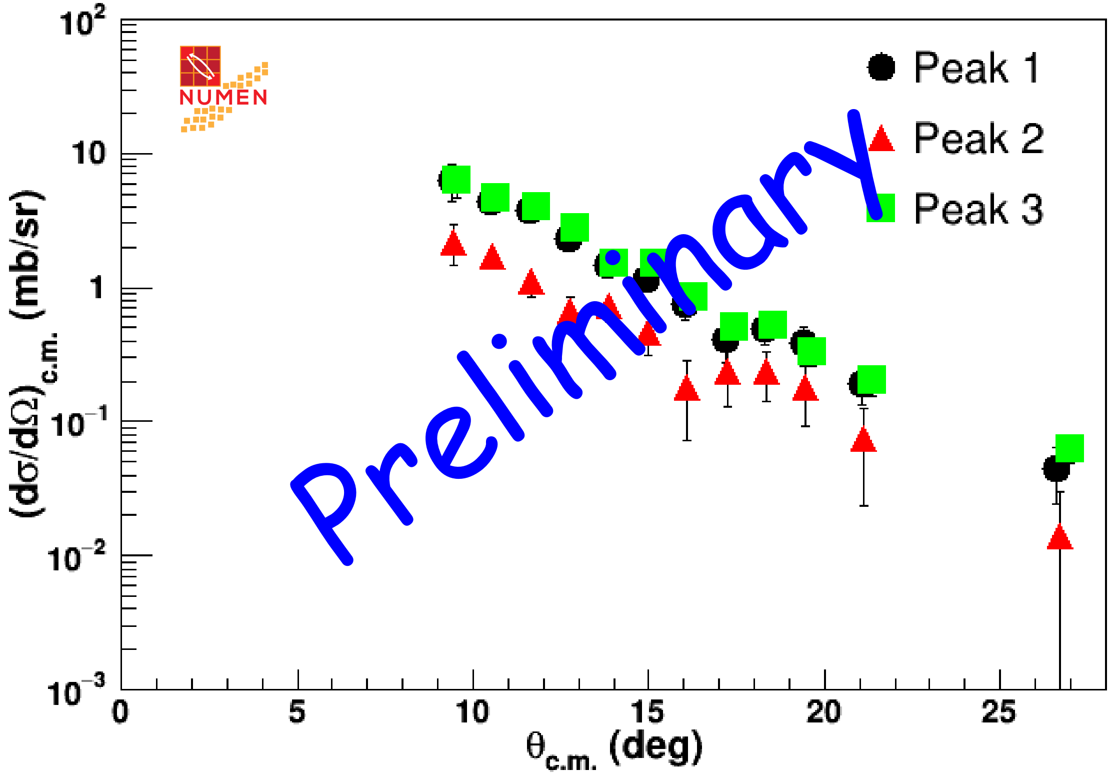
Background evaluation





$^{16}O(^{18}O,^{19}F)^{15}N$ - Determination of the absolute differential cross sections

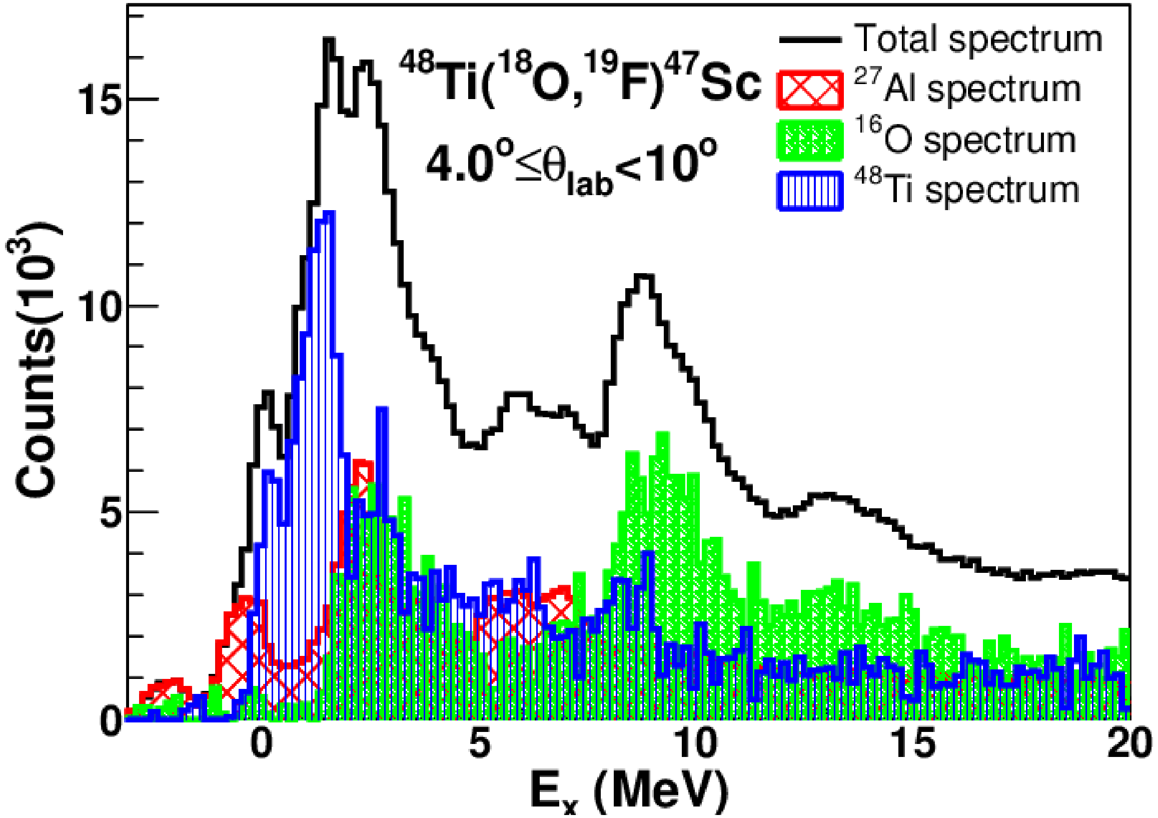


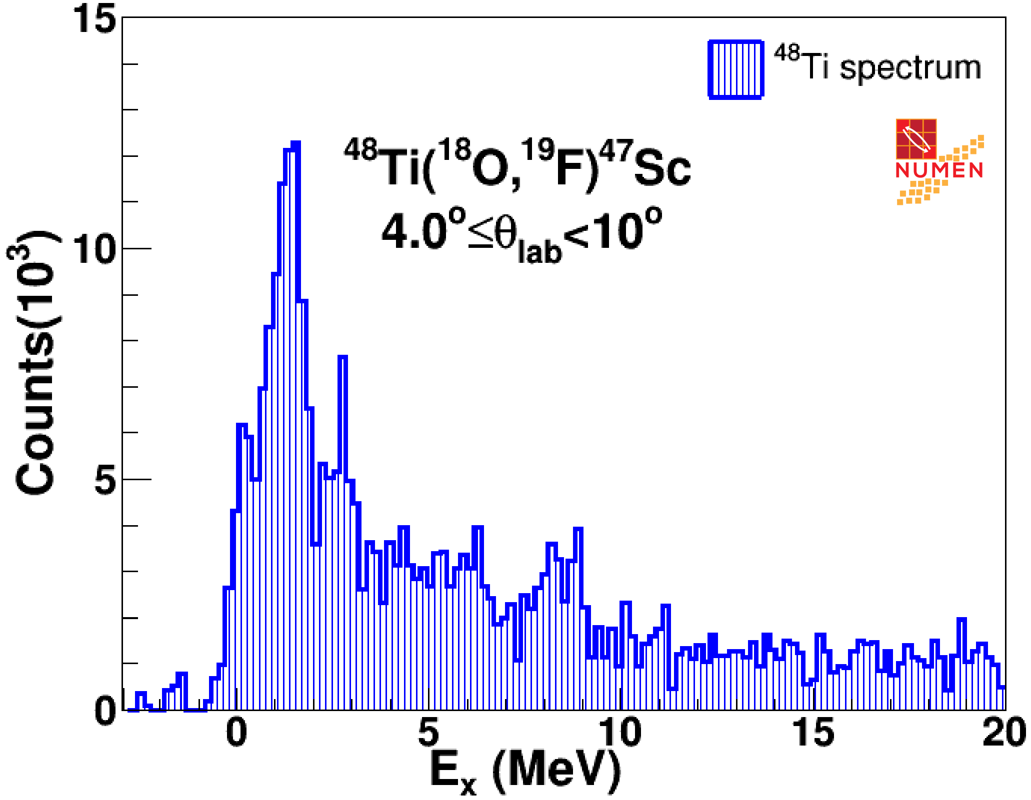


Peak label	Counts	Absolute cross section (μb)
1	3016	554±58
2	1080	205±32
2	3372	646±23

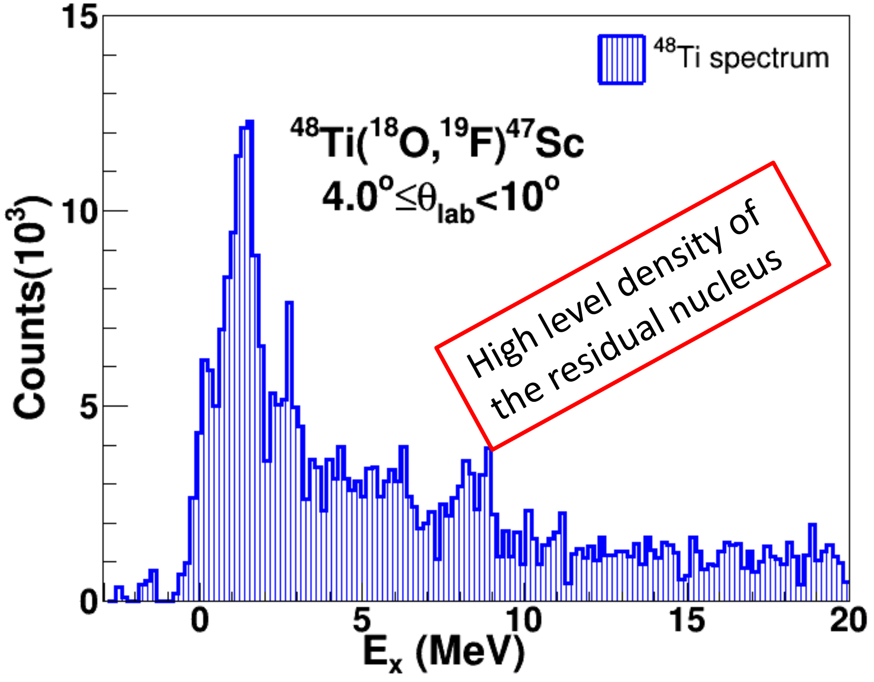
TiO_2+^{27}Al target

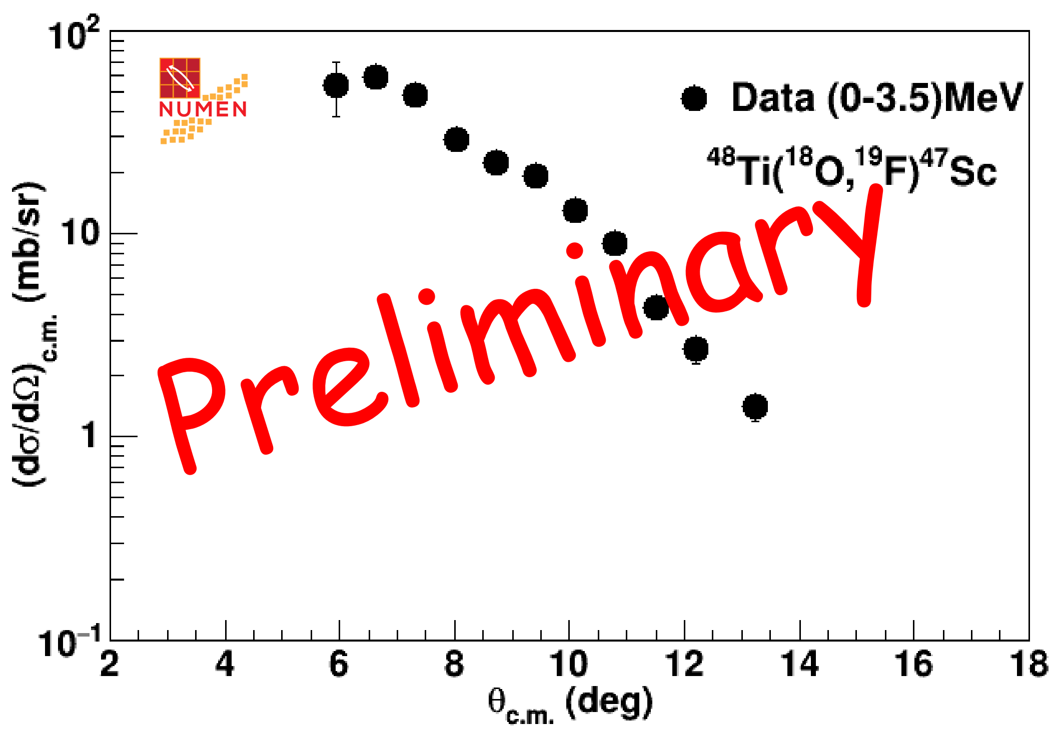
Determination of the E_x spectrum corresponding to the $^{48}Ti(^{18}O,^{19}F)^{47}Sc$ reaction





Determination of the absolute differential cross sections





Nucleus	E_x (MeV)	J^{π}
^{47}Sc	0.000	$7/2^-$
	0.767	$3/2^+$
	0.808	$3/2^-$
	1.147	$11/2^-$
	1.297	$5/2^-$
	1.391	$1/2^+$

Data interpretation – The Distorted-Wave Born Approximation

- The angular distribution data were analyzed within the Distorted-Wave Born Approximation (DWBA) framework.

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- The transfer process is weak compared to elastic scattering and thus it can be treated as a weak transition(perturbation) between elastic scattering states.

- Pickup Reaction: a + A ⟶ a + (B+x) ⟶ (a+x) + B ⟶ b + B

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

The Distorted-Wave Born Approximation ingredients

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

- Describe the elastic scattering at the entrance(α) and exit(β) channels.
- Solutions of Schrödinger equation adopting the **Optical Model**.

↓

São Paulo double-folding potential

- Overlap functions

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

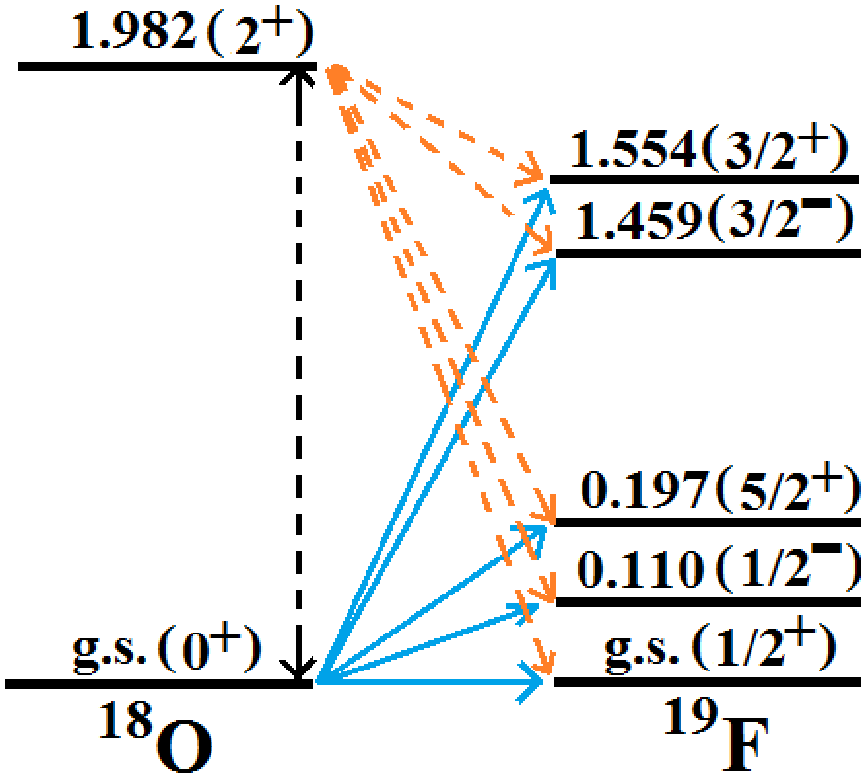
$$\langle \phi_b | \phi_a \rangle \propto B_{\ell sj} \varphi_{\ell sj}^{ax}$$

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

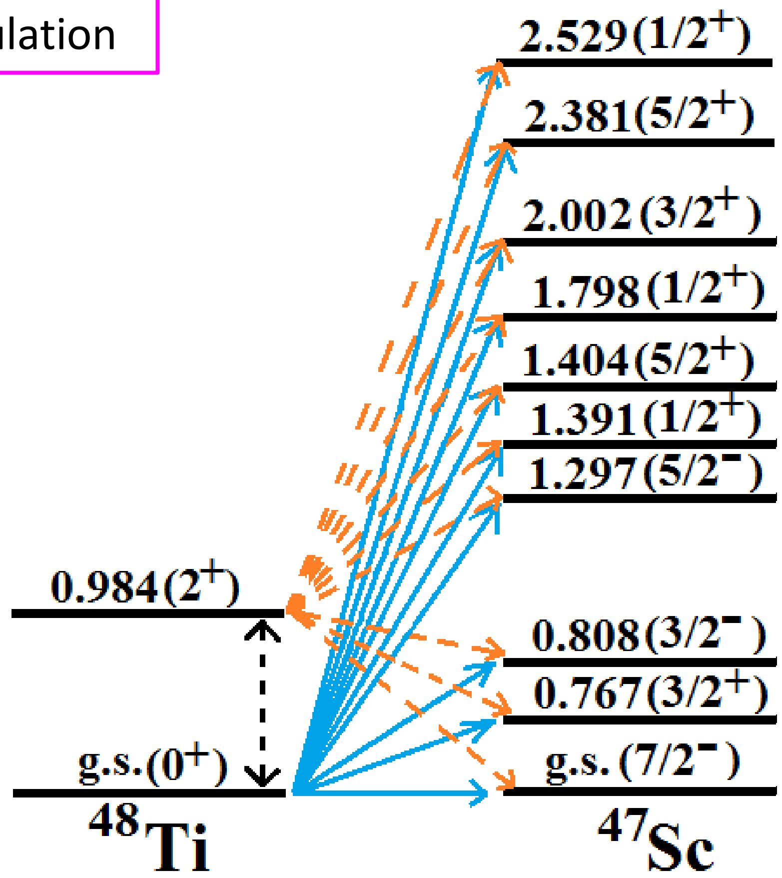
Overlaps	Interaction	Core	Nucleon orbital
<^{19}F|^{18}O>	P-SD-MOD	^{4}He	1p, 2s, 1d
<^{26}Mg|^{27}Al>	P-SD-MOD	^{4}He	1p, 2s, 1d
<^{15}N|^{16}O>	P-SD-MOD	^{4}He	1p, 2s, 1d
<^{47}Sc|^{48}Ti>	SDPF-MU	^{16}O	2s, 2d, 1f, 2p

Coupling Scheme – $^{18}O+^{48}Ti$ reaction

Blue arrows: DWBA calculation
Orange arrows: CCBA calculation

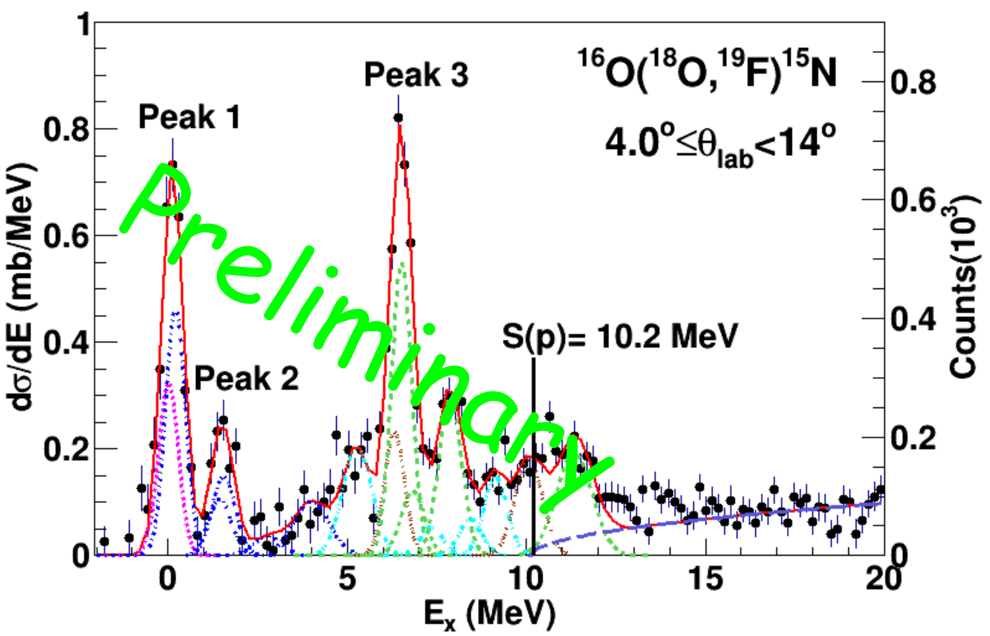


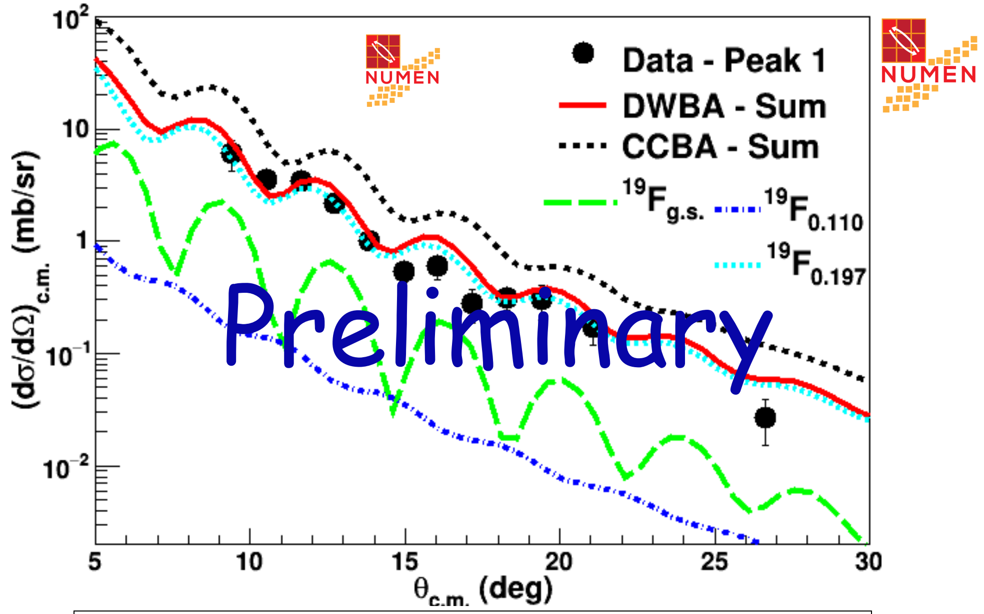
Projectile Overlaps

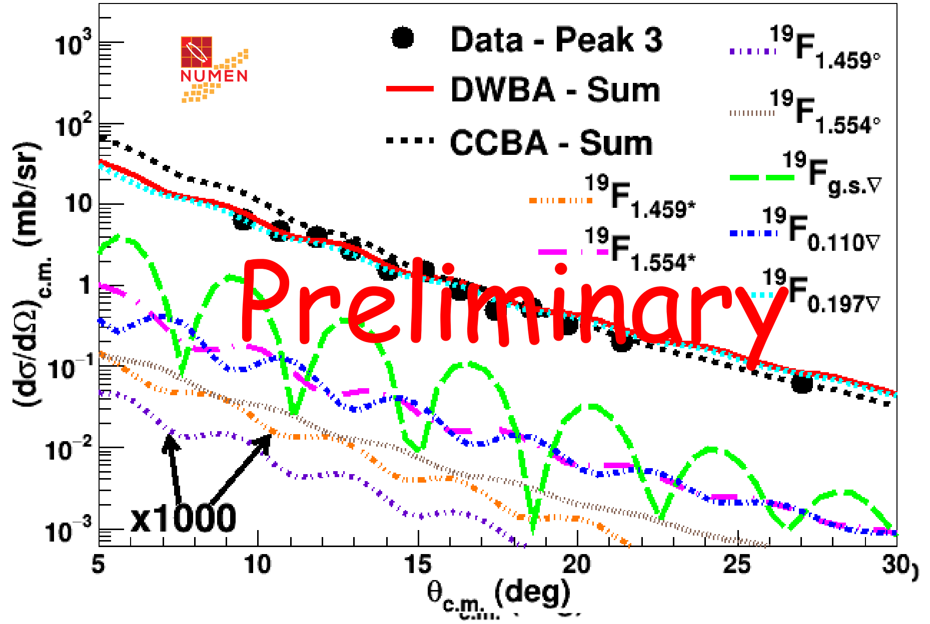


Target Overlaps

$^{16}O(^{18}O,^{19}F)^{15}N$ reaction



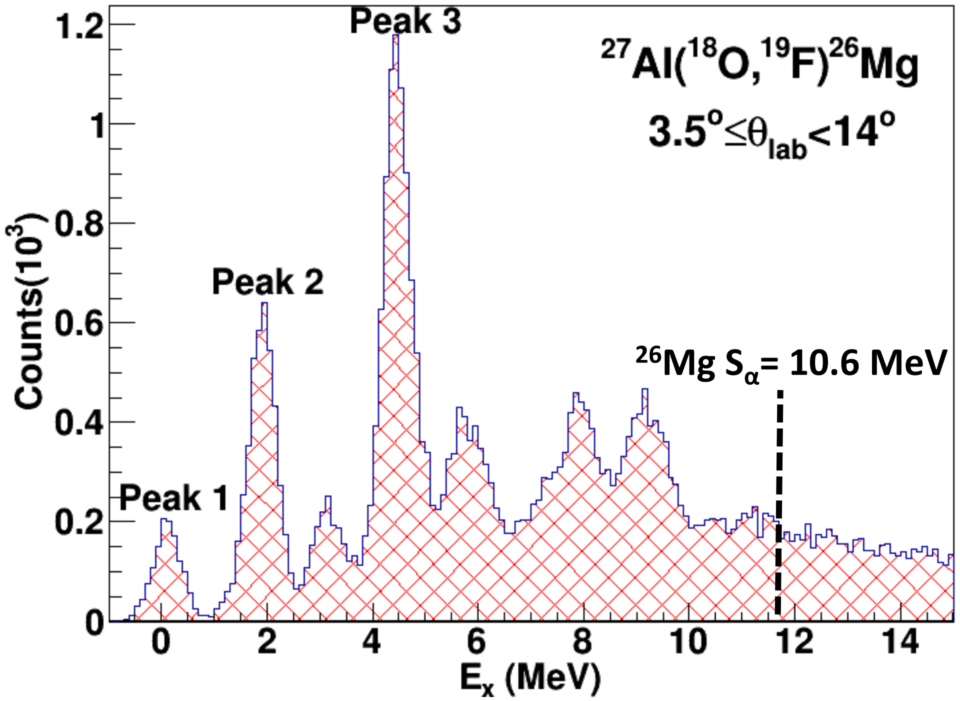


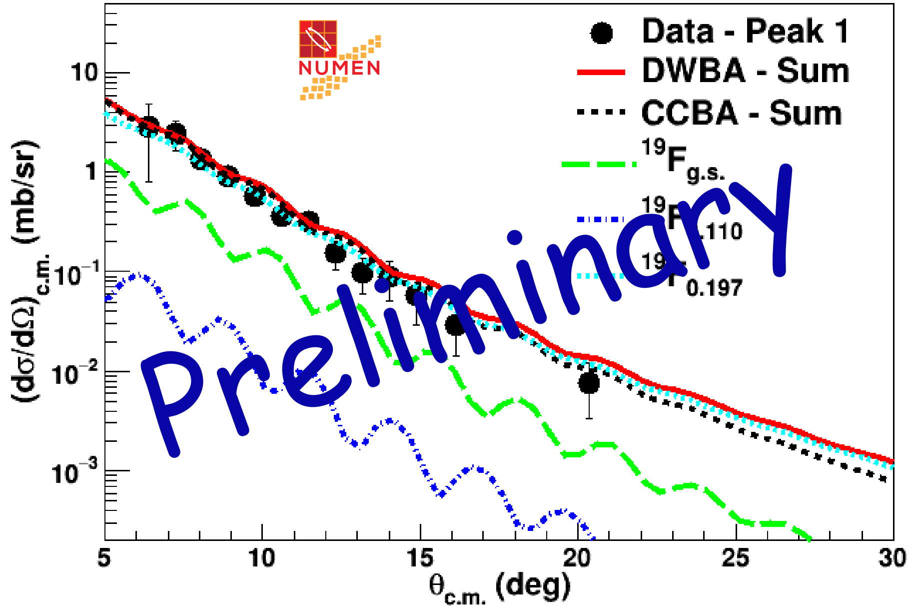


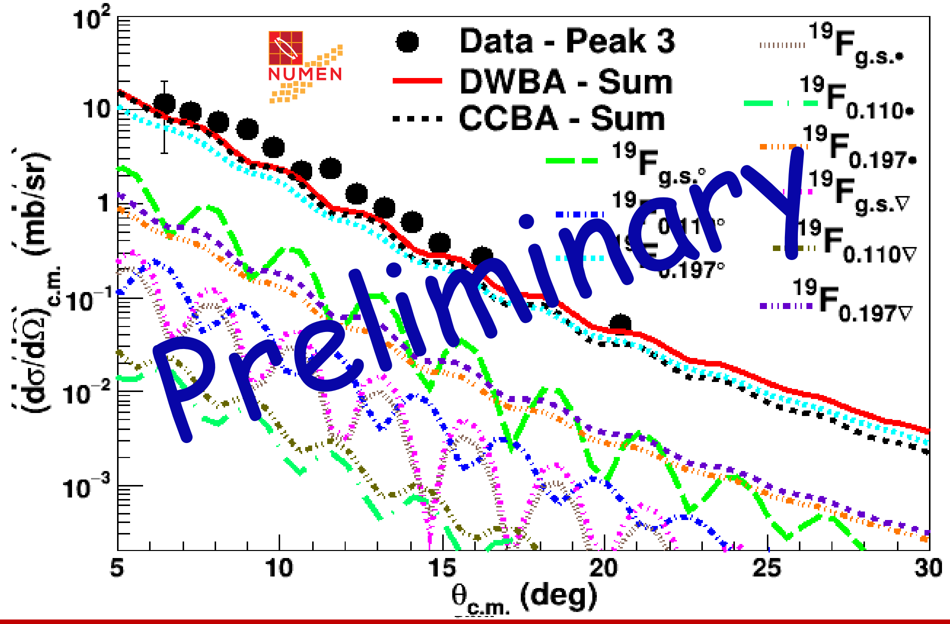
Nucleus	E_x (MeV)	J^π
^{19}F	0.000	$1/2^+$
	0.110	$1/2^-$
	0.197	$5/2^+$
	1.459	$3/2^-$
	1.554	$3/2^+$

Nucleus	E_x (MeV)	J^π
^{15}N	0.000	1/2-
	5.270 (*)	$5/2^+$
	5.299 (o)	$1/2^+$
	6.323 (∇)	$3/2^-$

$^{27}Al(^{18}O,^{19}F)^{26}Mg$ reaction

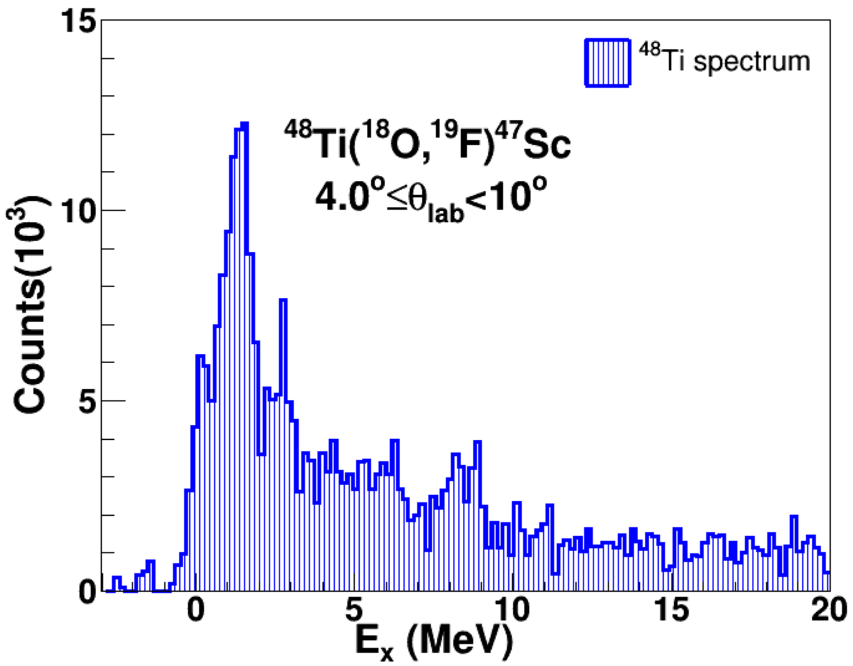


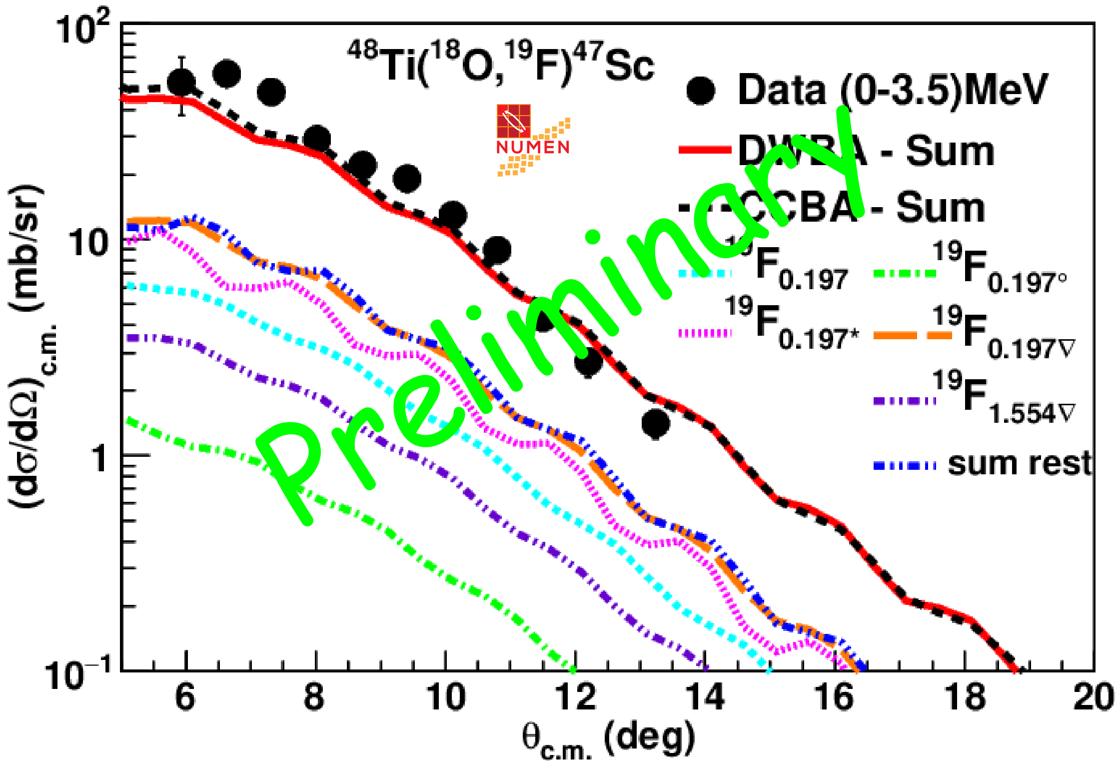




Nucleus	E_x (MeV)	J^{π}
^{26}Mg	0.000	0^+
	1.809 (*)	2^+
	4.319 (o)	4^+
	4.333 (●)	2^+
	4.350 (∇)	3^+

Determination of the absolute differential cross sections



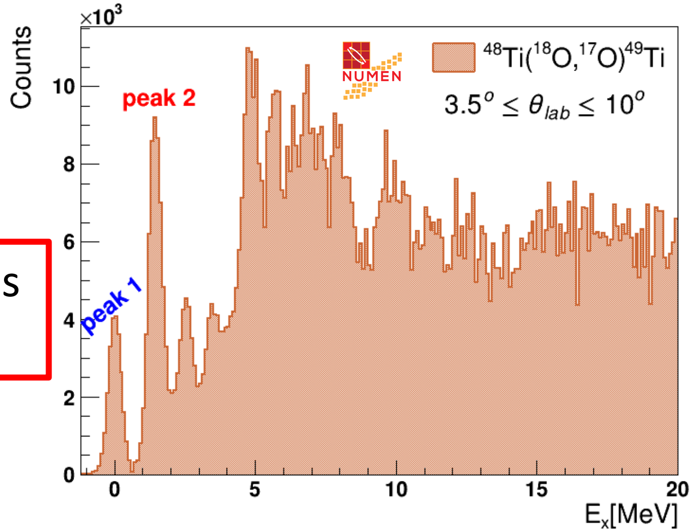


Nucleus	E_x (MeV)	J^π
^{47}Sc	0.000	$7/2^-$
	0.767 (*)	$3/2^+$
	0.808 (o)	$3/2^-$
	1.147	$11/2^-$
	1.297	$5/2^-$
	1.391 (∇)	$1/2^+$
	1.404	$5/2^+$

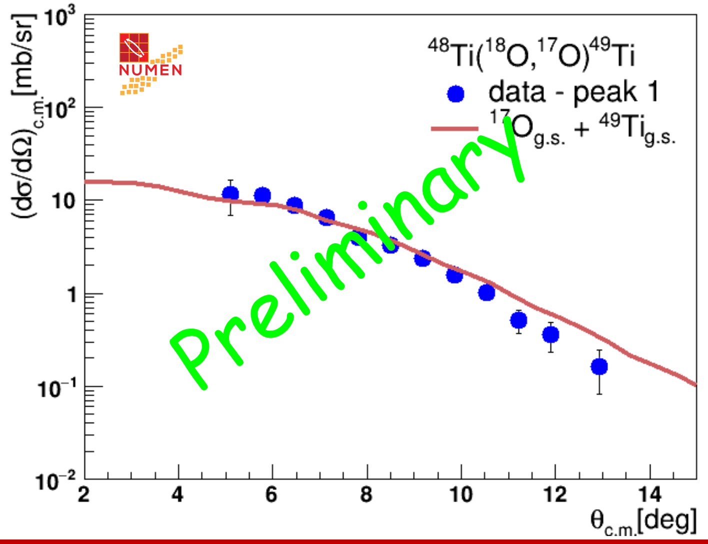
Nucleus	E_x (MeV)	J^π
^{47}Sc	1.798	$1/2^+$
	2.002	$3/2^+$
	2.381	$5/2^+$
	2.529	$1/2^+$

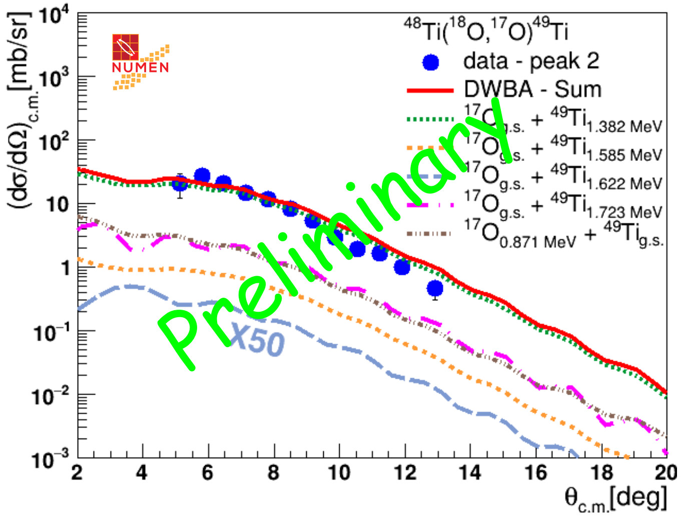
Other reaction channels

One-neutron transfer channel

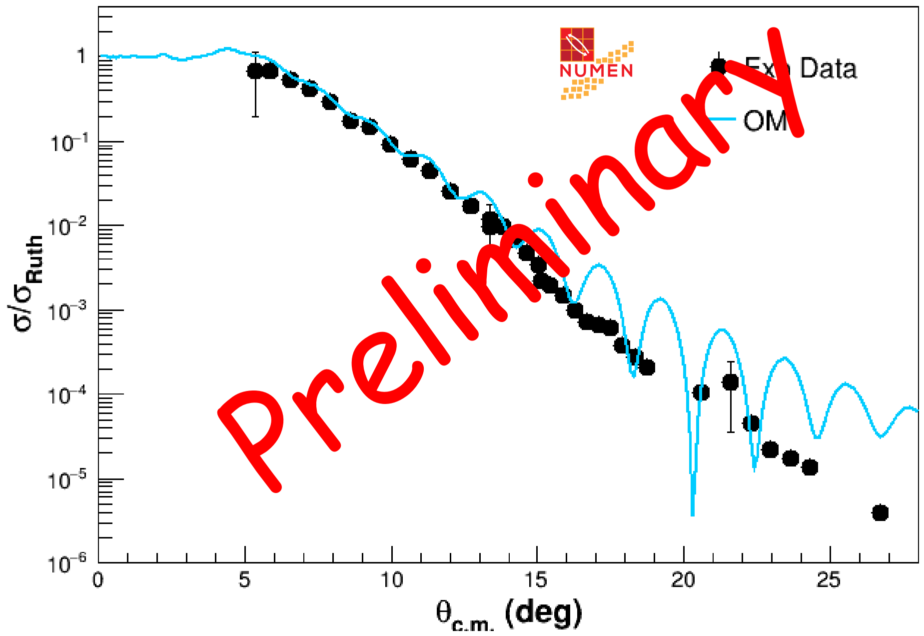


M. Cuti: MSc Thesis Completed!





Elastic channel



Analysis by G. A. Brischetto
In progress

Summary

- Angular distribution measurements for the $^{48}Ti(^{18}O,^{19}F)^{47}Sc$ reaction at the energy of 275 MeV were performed at the MAGNEX facility of INFN-LNS.

- Complementary measurements for the one –proton transfer reaction on ^{27}Al and WO_3 targets were performed, in order to estimate the background contaminations and draw stronger conclusions about the adopted reaction model.

- The theoretical angular distribution data were found to be in very good agreement with the experimental ones **suggesting the validity of the adopted Optical Potential and the shell-model description of the involved nuclei**.

- Future aspects: The same models could be applied for the description of the DCE and SCE reactions.

Thank you for your attention

The NUMEN collaboration

https://web.infn.it/NUMEN/index.php/it/
F. Cappuzzello et al., Eur. Phys. J. A (2018) 54: 72

(NUclear Matrix Elements for Neutrinoless double beta decay)

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