7th International Conference on Collective Motion in Nuclei under Extreme Conditions (COMEX7)

Experimental and theoretical analysis of ^{76}Se(^{18}O,^{17}O)^{77}Se and ^{76}Se(^{18}O,^{19}F)^{75}As transfer reactions at 15 MeV/u in a multi-channel approach within the NUMEN project

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INFN - Laboratori Nazionali del Sud

For the NUMEN Collaboration

https://web.infn.it/NUMEN/index.php/it/

NURE

NUclear
Matrix
Elements for
Neutrinoless double beta decay

Accessing information about nuclear matrix element (**NME**) from the double charge exchange (**DCE**) reaction **cross sections**

$$ {}^{a}_{z}x_{n} + {}^{A}_{Z}X_{N} \rightarrow {}^{a}_{z\mp2}y_{n\pm2} + {}^{A}_{Z\pm2}Y_{N\mp2} $$

DCE cross section is a combination of **3 different reaction mechanisms**:

1) One-step DCE - Majorana double charge exchange (**MDCE**)

   Exchange of two *correlated* charged mesons between projectile and target

   H. Lenske et al., Progr. Part. and Nucl. Physics 109 (2019) 103716

2) Two-step DCE - Double single charge exchange (**DSCE**)

   Exchange of two *uncorrelated* charged mesons between projectile and target

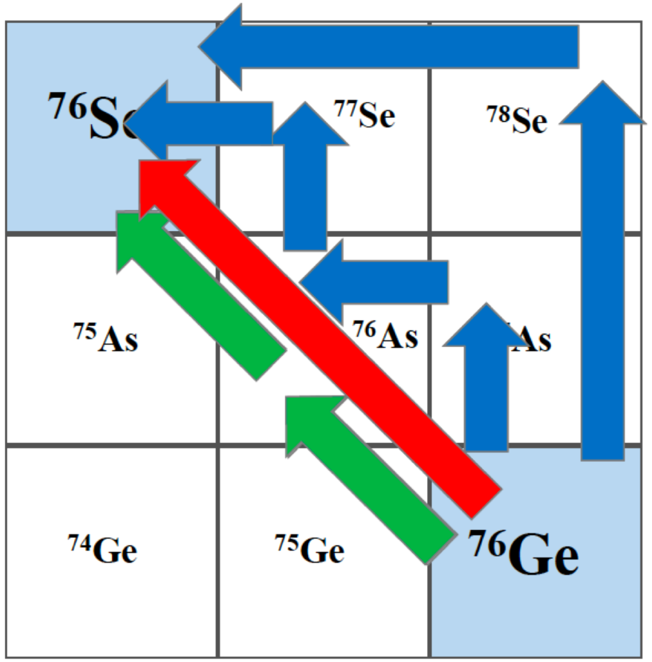
   J.I. Bellone et al., Phys. Lett. B 807 (2020) 135528

   J. Bellone talk

3) Sequential multi nucleon transfer (TDCE)

   Exchange of one or two *nucleons* between projectile and target

   J.L. Ferreira et al. Phys. Rev. C 105 (2022) 014630



F. Cappuzzello et al.,
Progr. Part. and Nucl. Physics 128, 103999 (2023)

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1) One-step DCE - Majorana double charge exchange (**MDCE**)

Exchange of two correlated charged mesons between projectile and target

H. Lenske et al., Progr. Part. and Nucl. Physics 109 (2019) 103716

2) Two-step DCE - Double single charge exchange (**DSCE**)

Exchange of two uncorrelated charged mesons between projectile and target

J.I. Bellone et al., Phys. Lett. B 807 (2020) 135528

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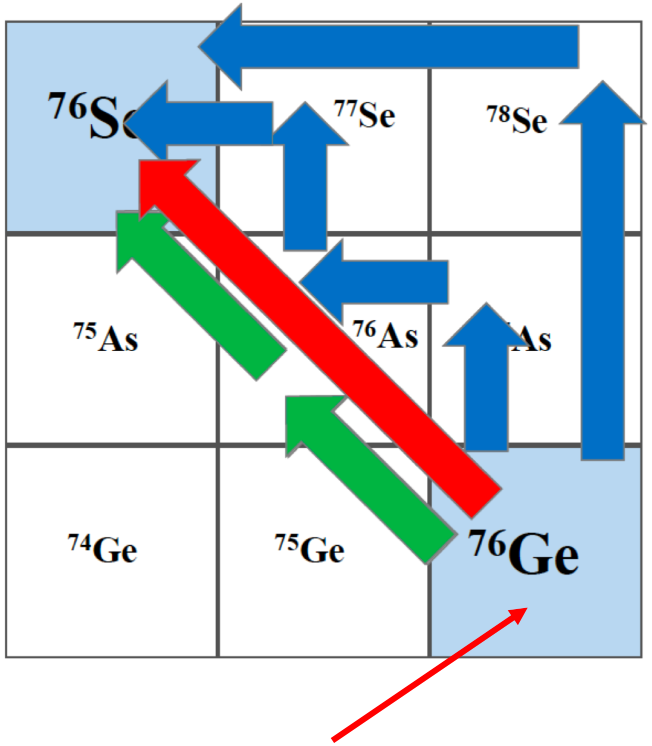
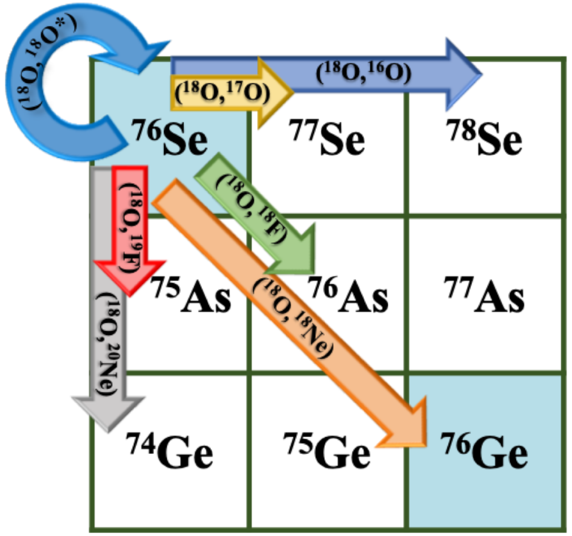


$0\nu\beta\beta$ decay candidate

Multi-channel approach



Example: ^{76}Se -> ^{76}Ge network of the nuclear reactions :

- Elastic and inelastic scattering ^{76}Se(^{18}O,^{18}O)^{76}Se
- Single charge exchange (SCE) ^{76}Se(^{18}O,^{18}F)^{76}As
- One-proton pickup ^{76}Se(^{18}O,^{19}F)^{75}As
- Two-proton pickup ^{76}Se(^{18}O,^{20}Ne)^{74}Ge
- One-neutron stripping ^{76}Se(^{18}O,^{17}O)^{77}Se
- Two-neutron stripping ^{76}Se(^{18}O,^{16}O)^{78}Se
- Double charge exchange (DCE) ^{76}Se(^{18}O,^{18}Ne)^{76}Ge

Challenging goal

Experiment

Measuring all the accessible quasi-elastic channels all at once

↓

gives a **high reliability of the measured observables**

Theory

constrained data analyses

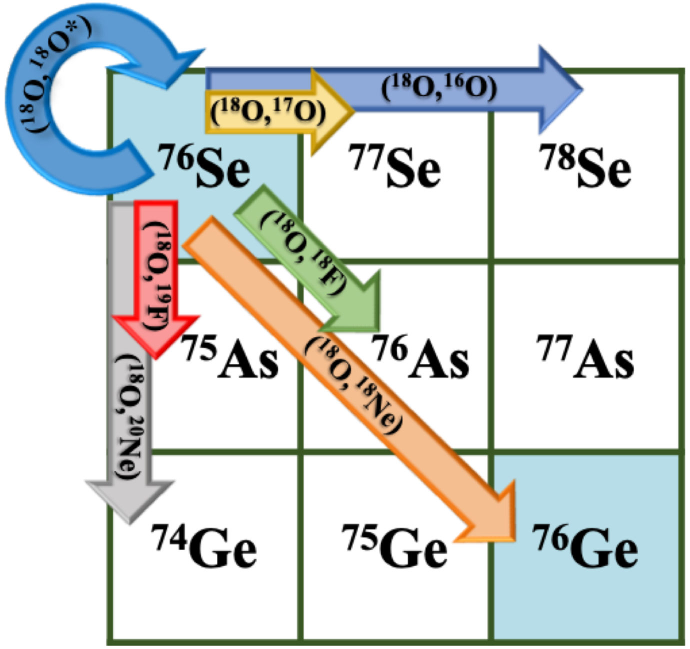
↓

largely **reduces the need of free parameters** in both nuclear structure and reaction models

A. Spatafora et al., Phys. Rev. C 107, 024605 (2023)
S. Burrello et al., Phys. Rev. C 105, 024616 (2022)
M. Cavallaro et al., Front. Astron. Space Sci. 8, 659815 (2021)

G. A. Brischetto talk

Multi-nucleon transfer reaction channels



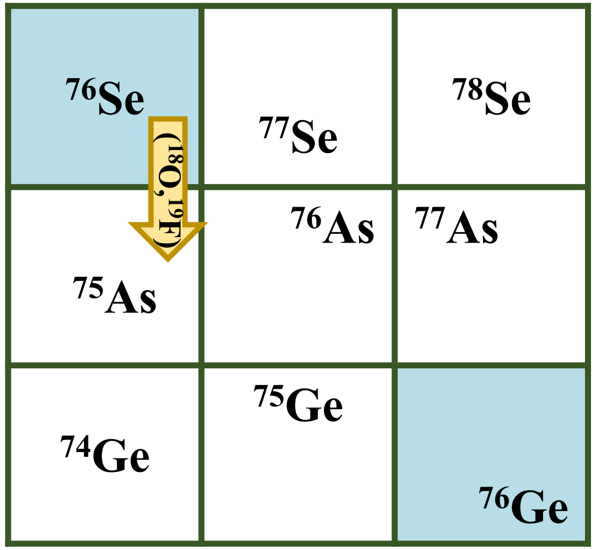
- One-proton pickup ^{76}Se(^{18}O,^{19}F)^{75}As
- Two-proton pickup ^{76}Se(^{18}O,^{20}Ne)^{74}Ge
- One-neutron stripping ^{76}Se(^{18}O,^{17}O)^{77}Se
- Two-neutron stripping ^{76}Se(^{18}O,^{16}O)^{78}Se

- Multi-nucleon transfer reactions are competing to double charge exchange ones
- They are essential tools to investigate specific features of the nuclear structure (occupation of valence orbits, pairing correlations)

A. Spatafora et al., Phys. Rev. C 107, 024605 (2023)
S. Burrello et al., Phys. Rev. C 105, 024616 (2022)
M. Cavallaro et al., Front. Astron. Space Sci. 8, 659815 (2021)

O. Sgouros et al., Phys. Rev. C 104, 034617 (2021).
S. Calabrese et al., Phys. Rev. C 104,064609 (2021)
I. Ciraldo et al., Phys. Rev. C 105 (2022) 044607

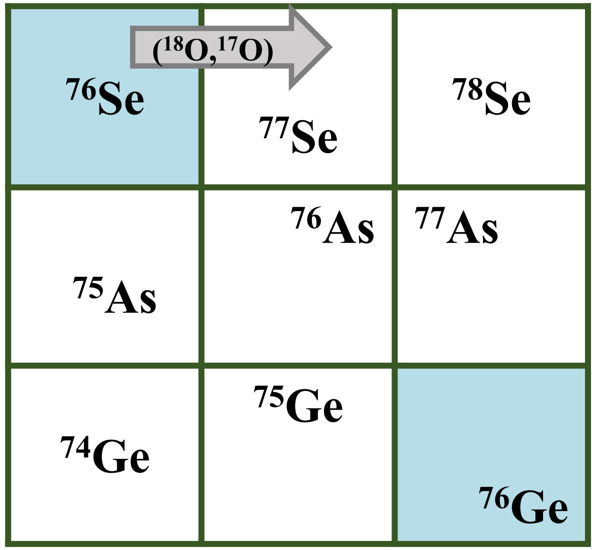
Multi-nucleon transfer reaction channels



- one-proton pickup ^{76}Se(^{18}O,^{19}F)^{75}As
- two-proton pickup ^{76}Se(^{18}O,^{20}Ne)^{74}Ge
- one-neutron stripping ^{6}Se(^{18}O,^{17}O)^{77}Se
- two-neutron stripping ^{76}Se(^{18}O,^{16}O)^{78}Se

- Multi-nucleon transfer reactions are concurrent to double charge exchange ones
- They are essential tools to investigate specific features of the nuclear structure

Multi-nucleon transfer reaction channels



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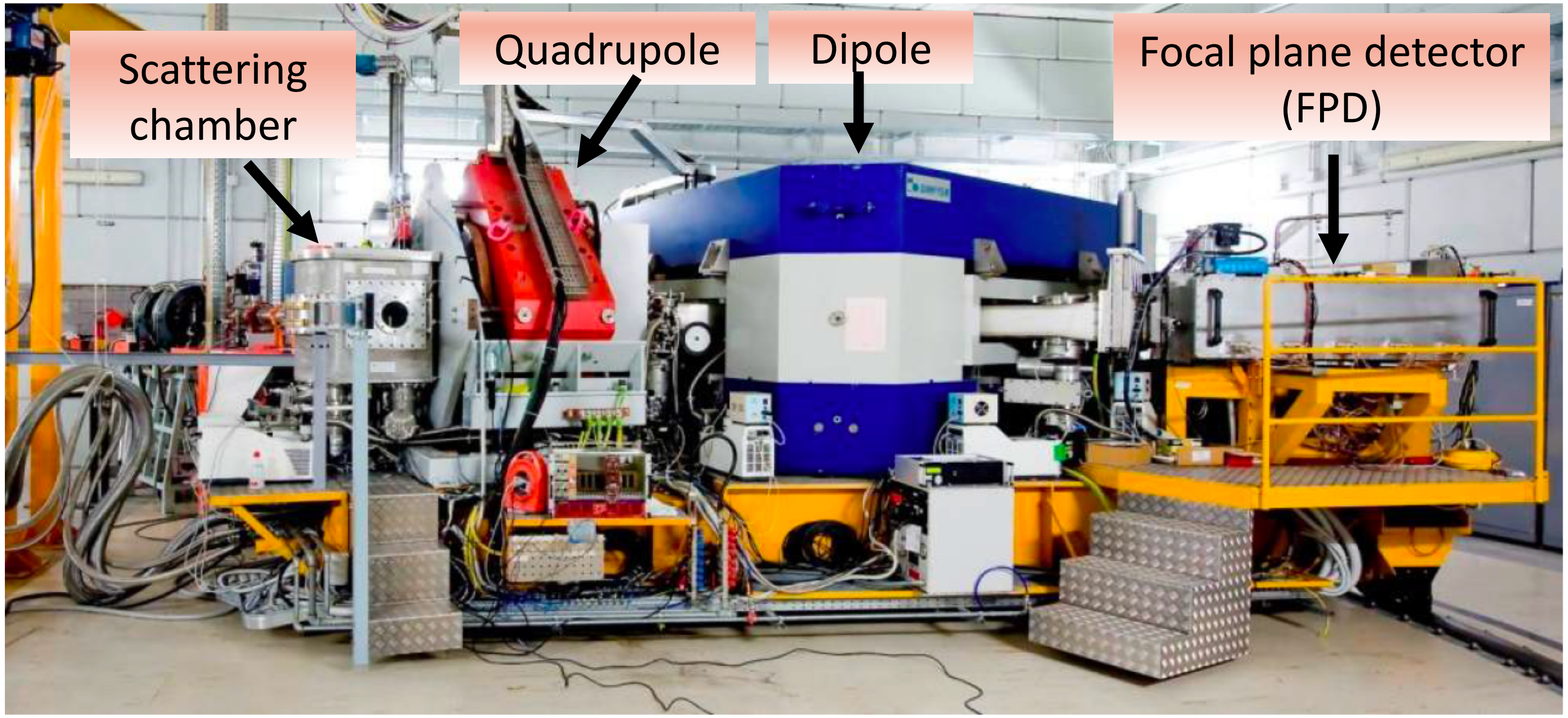
- Multi-nucleon transfer reactions are concurrent to double charge exchange ones
- They are essential tools to investigate specific features of the nuclear structure

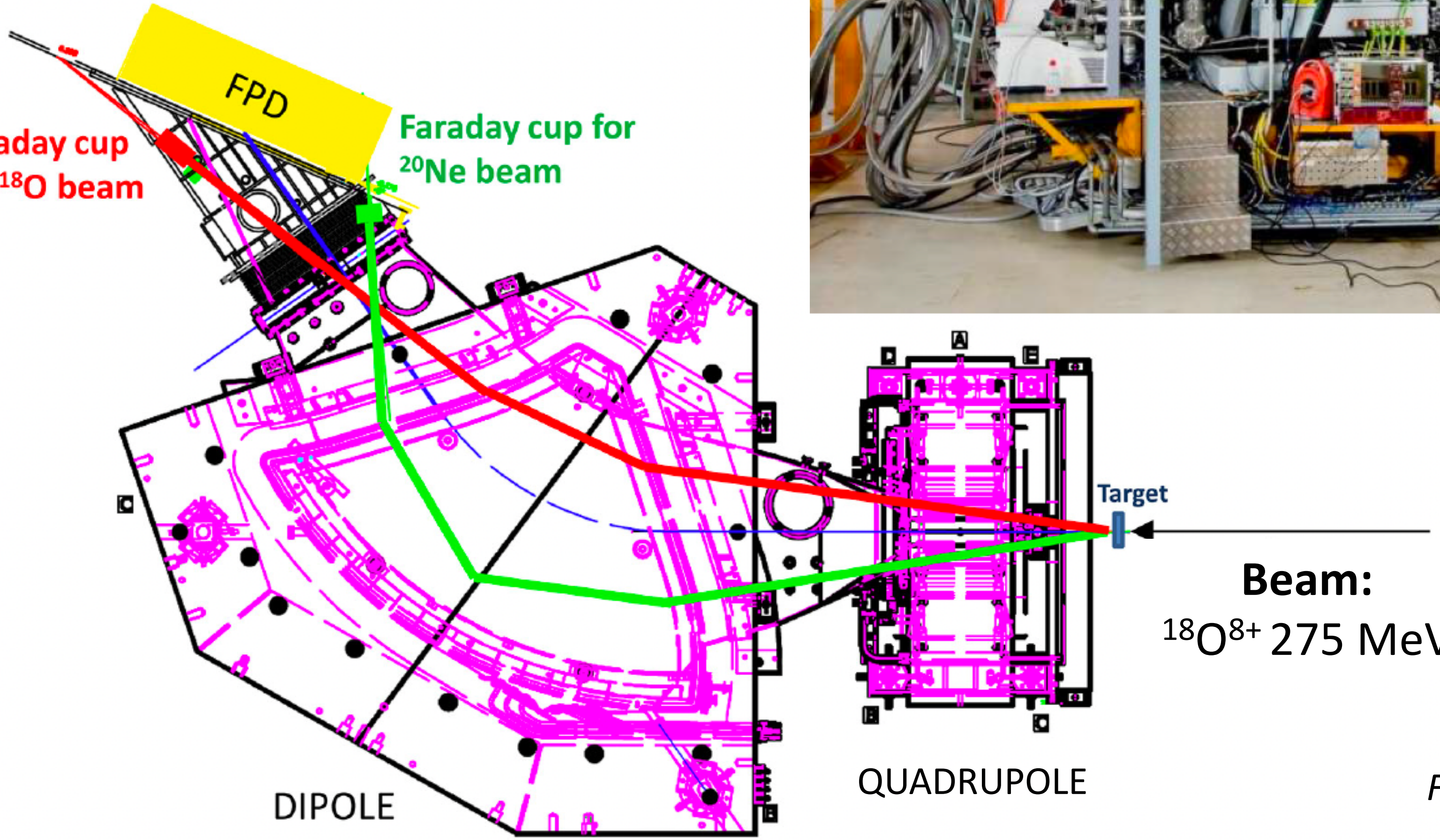
Experimental set-up @ INFN - LNS

Targets:

^{76}Se $(270\ \mu g/cm^2)$ + ^{12}C $(80 \mu g/cm^2)$

^{12}C $(400\ \mu g/cm^2)$





Beam:

$^{18}O^{8+}$ 275 MeV

MAGNEX

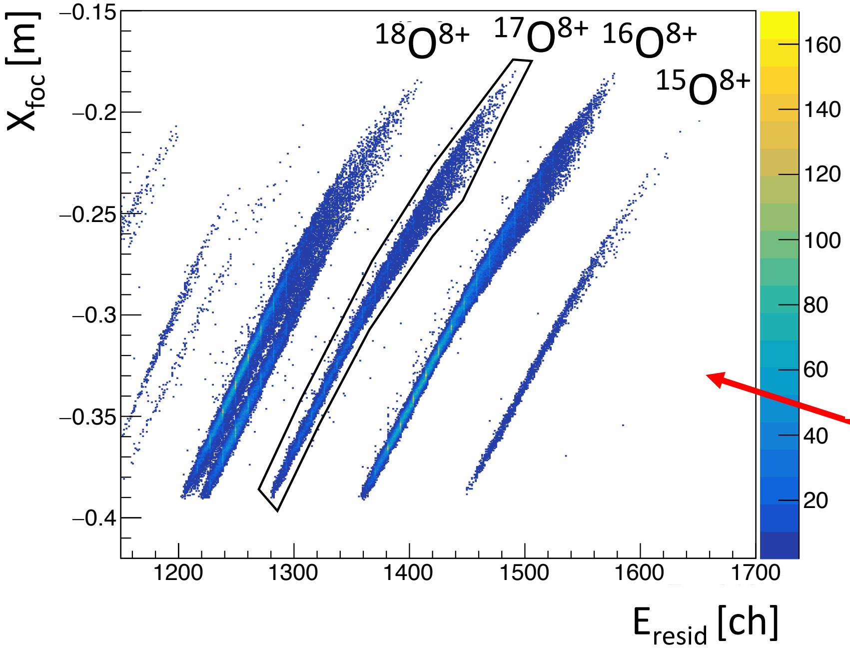
Large acceptance magnetic spectrometer

D. Carbone talk

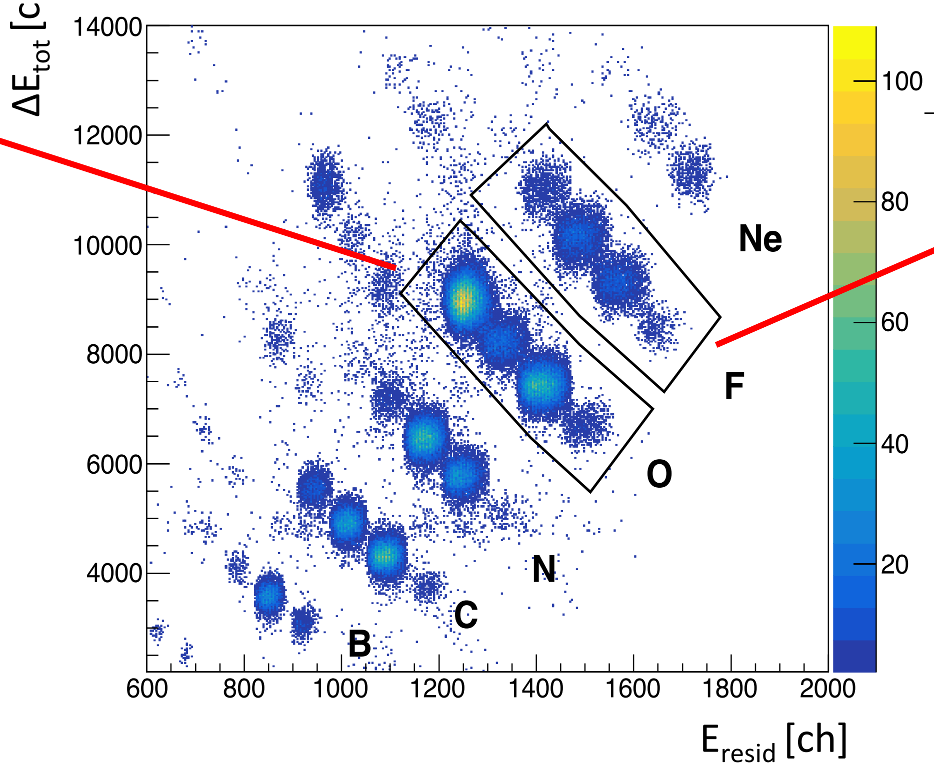
F. Cappuzzello et al., Eur. Phys. J. A 52 (2016) 167

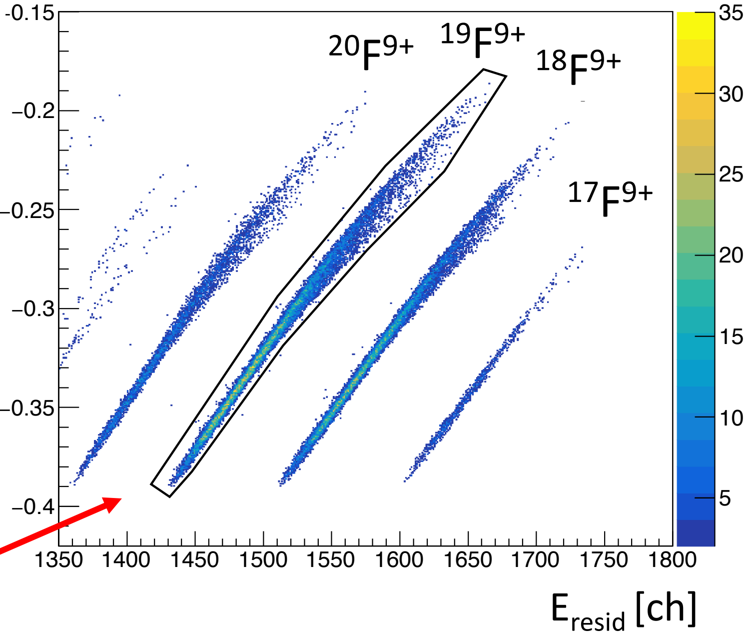
Data reduction: *particle identification*

Unambiguous selection of ejectiles in atomic number, charge, mass achieved!



Bethe – Bloch formula: $-\frac{dE}{dx} \propto \frac{Z^2 A}{E}$





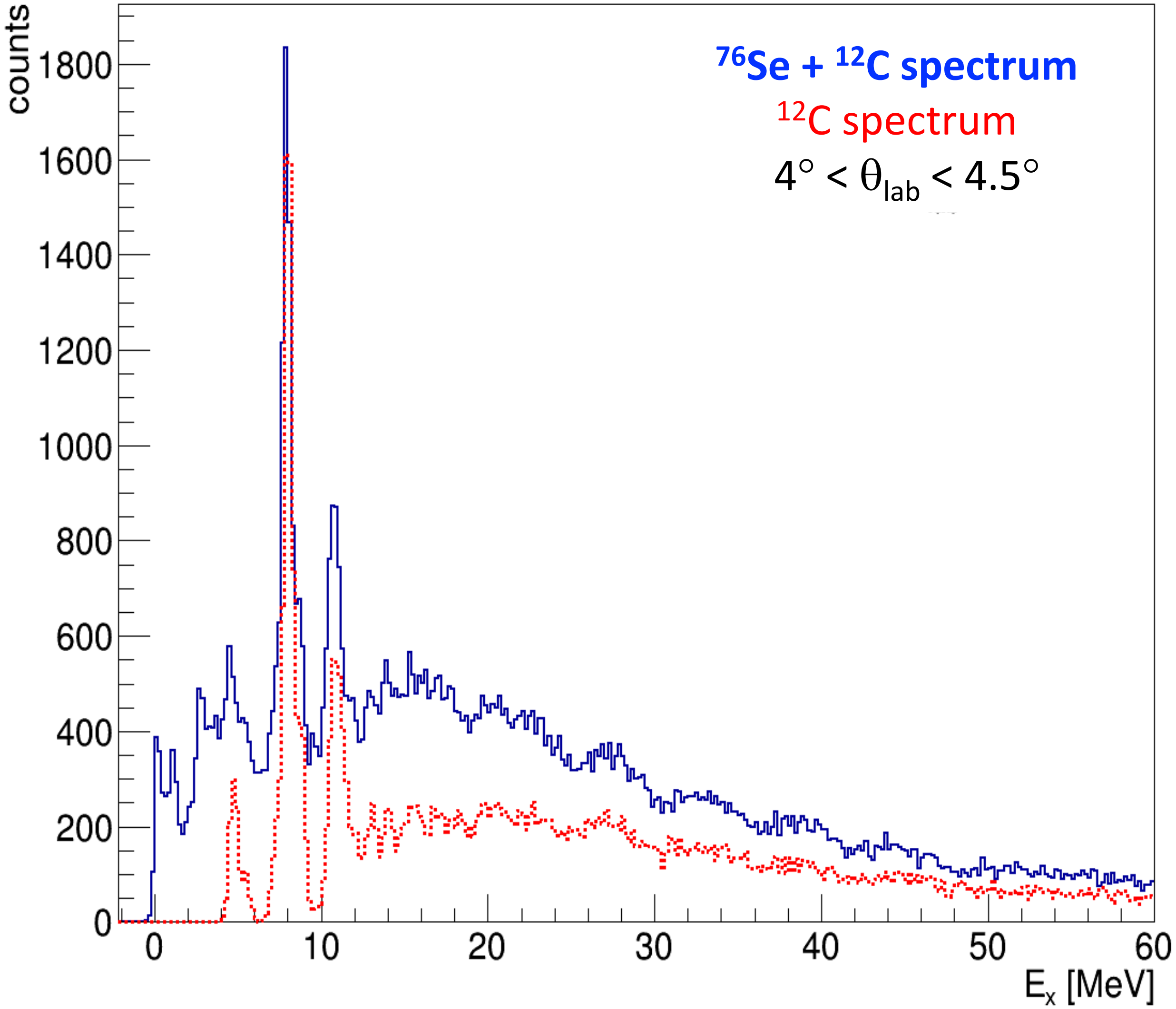
$$X_{foc} \propto \frac{\sqrt{m}}{q}\sqrt{E_{resid}}$$

S. Calabrese et al., NIM A 980 (2020) 164500
M. Cavallaro et al., NIM B 463 (2020) 334

Data reduction: *background evaluation*

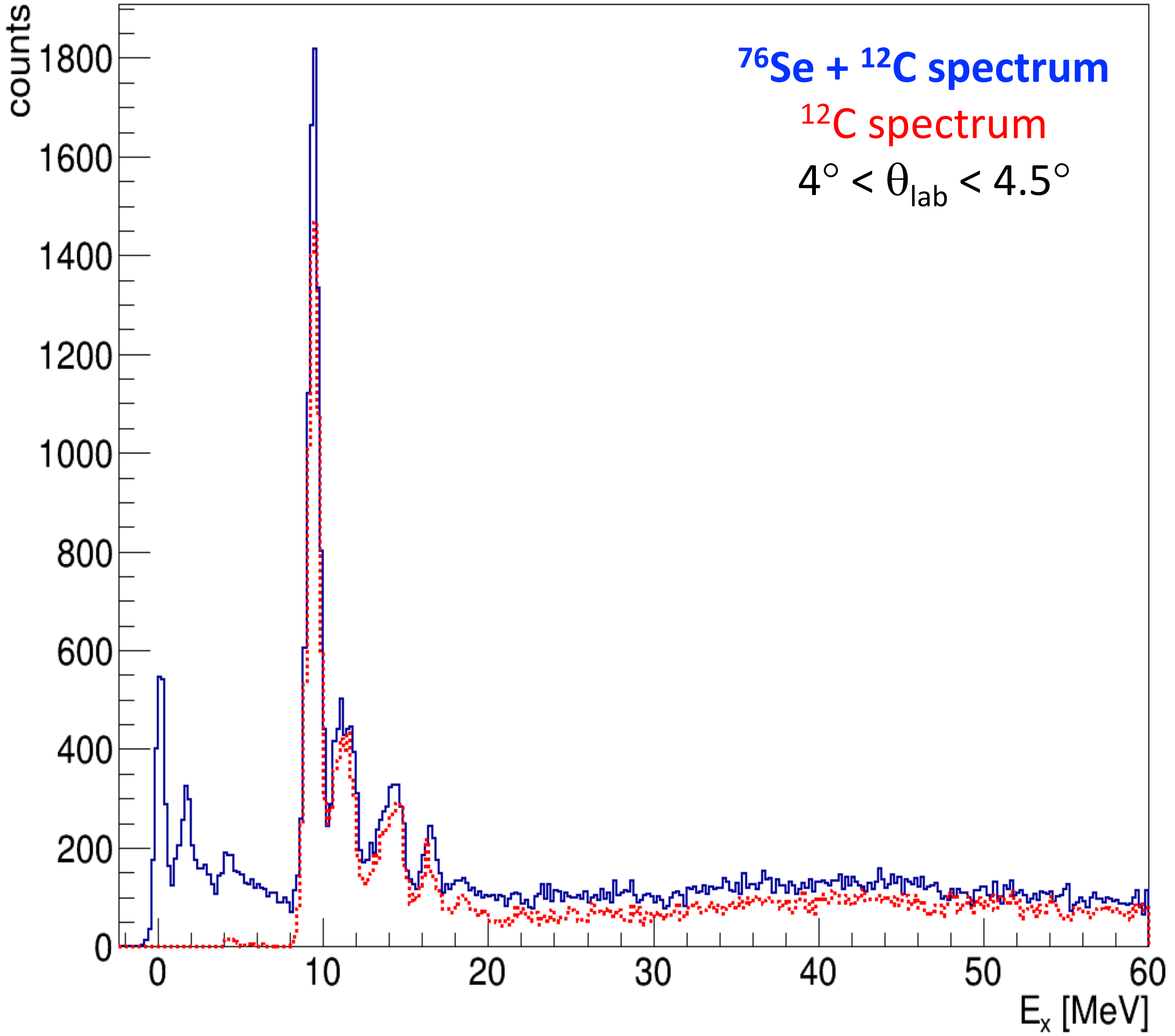
One-neutron transfer

^{76}Se(^{18}O,^{17}O)^{77}Se



One-proton transfer

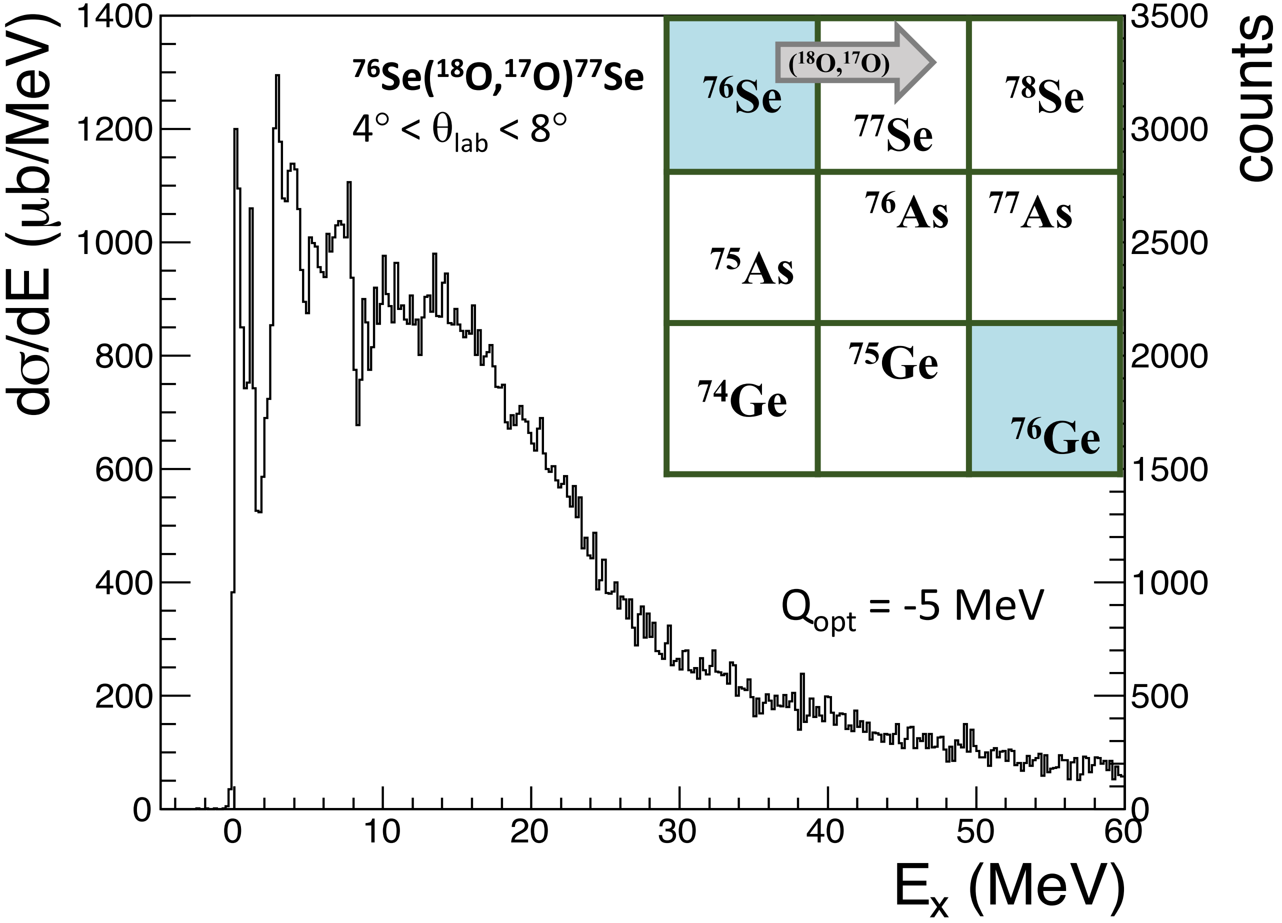
^{76}Se(^{18}O,^{19}F)^{75}As



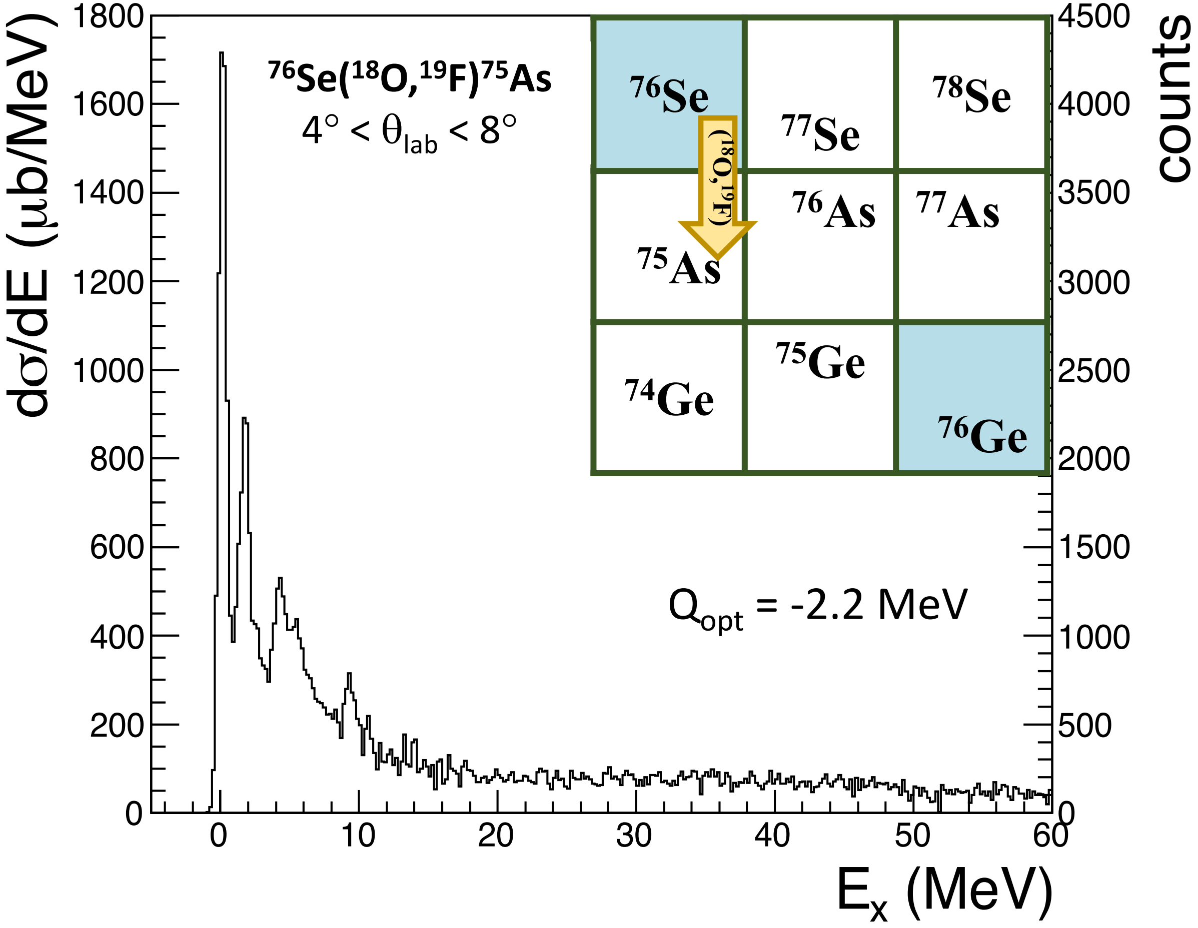
Results: *Energy differential Cross Sections*

$$\frac{d^2\sigma}{dE\,d\Omega} = \frac{N}{N_{beam}N_{target}\Delta E\Delta\Omega\mathcal{E}} \qquad \frac{d\sigma}{dE} = \int \frac{d^2\sigma}{dE\,d\Omega}\,d\Omega$$

One-neutron transfer



One-proton transfer



Results: *Energy differential Cross Sections*

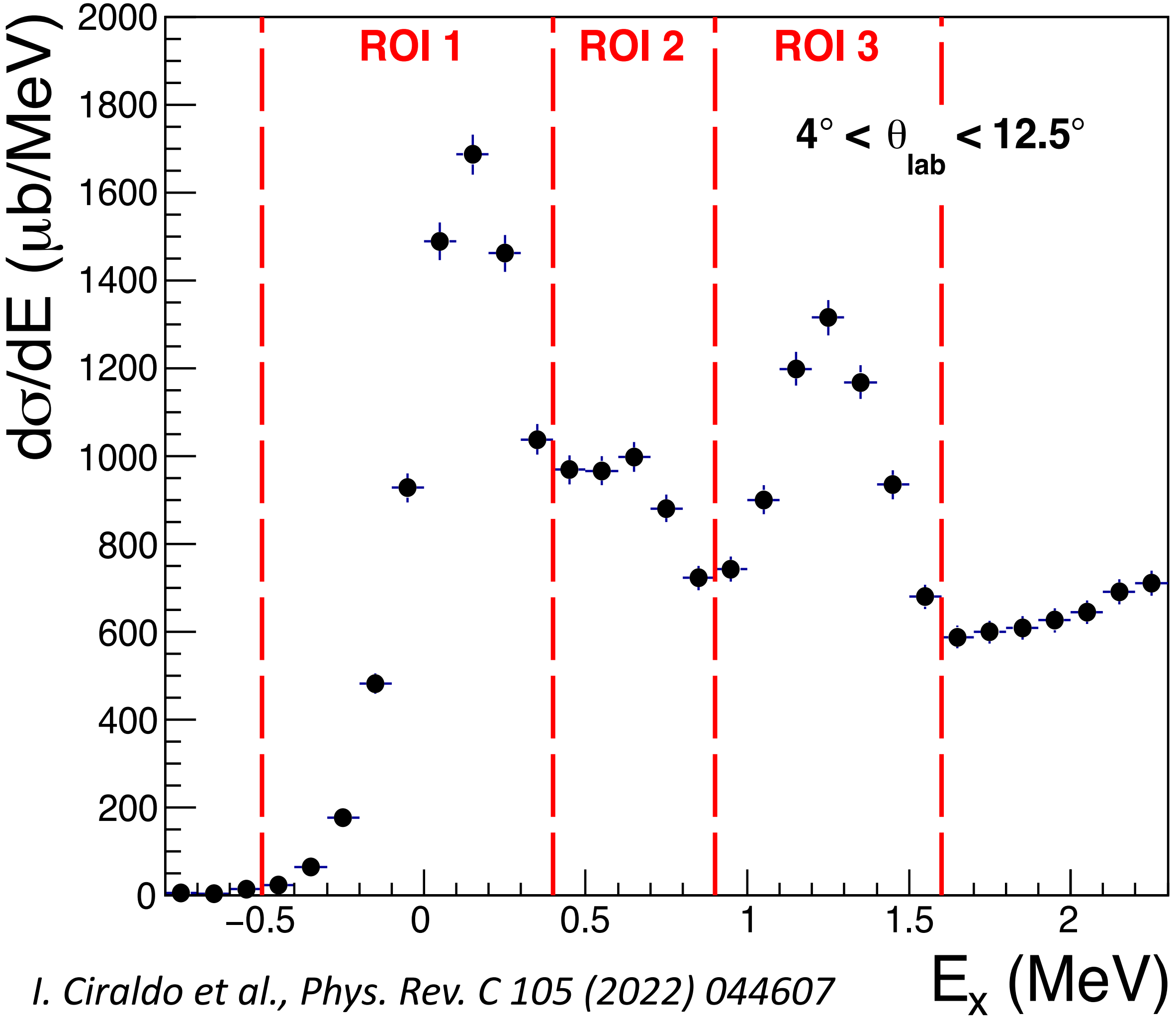
One-neutron transfer

^{76}Se(^{18}O,^{17}O)^{77}Se

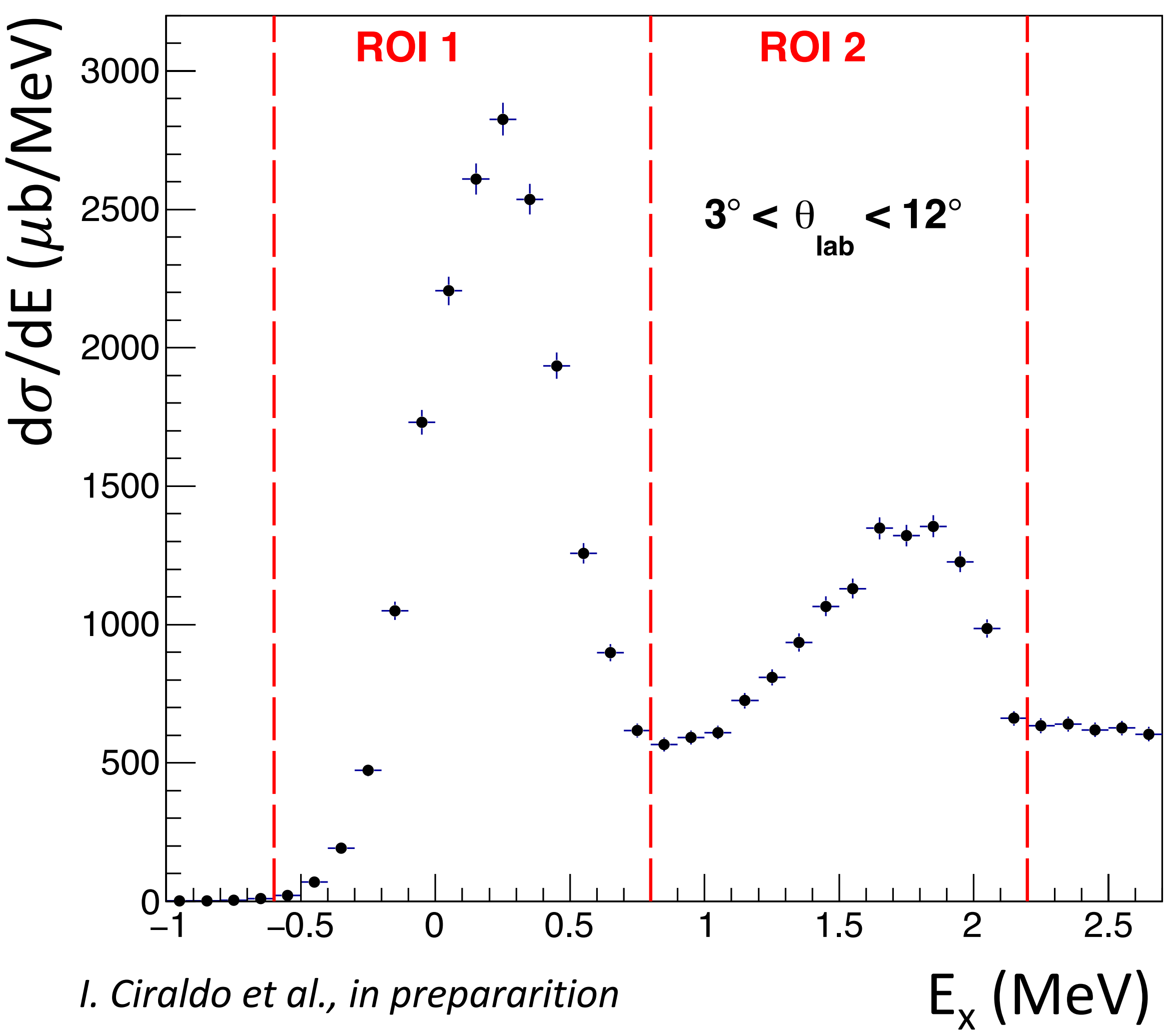
Energy resolution ~310 keV (FWHM)

One-proton transfer

^{76}Se(^{18}O,^{19}F)^{75}As



I. Ciraldo et al., Phys. Rev. C 105 (2022) 044607



I. Ciraldo et al., in prepararition

Theoretical calculations

- The angular distribution data were analyzed within the Distorted-Wave Born Approximation (DWBA) framework.
- The transfer process is weak compared to elastic scattering and thus it can be treated as a weak transition (perturbation) between elastic scattering states.

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

Different reaction models adopted:

__D__istorted __W__ave __B__orn __A__pproximation (DWBA)

__C__oupled __C__hannel __B__orn __A__pproximation (CCBA)

__C__oupled __R__eaction __C__hannel (CRC)

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

- Describe the reaction dynamics at the entrance(α) and exit(β) channel.

Implemented in *FRESCO*

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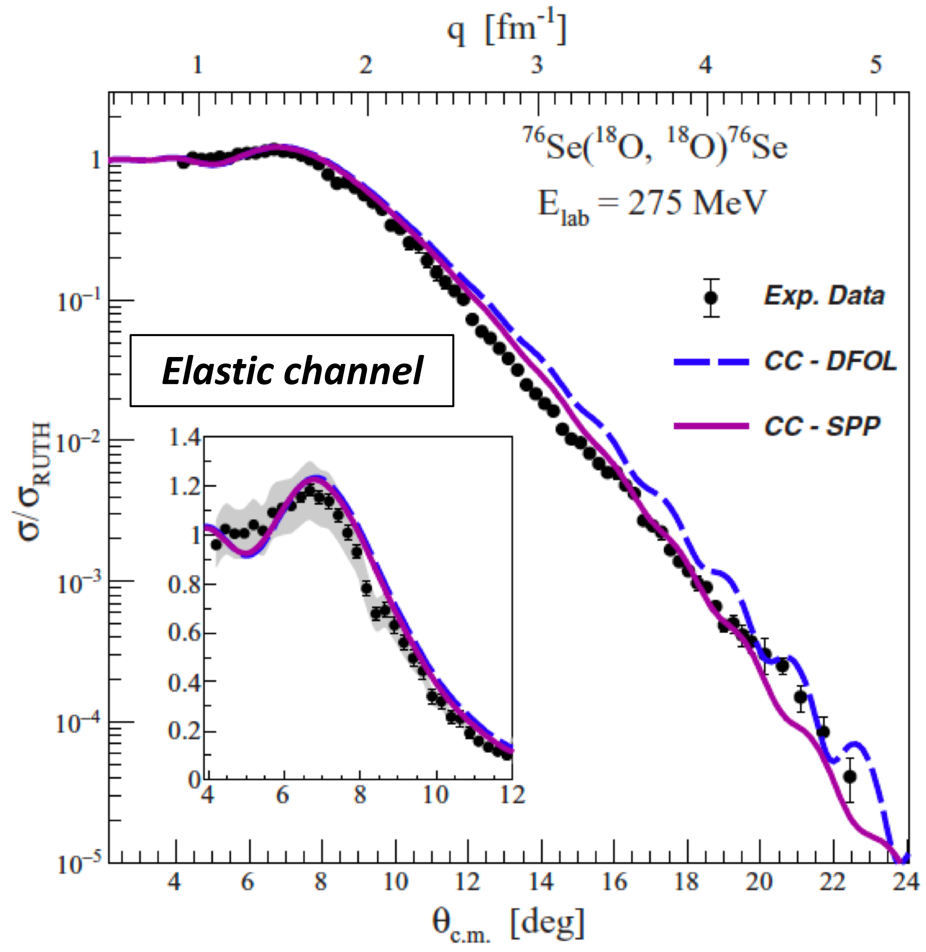
Distorted waves $x_{\alpha,\beta}$

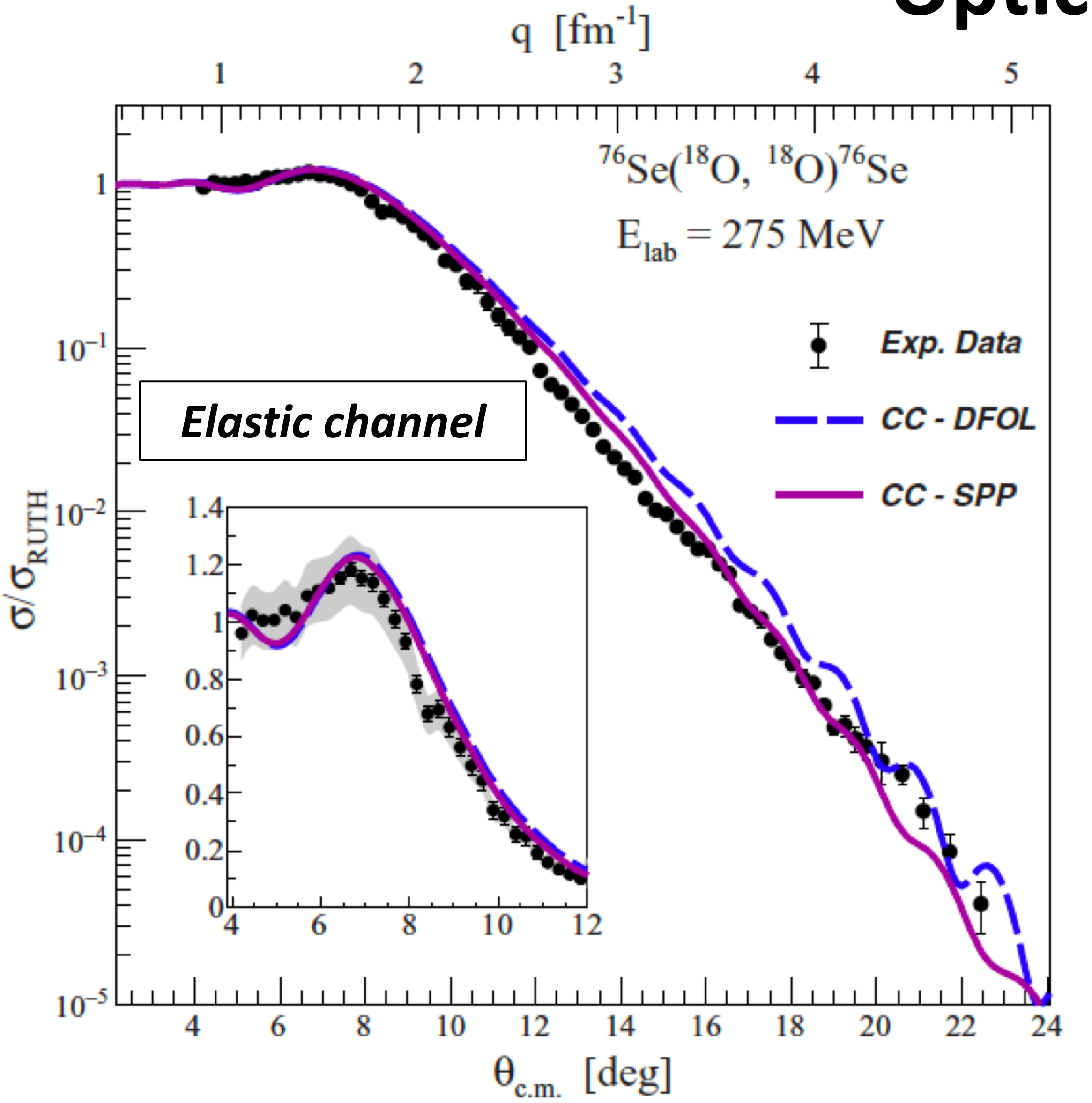
- Describe the reaction dynamics at the entrance(α) and exit(β) channel.
- Solutions of Schrödinger equation using the **nucleus-nucleus potential** chosen according *^{18}O + ^{76}Se elastic and inelastic scattering* analysis

Implemented in *FRESCO*



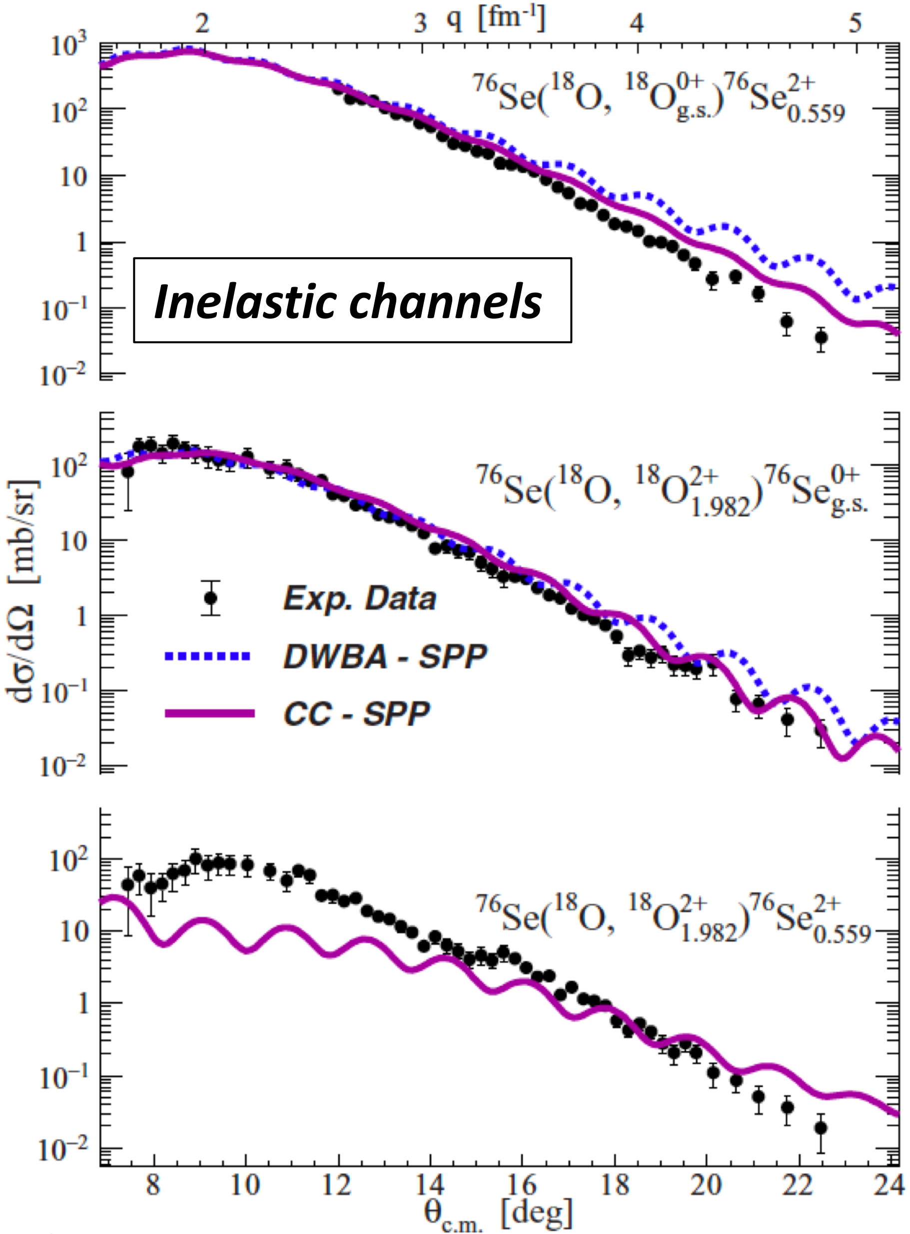
L. La Fauci et al., PRC 104, 054610 (2021)

Optical potential



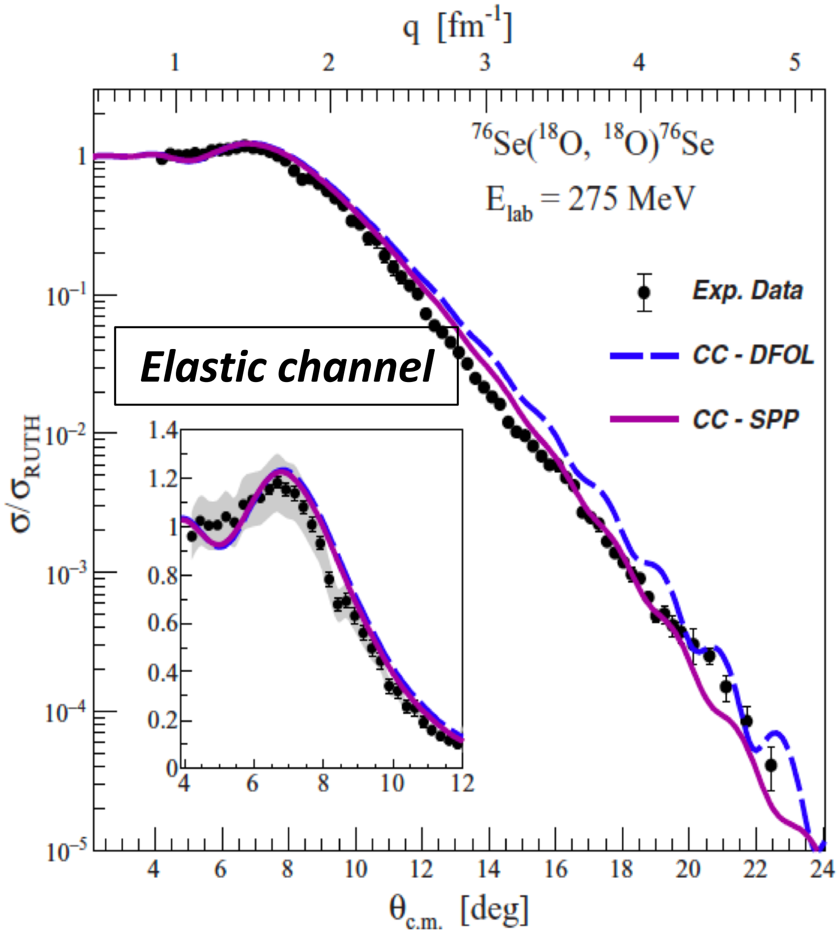
Elastic channel

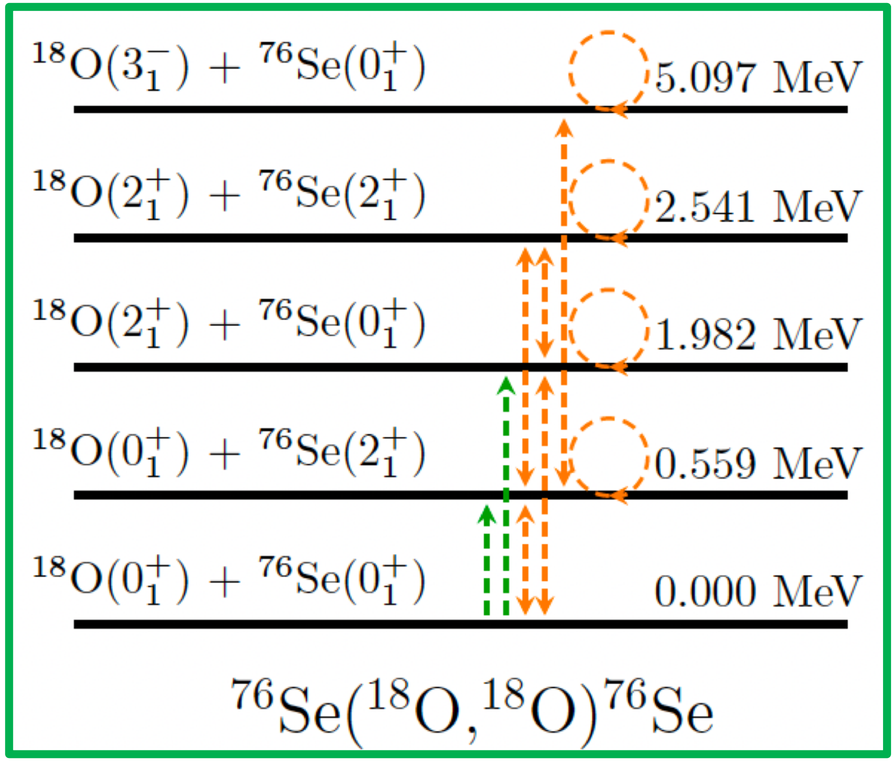
L. La Fauci et al., PRC 104, 054610 (2021)

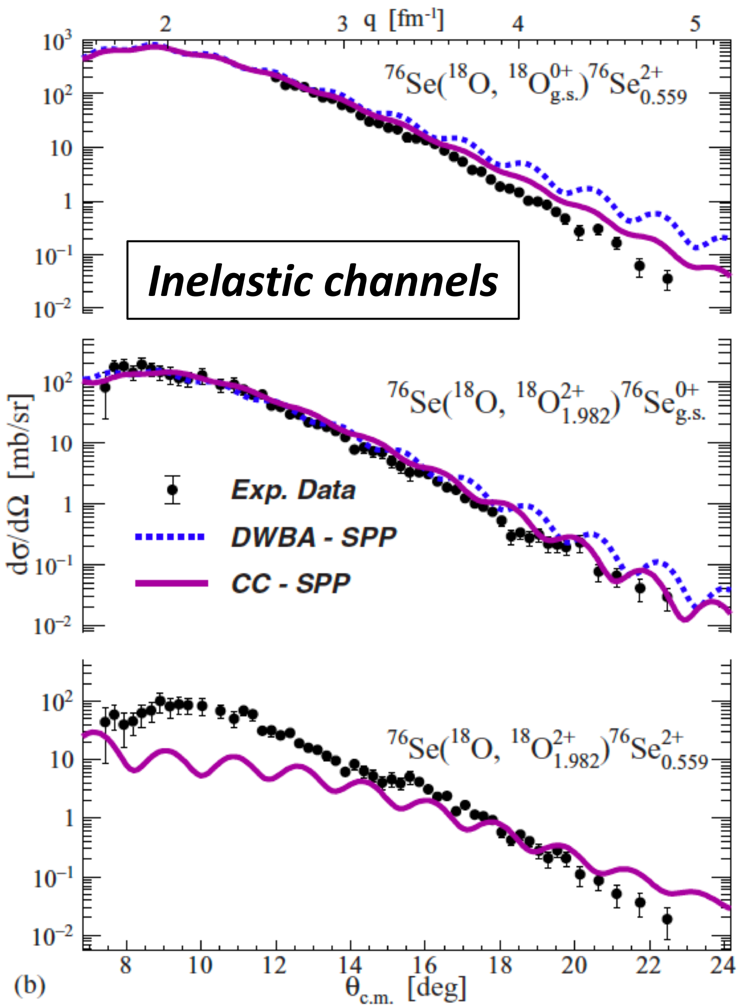


Inelastic channels

Optical potential







- 2^+ and 3^- states of projectile and 2^+ state of target are relevant

Theoretical calculations

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

- Describe the reaction dynamics at the entrance(α) and exit(β) channel.
- Solutions of Schrödinger equation using the nucleus-nucleus potential chosen according $^{18}O + {}^{76}Se$ *elastic and inelastic scattering* analysis
  L. La Fauci et al., PRC 104, 054610 (2021)

Implemented in *FRESCO*

Overlap functions

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

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

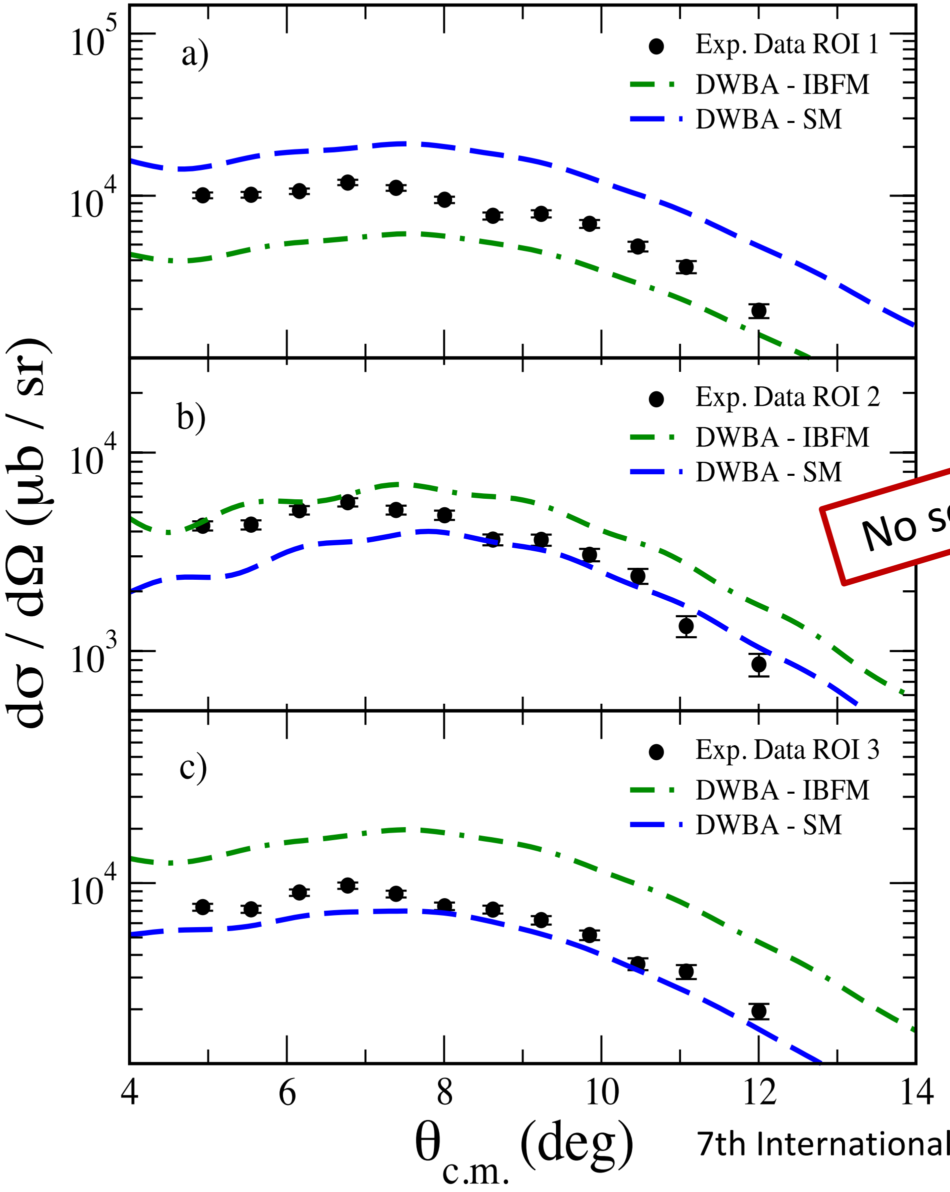
- $\varphi_{\ell sj}$ are single-particle solutions of a Woods-Saxon potential.
- Coefficients $A_{\ell sj}$ and $B_{\ell sj}$ are the spectroscopic amplitudes derived from different nuclear structure models:

Large scale shell-model (SM)

Interacting boson-fermion model (IBFM)

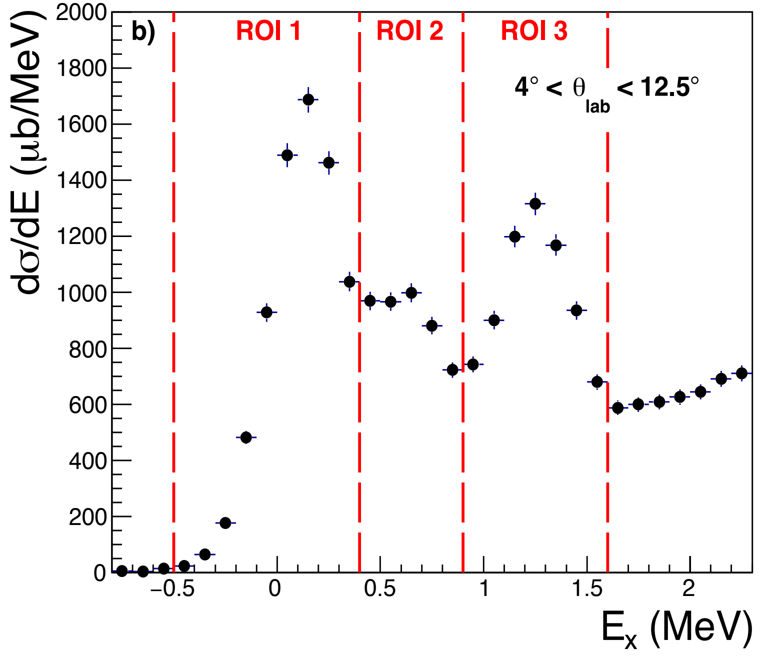
One-neutron transfer
^{76}Se(^{18}O,^{17}O)^{77}Se

Results



Different nuclear structure models:
Large scale shell-model (SM)
Interacting boson-fermion model (IBFM)
Same model space

No scaling factor adopted!



- SM results better than IBFM ones

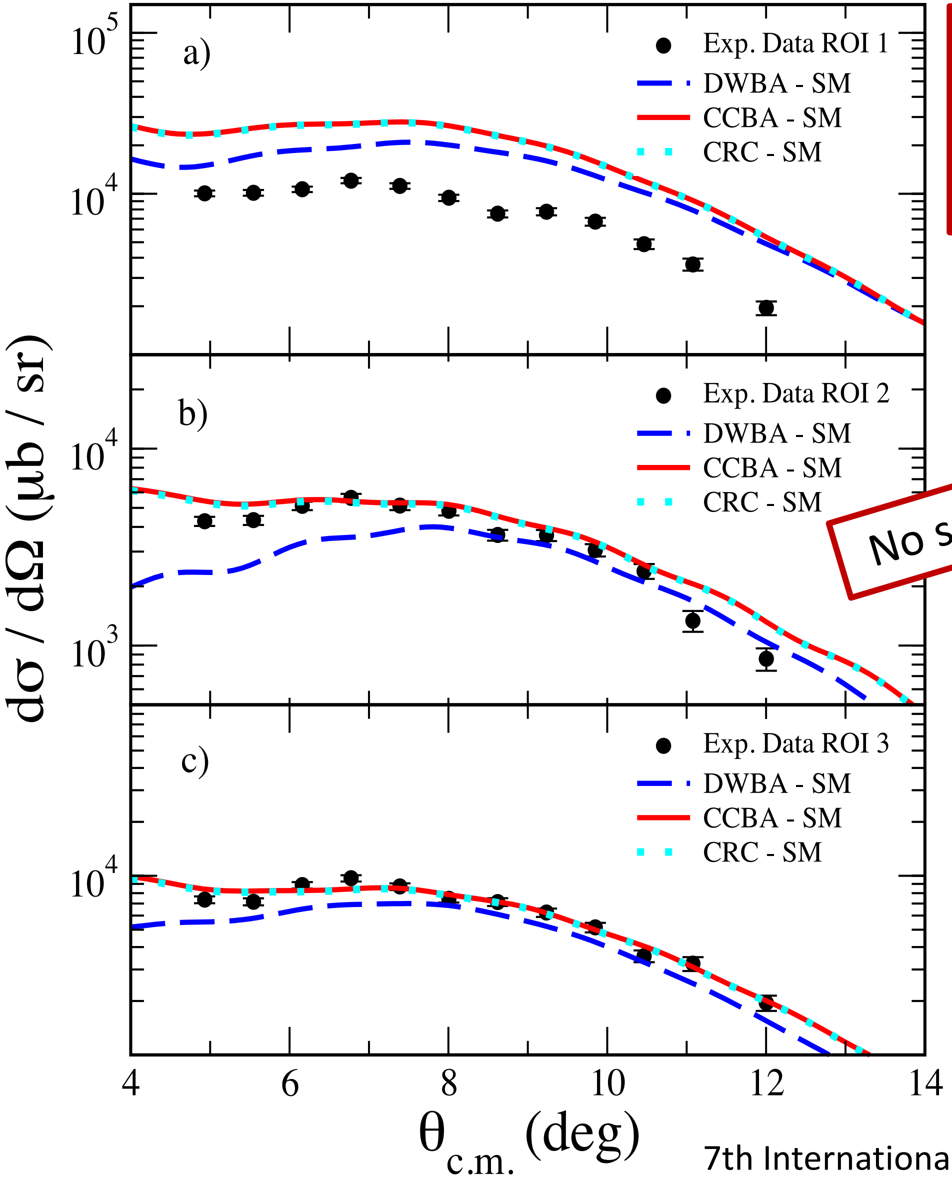
Experimental data sensitive to different nuclear structure models!

I. Ciraldo et al., PRC 105 (2022) 044607

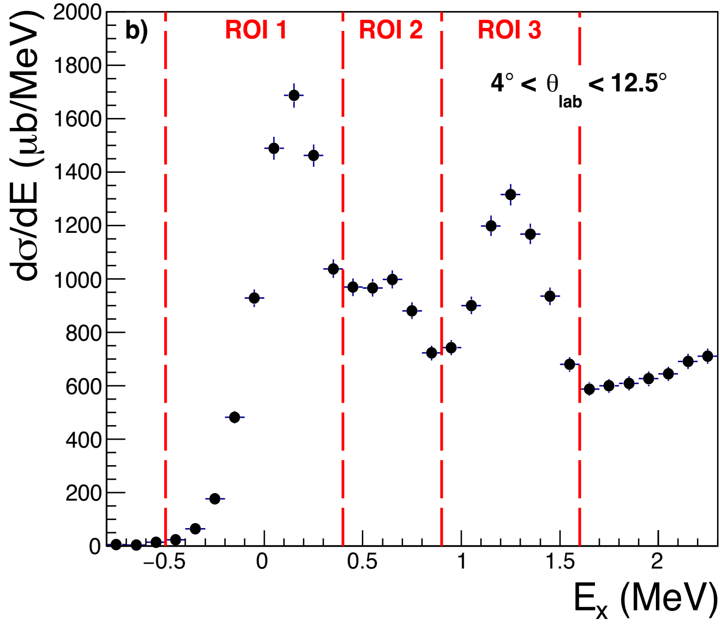
One-neutron transfer

^{76}Se(^{18}O,^{17}O)^{77}Se

Results



Different reaction models:
Distorted Wave Born Approximation (DWBA)
Coupled Channel Born Approximation (CCBA)
Coupled Reaction Channel (CRC)



No scaling factor adopted!

- CCBA significant improvement respect to DWBA
- CCBA – CRC equivalence
- Good description of the data

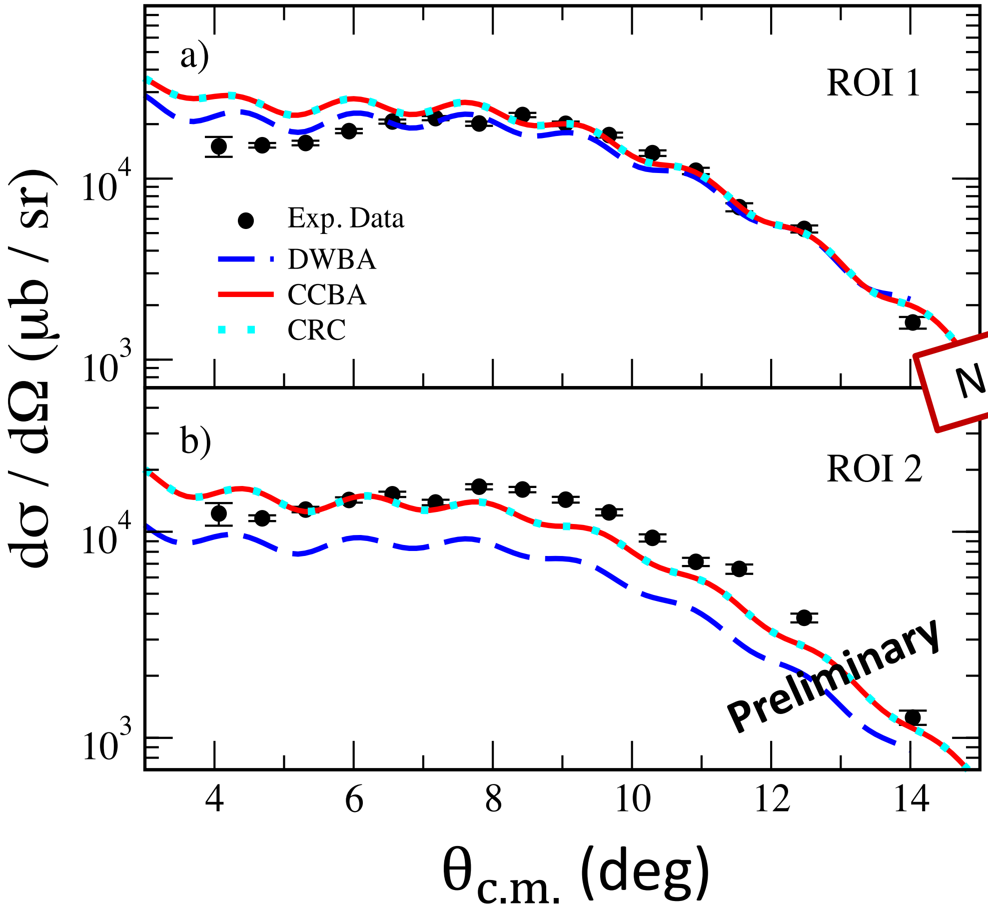
Reaction mechanism under control!

I. Ciraldo et al., PRC 105 (2022) 044607

Results

One-proton transfer

$^{76}Se(^{18}O,^{19}F)^{75}As$



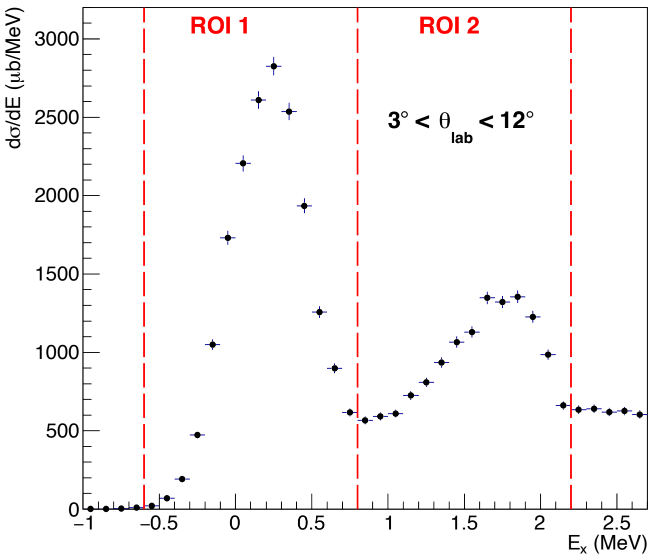
No scaling factor adopted!

Different reaction models:

*Distorted **W**ave **B**orn **A**pproximation (DWBA)*

*Coupled **C**hannel **B**orn **A**pproximation (CCBA)*

***C**oupled **R**eaction **C**hannel (CRC)*



- CCBA significant improvement respect to DWBA
- CCBA – CRC equivalence
- Satisfactory description of the data

Reaction mechanism under control!

I. Ciraldo et al., in preparation

Conclusions and perspectives

- ✓ Energy spectrum and cross section angular distributions for transitions to low-lying states have been extracted and compared to theoretical calculations

- ➢ Thank to the **multi-channel approach,** the description of the **elastic, inelastic and one-nucleon transfer reactions** is **satisfactory**
- ➢ CCBA provides significant improvement respect to DWBA

envisaged also for **single and double charge exchange reactions**

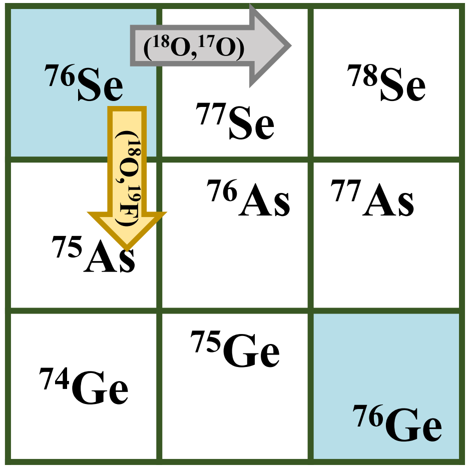
Reaction mechanism is under control!

- ➢ **Heavy-ion induced one-nucleon transfer** reactions data are **sensitive to different nuclear structure models**
- ➢ SM results better than IBFM ones in one-neutron transfer analysis

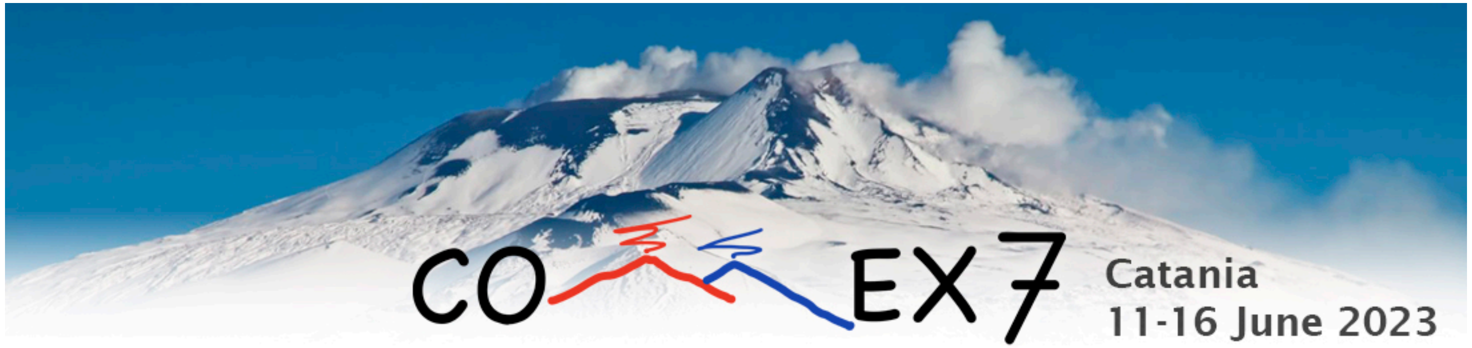
envisaged also for **one-proton transfer reaction**

New constraints for NUMEN purposes are achieved!

One-proton pickup
$^{76}Se(^{18}O,^{19}F)^{75}As$



One-neutron stripping
$^{76}Se(^{18}O,^{17}O)^{77}Se$



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Thank you for your attention!