Differential cross-section measurements and R – matrix calculations for the elastic scattering of low energy protons on ^{19}F, suitable for IBA purposes

E. Taimpiri[1,2], A. Lagoyannis[1], M. Axiotis[1], V. Foteinou[3], M. Kokkoris[2], F. Maragkos[4]

[1] *Tandem Accelerator Laboratory, Institute of Nuclear and Particle Physics, N.C.S.R. "Demokritos", Aghia Paraskevi, 15310 Athens, Greece*

[2] *Department of Physics, National Technical University of Athens, Zografou Campus, 15780 Athens, Greece*

[3] *Department of Physics, University of Ioannina, 45110 Ioannina, Greece*

[4] *Central Unit for Ion Beams and Radionuclides, Ruhr University Bochum, 44801 Bochum, Germany*

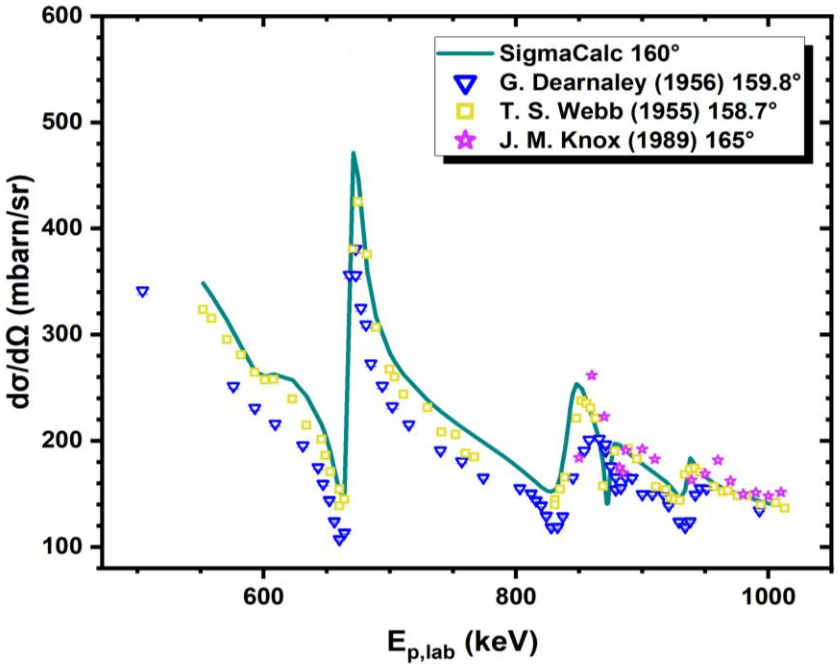
34th Annual Symposium of the Hellenic Nuclear Physics Society, HNPS2026
5 – 6 June 2026, Lamia, University of Thessaly, Physics Department

Motivation

Fluorine : monoisotopic **100% ^{19}F** ➡ Industrial and technological applications ➡ Need for detection and depth profiling via the **p-EBS** technique

- Effective **MEIS** (**M**edium **E**nergy **I**on **S**cattering) technique ($E_{p,lab}$=100 – 300 keV) ➡ Highly sensitive to surface layers

<u>Necessity of reliable differential cross sections and extension of the theoretically evaluated datasets below 0.5 MeV</u>



- No data below 515 keV
- Evaluation above 550 keV
- Discrepancies in the whole energy range

! Indications for the presence of resonances below 500 keV

➢ **Aim:** Differential cross-section data for the elastic scattering of protons on ^{19}F, followed by R – matrix calculations

Experimental setup

Tandem Laboratory of RUBION, Ruhr University Bochum, Germany

500 kV accelerator (single – ended)

Proton energy range**:** 200 – 340 keV

➡ 10 keV step

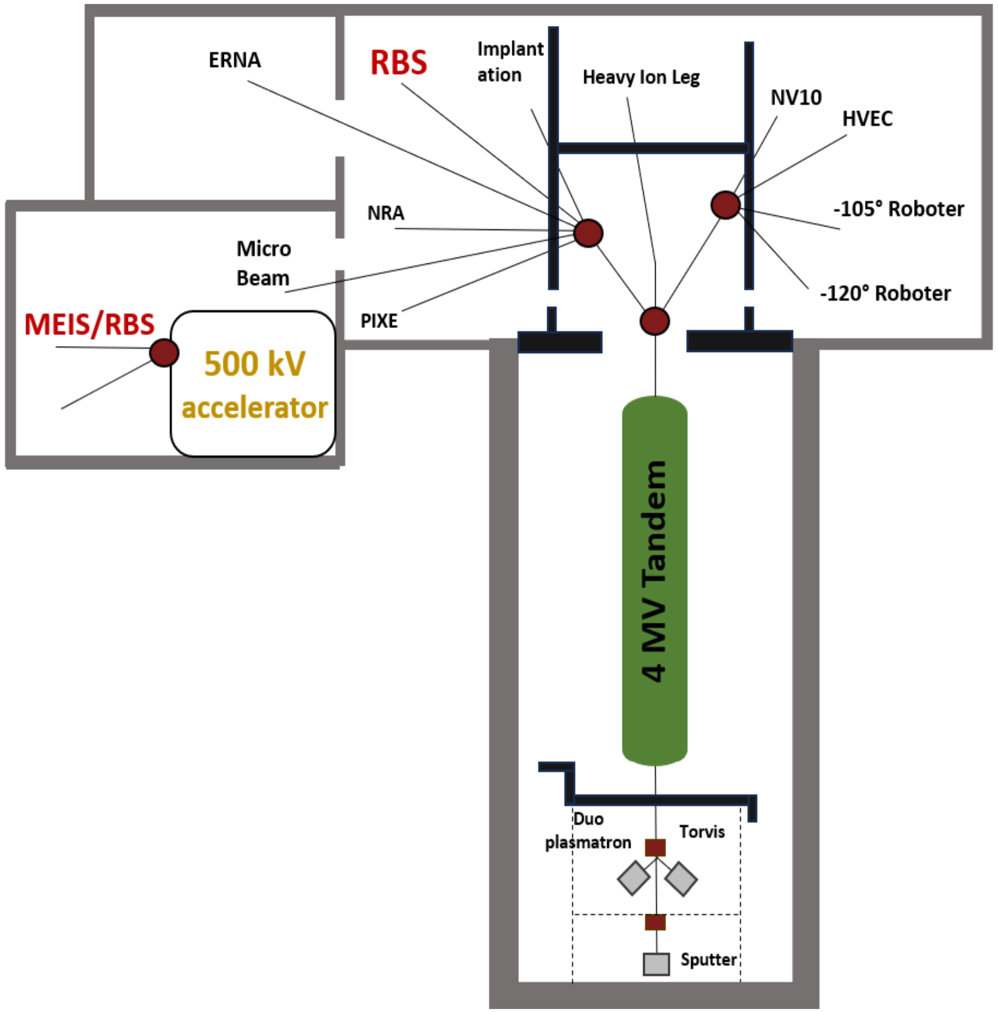
- Energy calibration: Ripple: 0.8 keV

4 MV Dynamitron Accelerator

Proton energy range**:** 300 – 1000 keV

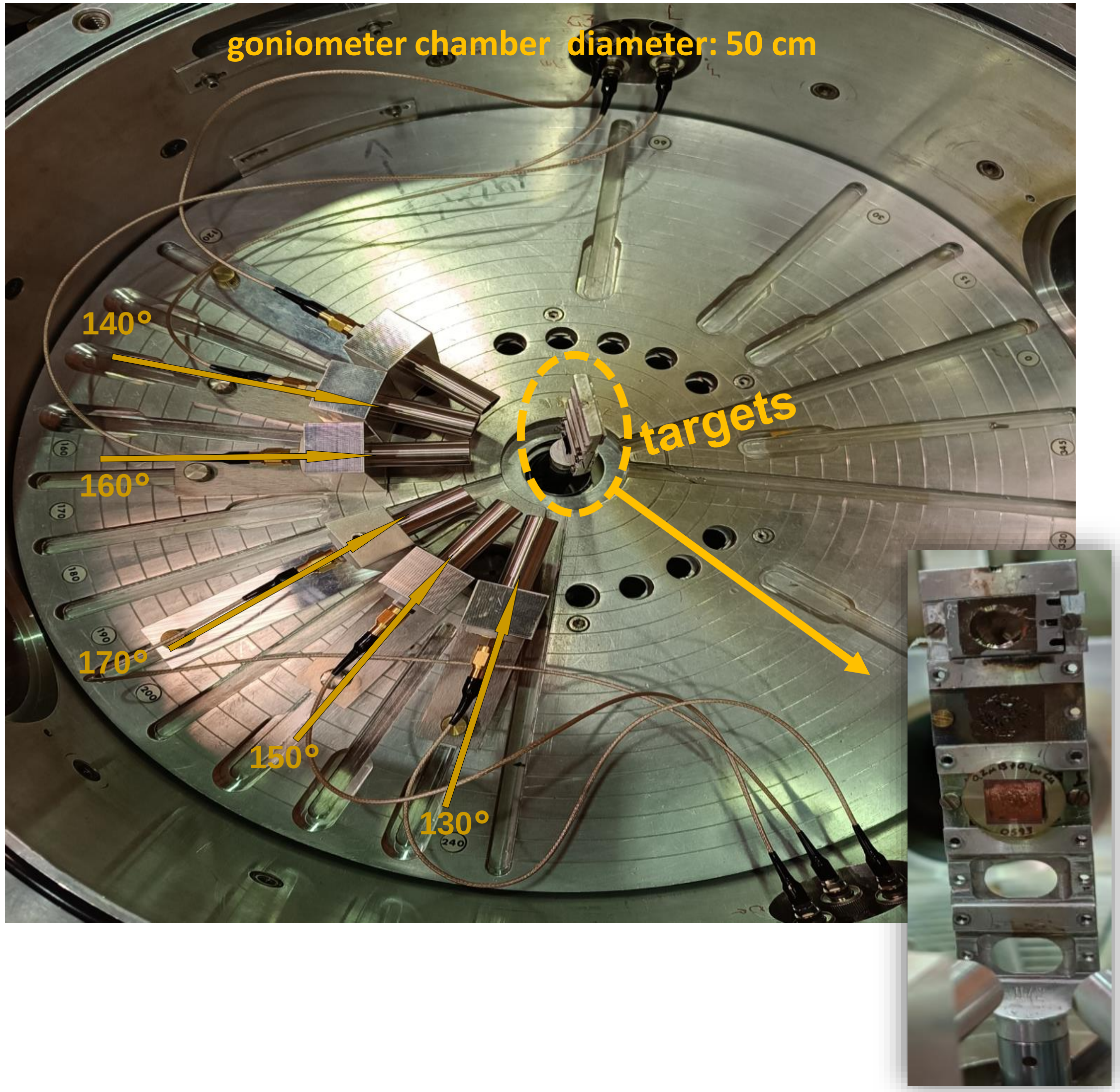
➡ 25 keV step

- Energy calibration: Ripple: 0.4 keV



Experimental setup

Tandem Laboratory of RUBION, Ruhr University Bochum, Germany



Targets

- 2 different thin LiF (95% ^{6}Li, 5% ^{7}Li) evaporated on top of a ^{12}C substrate
  - The LiF target used in the measurements at the 500 kV accelerator, contained an ultra-thin layer of ^{197}Au on top

* ^{197}Au and ^{nat}C were used for normalization purposes

Detection system

- Five backscattering detection angles
  - 4 SSB detectors placed at 130°,140° and 160°
  - 2 PIPS detectors placed at 150° and 170°
- ~ 7.5 cm far from the targets
- Orthogonal tantalum slits (~ 4×8 mm^2) to reduce the azimuthal angular uncertainty (~± 1.5°)
- Aluminum tubes (length: 3.4 cm, d=1 cm) to reduce background due scattering on the chamber walls

Data Analysis

Relative measurement

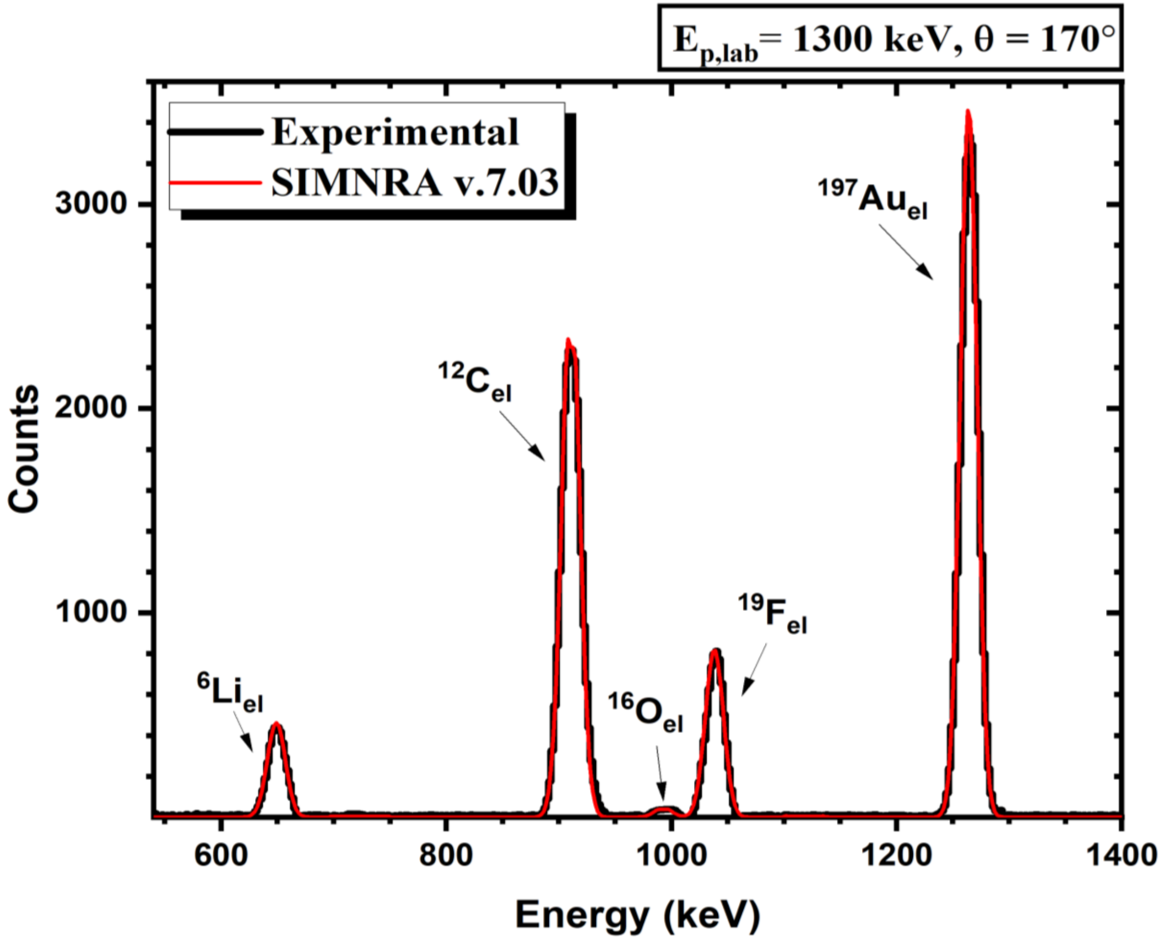
$$\left(\frac{d\sigma}{d\Omega}\right)_{E_1,\theta}^{reaction} = \left(\frac{d\sigma}{d\Omega}\right)_{E_2,\theta}^{^{197}Au,^{12}C} \frac{Y_{reaction}}{Y_{^{197}Au,^{12}C}} \frac{N_{^{197}Au,^{12}C}}{N_{isotope}}$$

where,

- $\left(\frac{d\sigma}{d\Omega}\right)_{E_2,\theta}^{^{197}Au,^{12}C}$: the differential cross-section of Au, C, where E_2 corresponds to the energy at half of ^{197}Au,^{12}C thickness and θ the detection angle in the lab frame
  - For $\left(\frac{d\sigma}{d\Omega}\right)_{E_2,\theta}^{^{197}Au}$, the Rutherford formula was used, corrected for the electronic screening effect
  - For $\left(\frac{d\sigma}{d\Omega}\right)_{E_2,\theta}^{^{12}C}$, evaluated data were used, provided by the SigmaCalc code
- $\frac{Y_{reaction}}{Y_{^{197}Au,^{12}C}}$: $\frac{\text{experimental yield of the studied reaction}}{\text{experimental yield of } ^{197}Au,^{12}C \text{ peak}}$: *Yield ratio*
- $\frac{N_{^{197}Au,^{12}C}}{N_{isotope}}$: $\frac{\text{thickness of the } ^{197}Au,^{12}C \text{ layer, in } atoms/cm^2}{\text{thickness of the studied isotope layer, in } atoms/cm^2}$: *Thickness ratio*

Data Analysis: *Thickness ratio*

- ^{6}LiF (95% ^{6}Li, 5% ^{7}Li) targets: via the **EBS** technique, for proton energies of E_p = 1.3 MeV, 1.5 MeV, 1.62 MeV, 2 MeV
- Simulation via the SIMNRA code

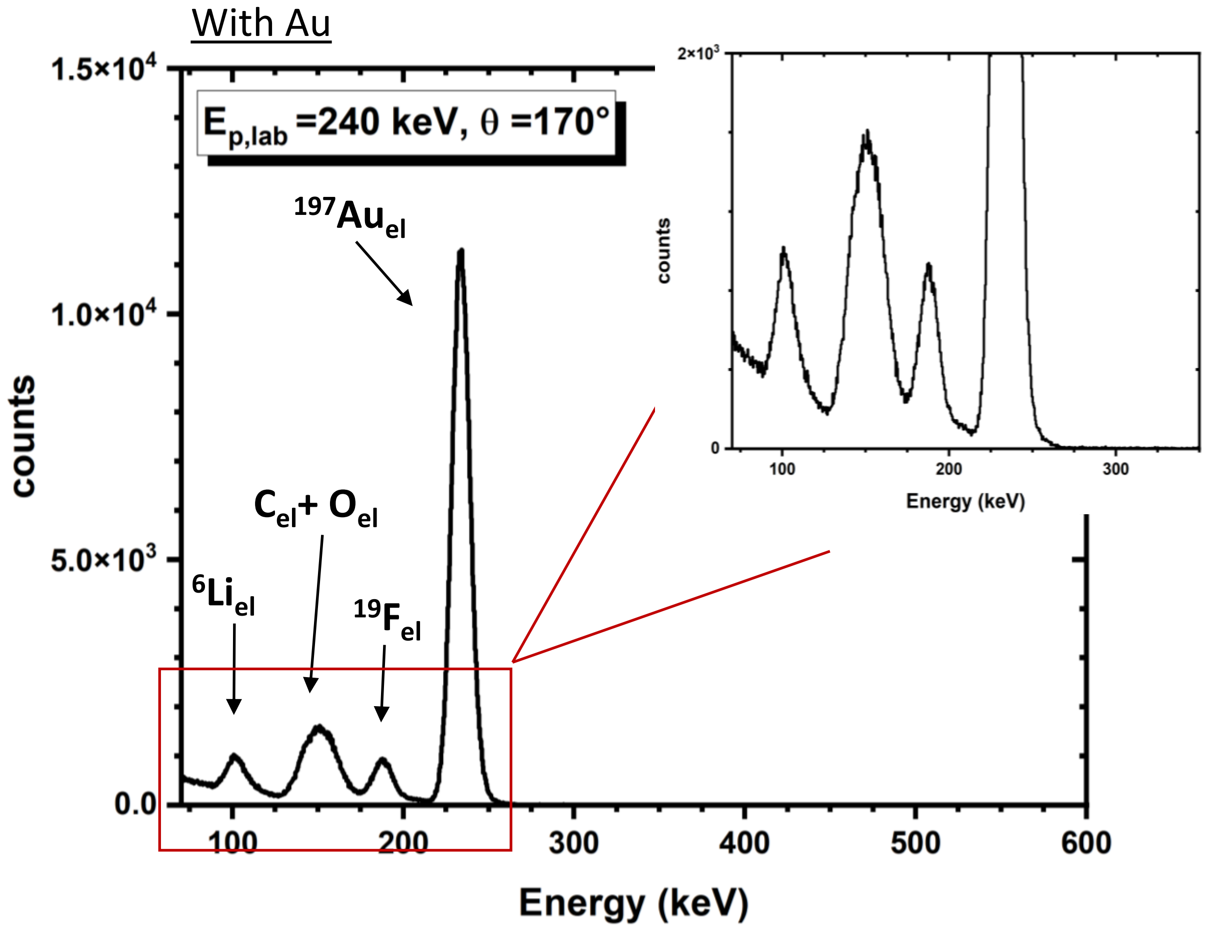


- Rutherford cross section for ^{197}Au(p,p_0) ^{197}Au
- Data for ^{6}Li(p,p_0) ^{6}Li : U. Fasoli *et al.*
- Evaluated cross-section data for ^{19}F(p,p_0) ^{19}F and ^{12}C(p,p_0) ^{12}C (SigmaCalc 2.0)

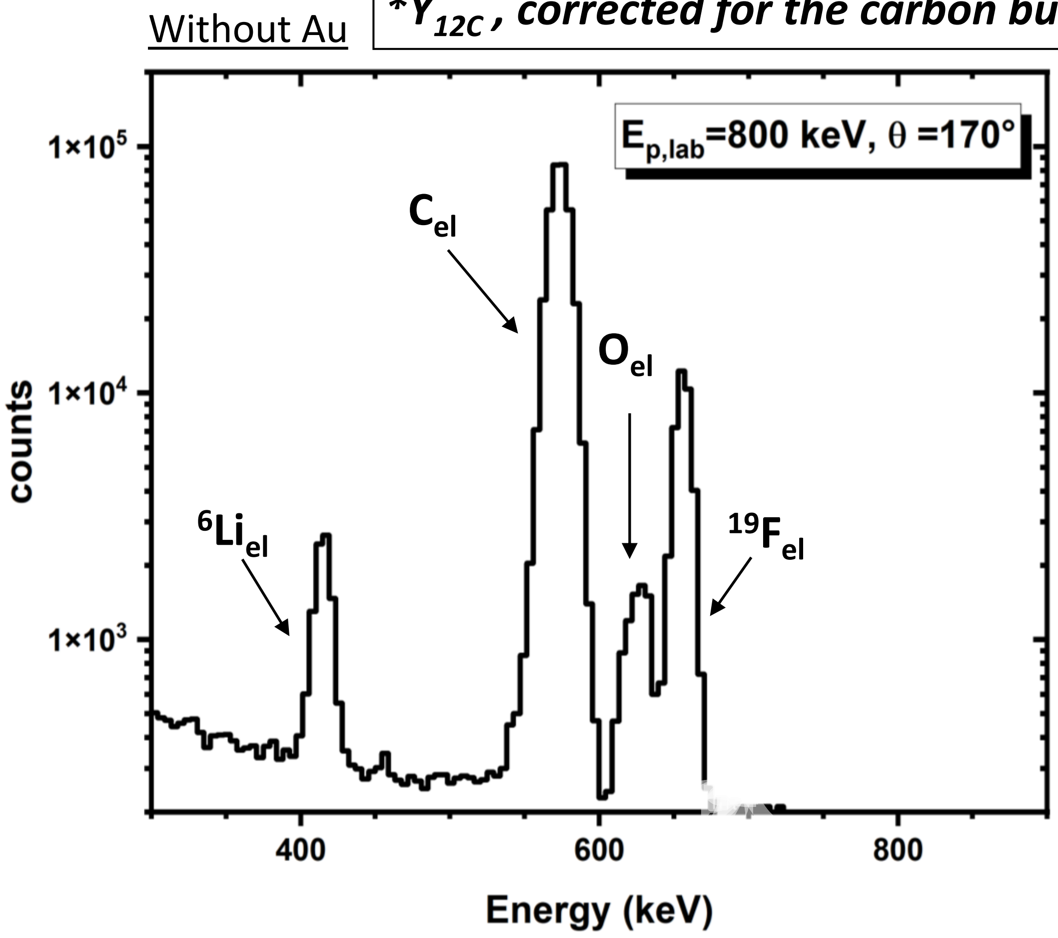
Uncertainty: ~ 5%

Data Analysis: *Yield ratio*

- Peak integration/fit via the TV code, Uncertainty: ~4 % for ^{19}F, ~0.5% for ^{12}C & ~0.2 % for Au peaks, in all spectra
  ^{6}LiF (95% ^{6}Li, 5% ^{7}Li) targets

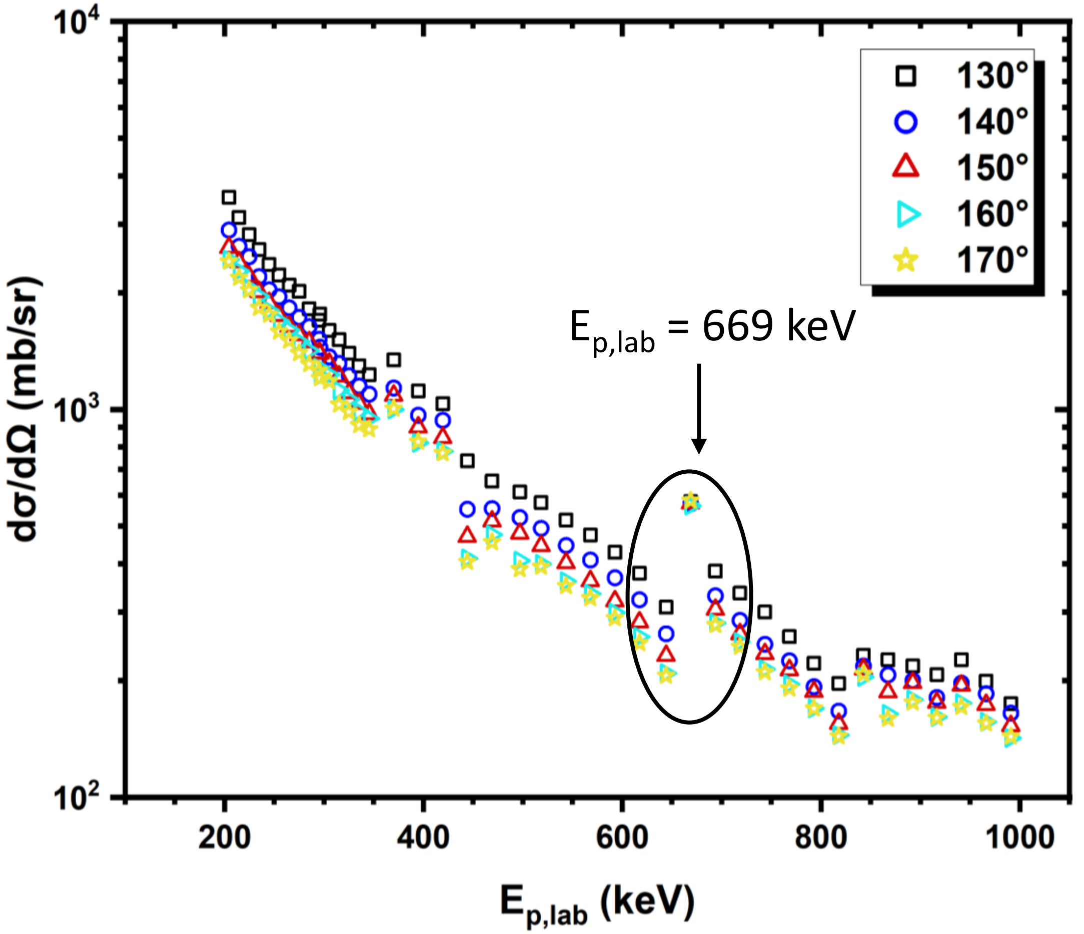


$^{*}Y_{12C}$, corrected for the carbon built-up*

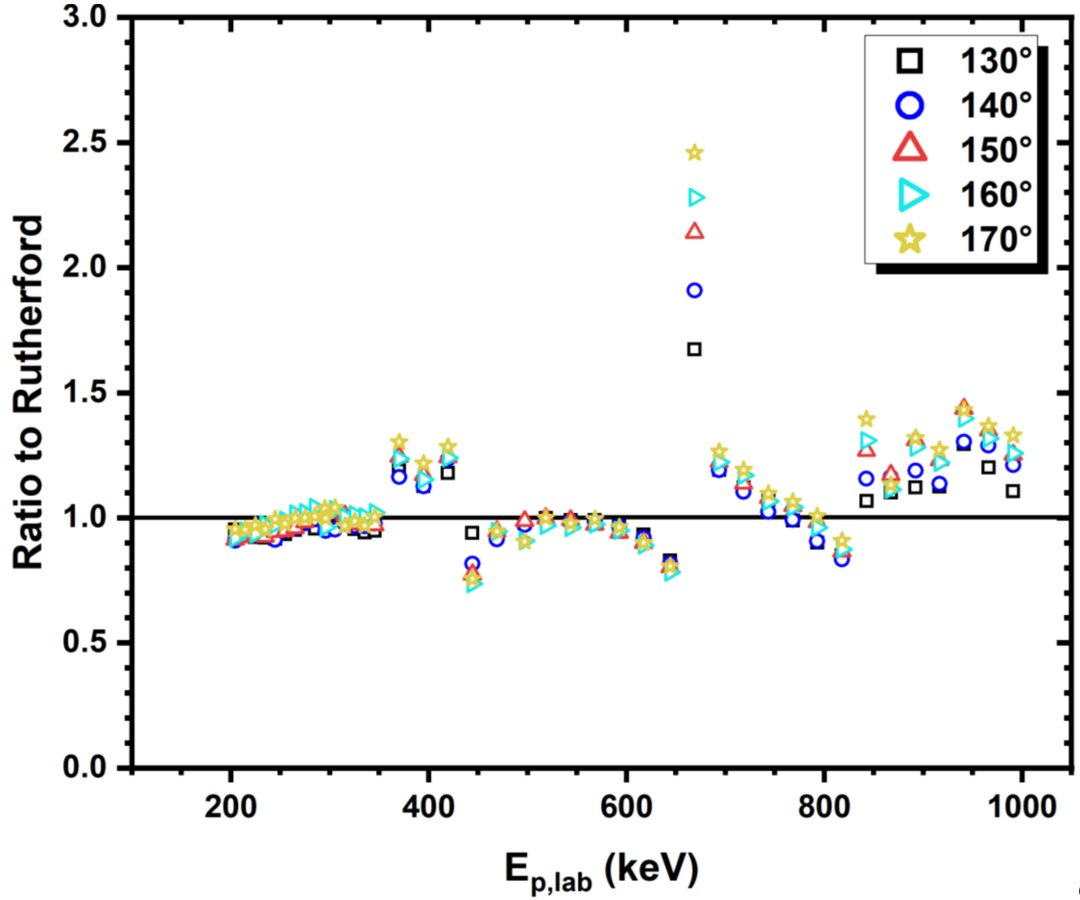


Results: Differential cross section

$^{19}F(p,p_0)^{19}F$



Ratio to Rutherford



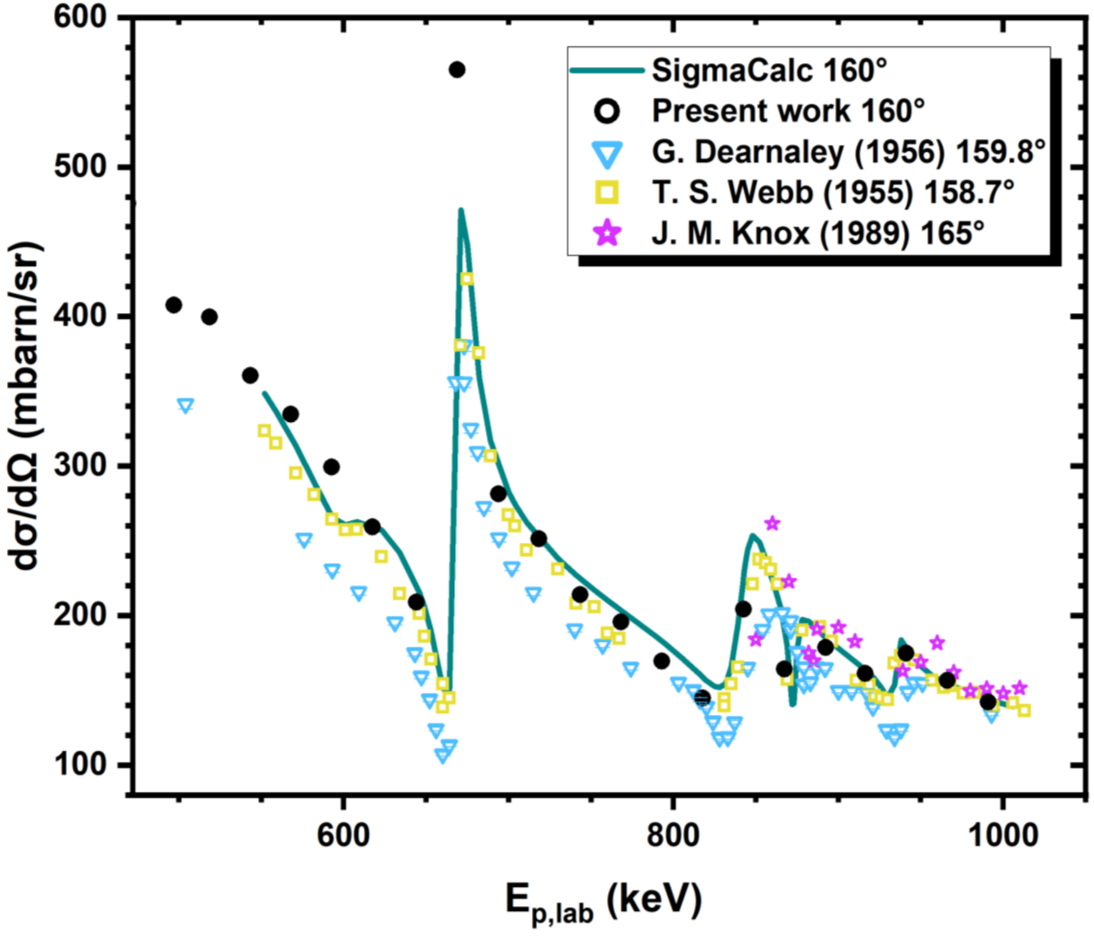
- δE ~3 keV, up to 350 keV
- δE ~2 keV, up to 1000 keV

- <u>Uncertainties</u>
  Systematic: ~ 5%
  Statistical: ~ 4%

Results: Comparison with literature

$^{19}F(p,p_0)^{19}F$

160°

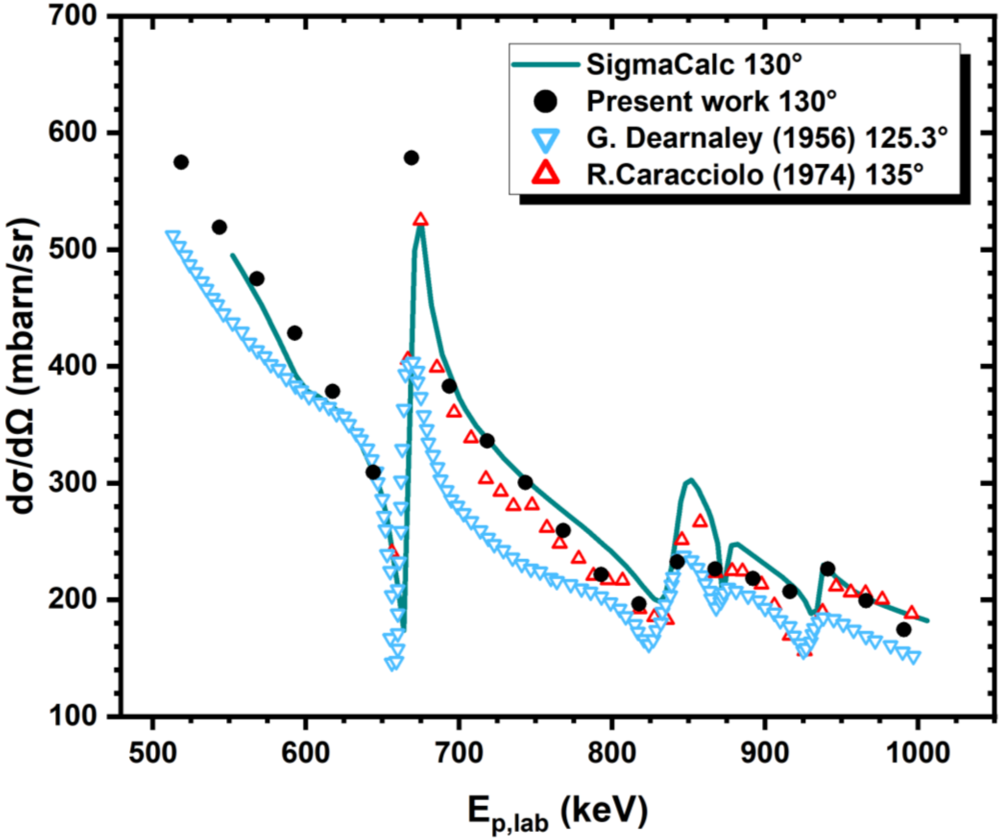


- Satisfactory agreement with SigmaCalc (< 7%, in most cases)
- ~ 14% difference for the resonance at $E_{p,lab}$ = 669 keV
- Underestimated data by Dearnaley (159.8°): 6% to 22%
- Differences with data by Webb (158.7°): 4% - 15%, below 700 keV
  Really good agreement (< 5%) for higher energies
- Data by Knox (165°): energy shifted

Results: Comparison with literature

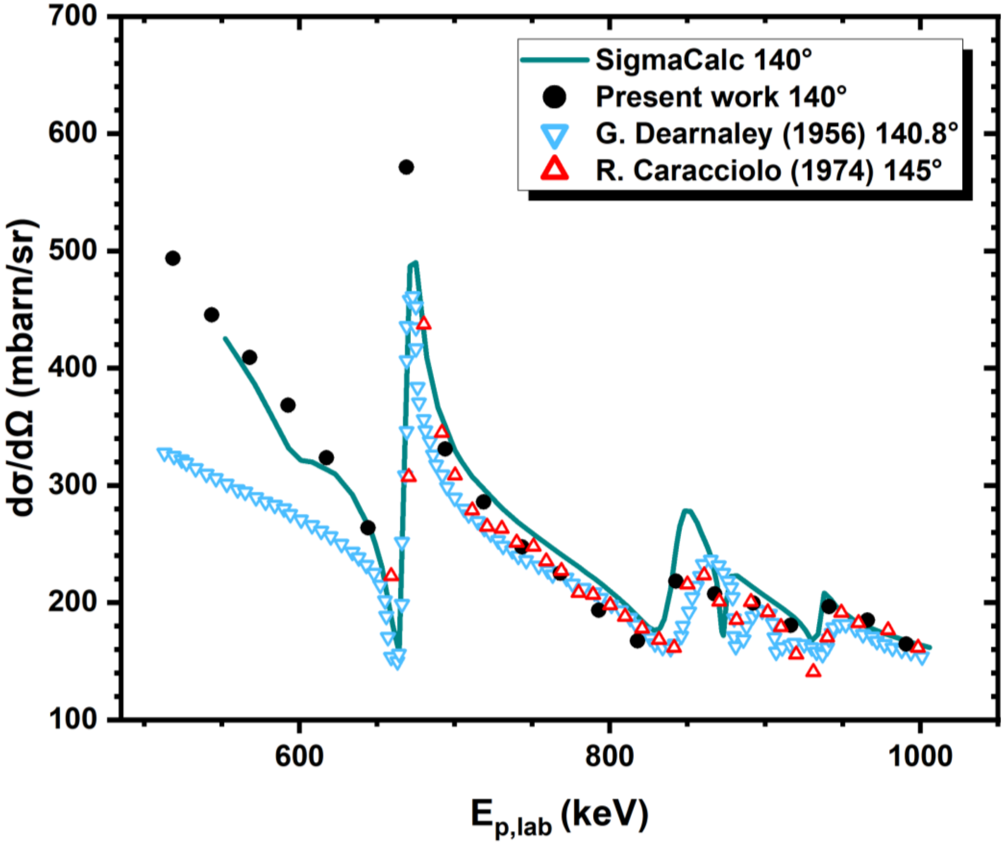
$^{19}F(p,p_0)^{19}F$

130°



- Satisfactory agreement with SigmaCalc (< 7%, in most cases)
- ~ 14% difference for the resonance at $E_{p,lab}$ = 669 keV

140°

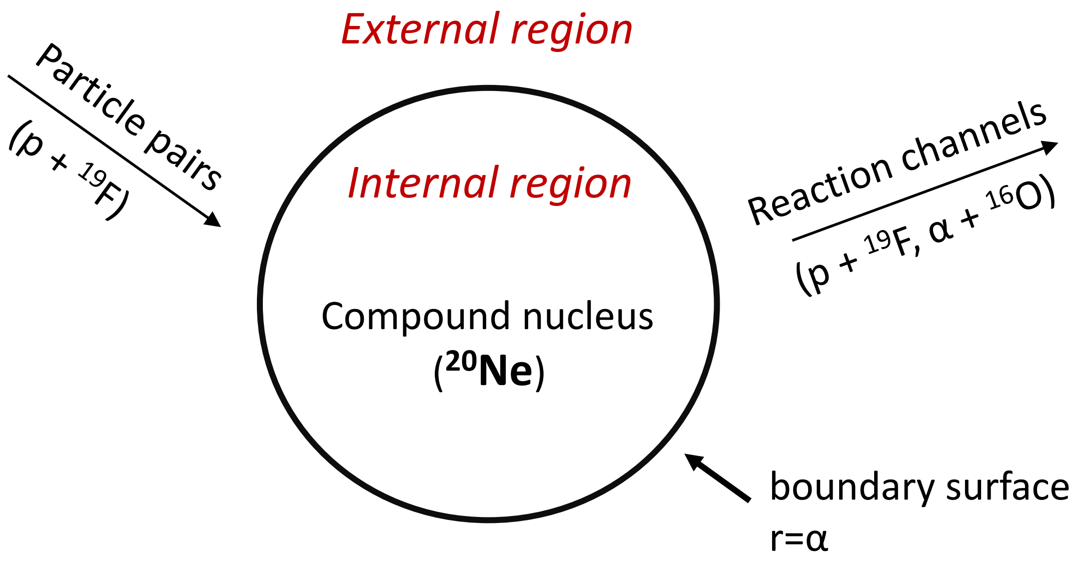


- Deviations with data by R. Caracciolo at specific energies
  Good agreement (< 6%) in most cases
- Underestimated data by Dearnaley (159.8°): 6% to 22%

Theoretical Investigation: R – matrix framework

- Theoretically describes experimental cross-section data (dominated by *Breit-Wigner* resonances)
- Compound nucleus remains in the discrete level energy range
- Hard-sphere approximation

Basic principle



- Adjustable parameters

  $E_{R,CM}$, l, J^{π}, Γ_{total} and Γ_l, r

- Solves the Schrödinger equation in the internal and external regions, matching them at the channel radius r (B_c, δ_l)

- $\sigma \propto \sin^2\delta_l$

Theoretical Investigation: AZURE 2.0 code

- **6 particle pairs/reaction channels**

Light Particle		Heavy Particle		Excitation Energy (MeV)	Separation Energy (MeV)	Radius (fm)
Symbol	J^{π}	Symbol	J^{π}			
p	$1/2^+$	^{19}F	$1/2^+$	0	12.843	5.1357
p	$1/2^+$	^{19}F	$1/2^+$	0.1099	12.843	5.1357
p	$1/2^+$	^{19}F	$1/2^+$	0.1971	12.843	5.1357
α	0^+	^{16}O	0^+	0	4.73	5.7501
γ	1^+	^{20}Ne	0^+	0	0	0
^{8}Be	0^+	^{12}C	0^+	0	11.984	6.0051

- **10 excited states of the compound $^{20}Ne^*$ were used** (out of the 28 included) and **3 outside levels**

Present work			Literature		
$E_{R,CM}$ (MeV)	J^{π}	Γ_{total} (keV)	$E_{R,CM}$ (MeV)	J^{π}	Γ_{total} (keV)
13.2175	**0^+**	**40**	**13.222**	**0^+**	**40**
13.265	**1^-**	**80**	**13.224**	**1^-**	**80**
13.3075	**1^+**	**1**	**13.3075**	**1^+**	**0.9**
13.414	**3^-**	**24**	**13.414**	**3^-**	**24**
13.461	**1^-**	**195**	**13.461**	**1^-**	**195**
13.477	**1^+**	**6.4**	**13.484**	**1^+**	**6.4**
13.645	**0^+**	**18**	**13.642**	**0^+**	**17**
13.674	**2^-**	**4.5**	**13.676**	**(2^-)**	**4.5**
13.735	**1^+**	**7.7**	**13.736**	**1^+**	**7.7**
13.744	**0^+**	**80**	**13.744**	**0^+**	**80**
13.866	1^-	170	13.866	1^-	175
13.908	2^+	74	13.908	2^+	74
14.5	1^+	800	Artificial		

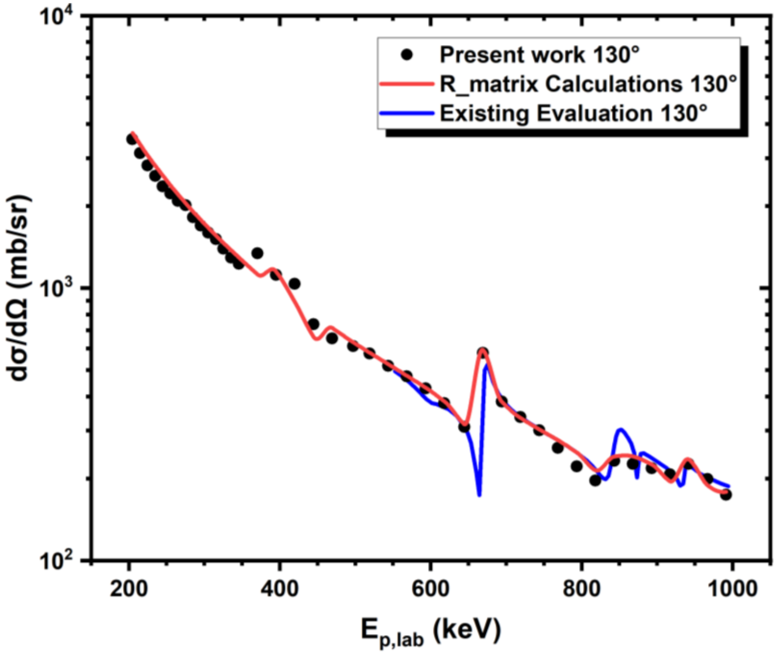
$E_{exc}^{lower} = 13.03\ MeV$

$E_{exc}^{upper} = 13.79\ MeV$

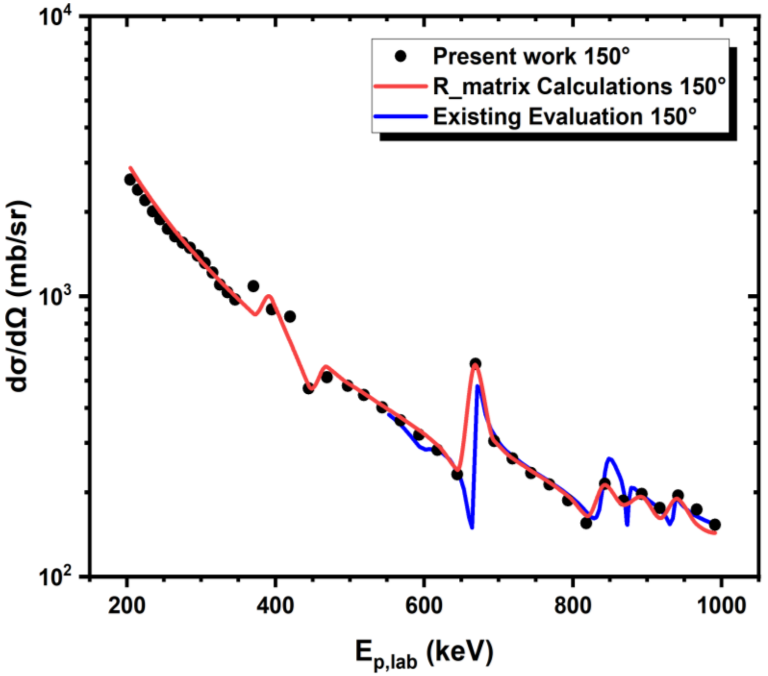
https://www.nndc.bnl.gov/nudat3/

Theoretical Investigation: Results

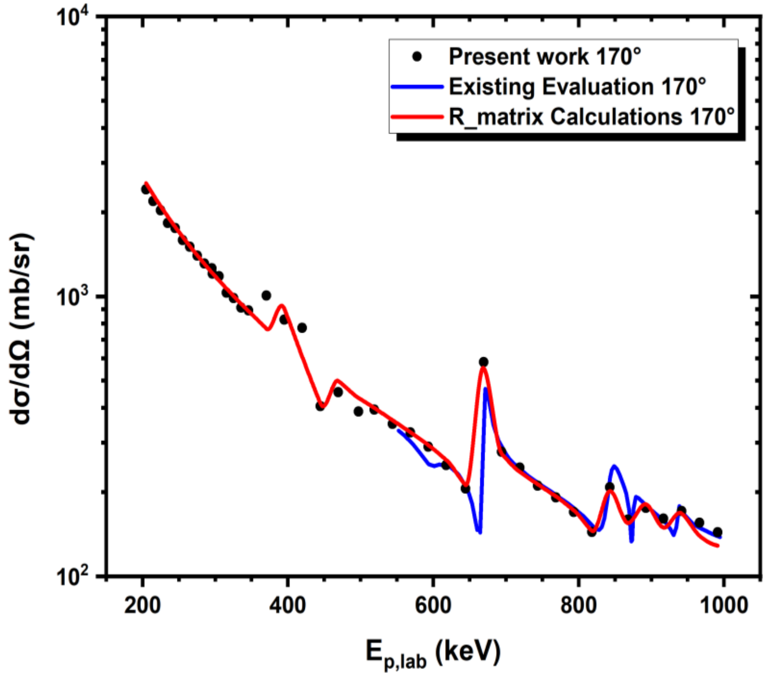
130°



150°



170°



- ✓ Satisfactory reproduction of the current experimental differential cross-section data
- ✓ Good agreement (6% - 8%) with current Evaluation on the matching point

Conclusions & Future Perspectives

- Experimental differential cross-section data for $^{19}F(p,p_0)^{19}F$, for $E_{p,lab}$ = 200 keV – 1000 keV
- 5 different detection angles (θ = 130° - 170°, with a 10° step)
- Deviations from Rutherford cross section – Presence of resonances below 500 keV
- Good agreement with existing Evaluation
- Theoretical investigation via the AZURE 2.0 code reproduce the experimental differential cross-section data

- Benchmarking experiment, to further validate the present experimental data
- Extension of the theoretically evaluated datasets well below 0.5 MeV

Thank you for your attention!