Differential cross-section measurements for ^{3}He-induced reactions and elastic scattering on ^{16}O

V. Stefanidis-Toulkeridis[1],*, V. Foteinou[1], F. Maragkos[3], H.-W. Becker[2], M. Grigoriou[1], M.Kokkoris[3], N. Patronis[1], D. Rogalla[2], N. Sarris[1], N. Theodosiou[1], and T. Tsiakos[1]

[1]Department of Physics, University of Ioannina, 45110 Ioannina, Greece

[2]RUBION, Ruhr University Bochum, 44801 Bochum, Germany

[3]Department of Physics, National Technical University of Athens, 15780 Athens, Greece

Introduction

Ion Beam Analysis (IBA)

- High sensitivity
- High accuracy
- Least destructive
- (Isotope-specific and depth profiling)

PIGE	PIXE	NRA	EBS/RBS	ERDA
Particle Induced γ-ray Emission	Particle Induced X-ray Emission	Nuclear Reaction Analysis	Elastic Rutherford Backscattering Spectrometry	Elastic Recoil Detection Analysis

Introduction

IBA require differential cross-section datasets

There are still important gaps in literature limiting IBA capabilities

Introduction

^{3}He beams advantages

1. High cross section values and high Q-values for induced reactions with light isotopes.

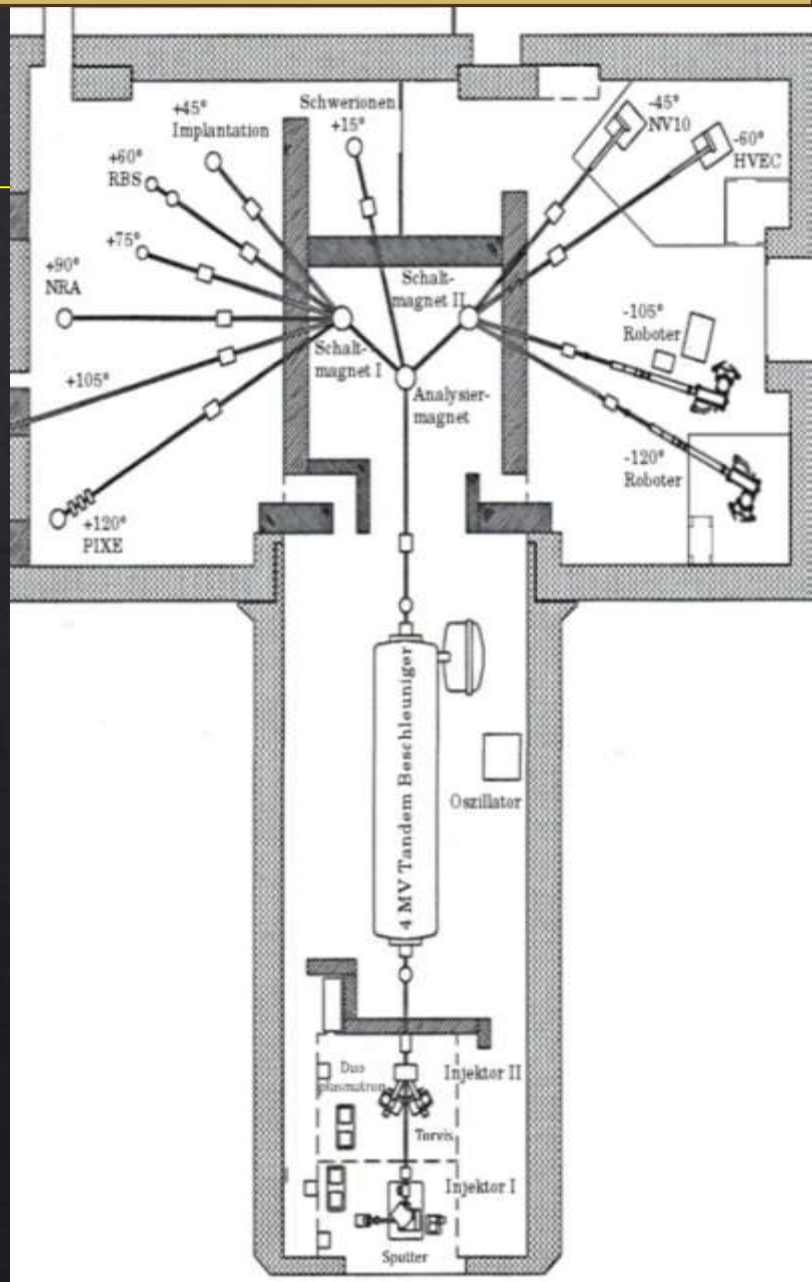
2. No special radiation protection measures are needed.

3. Can study deuterium inside materials.

Experimental Setup

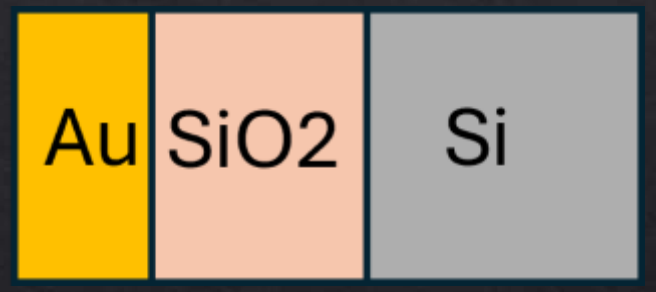
Details about the experiment

- All experiments took place at RUBION laboratory at University of Bochum in Germany.
- ^{3}He ions were accelerated between 2.2-5 MeV.
- 5 detection angles between 130° and 170° were covered.



Experimental Setup -- Target

- Surface layer of gold (~3 nm)
- Layer of SiO_2 (~300 nm)
- Thick substrate of Si



Analysis

Experimental formula for differential cross section

$$\frac{d\sigma}{d\Omega} = \frac{Y}{Q \cdot \Omega \cdot N}$$

Y : integral of the corresponding peak

Q : total charge of the beam

Ω : solid angle of the detector

N : areal density of the isotope under study

Analysis

$$\frac{d\sigma_{Au}}{d\Omega} = \frac{Y_{Au}}{Q \cdot \Omega \cdot N_{Au}}$$

$$\frac{d\sigma_{reac}}{d\Omega} = \frac{Y_{reac}}{Q \cdot \Omega \cdot N_{reac}}$$

$$\frac{d\sigma_{reac}}{d\Omega} = \frac{Y_{reac}}{Y_{Au}} \frac{N_{Au}}{N_{reac}} \frac{d\sigma_{Au}}{d\Omega}$$

Integration of the corresponding peaks

Analysis

$$\frac{d\sigma_{Au}}{d\Omega} = \frac{Y_{Au}}{Q \cdot \Omega \cdot N_{Au}}$$

$$\frac{d\sigma_{reac}}{d\Omega} = \frac{Y_{reac}}{Q \cdot \Omega \cdot N_{reac}}$$

$$\frac{d\sigma_{reac}}{d\Omega} = \frac{Y_{reac}}{Y_{Au}} \frac{N_{Au}}{N_{reac}} \frac{d\sigma_{Au}}{d\Omega}$$

Additional experiment was carried out

Analysis

$$\frac{d\sigma_{Au}}{d\Omega} = \frac{Y_{Au}}{Q \cdot \Omega \cdot N_{Au}}$$

$$\frac{d\sigma_{reac}}{d\Omega} = \frac{Y_{reac}}{Q \cdot \Omega \cdot N_{reac}}$$

$$\frac{d\sigma_{reac}}{d\Omega} = \frac{Y_{reac}}{Y_{Au}} \frac{N_{Au}}{N_{reac}} \frac{d\sigma_{Au}}{d\Omega}$$

Rutherford formula
+
Screening correction factor

Analysis

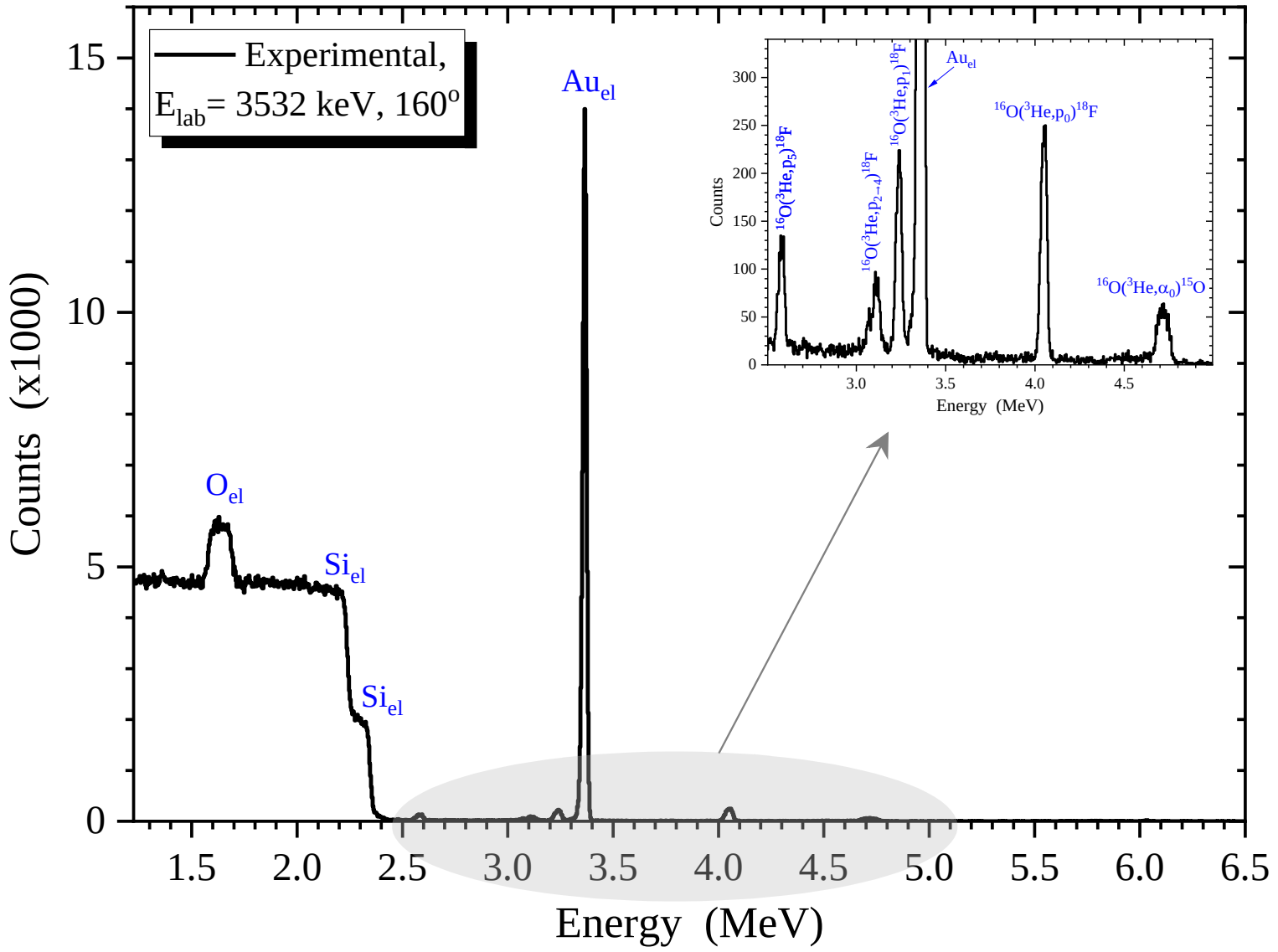
Differential cross section of gold in our target

$$\frac{d\sigma_{Ruth}}{d\Omega} = 5.1839 * 10^6 * \left(\frac{z_1 z_2}{E(keV)}\right)^2 * \frac{\left((\mathrm{M}_2^2 - M_1^2 * \sin^2\theta)^{0.5} + \mathrm{M}_2 * cos\theta\right)^2}{\mathrm{M}_2 * \sin^4\theta * (\mathrm{M}_2^2 - \mathrm{M}_1^2 * \sin^2\theta)^{0.5}}$$

$$F_{L'Ecyer} = 1 - \frac{0.04873 * Z_1 * Z_2^{4/3}}{E_{cm}}$$

$$\frac{d\sigma_{\mathrm{Au}}}{d\Omega} = F_{L'Ecyer} * \frac{d\sigma\_Ruth}{d\Omega}$$

Analysis


Experimental,
E_lab = 3532 keV, 160°
Au_el
O_el
Si_el
Si_el
Counts (x1000)
Energy (MeV)
16O(3He,p5)18F
16O(3He,p2-4)18F
16O(3He,p1)18F
Au_el
16O(3He,p0)18F
16O(3He,α0)15O
Counts
Energy (MeV)

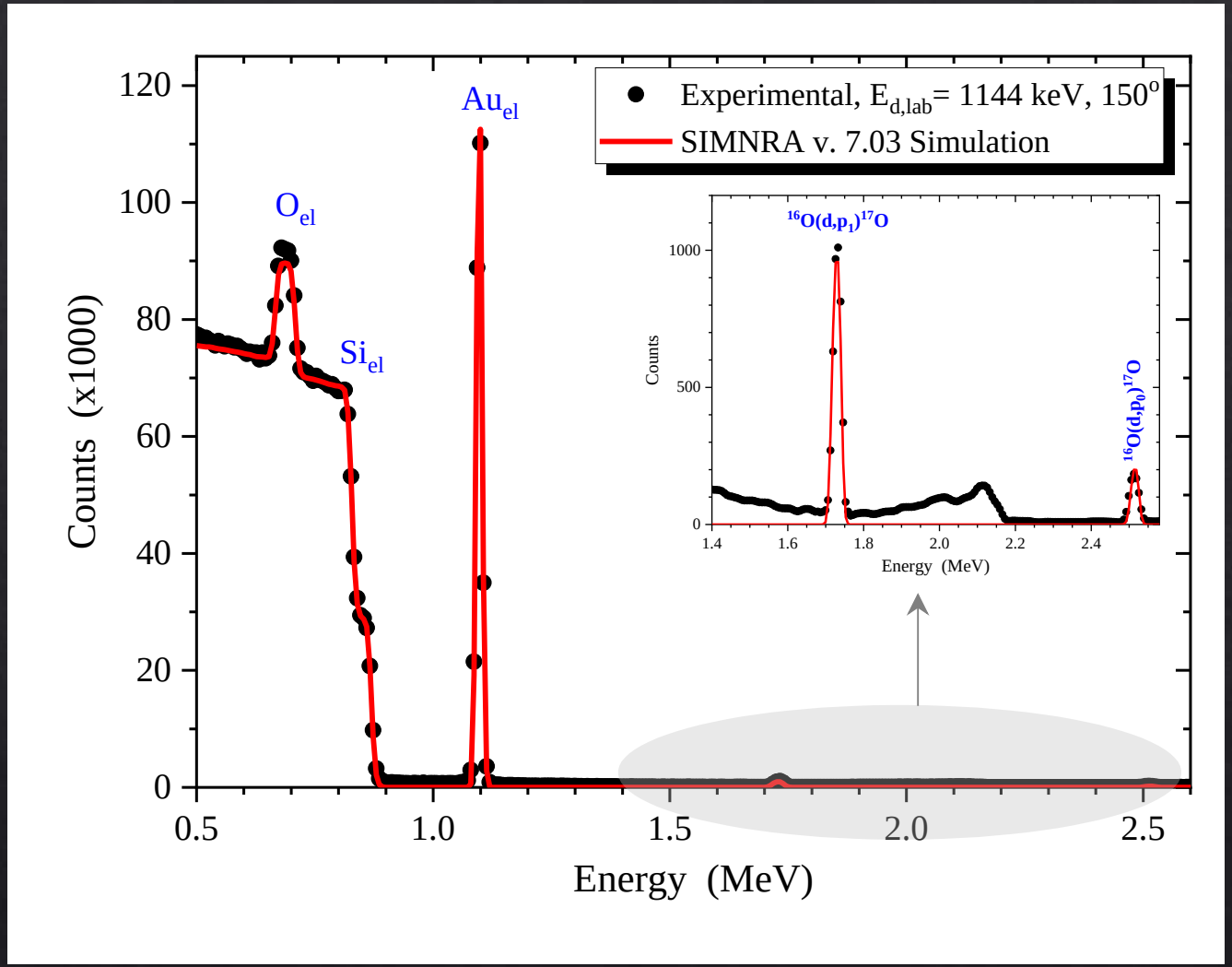
Analysis

Measure the thickness ratio of gold and oxygen

The thickness ratio between gold and oxygen was determined in RUBION through an additional experiment

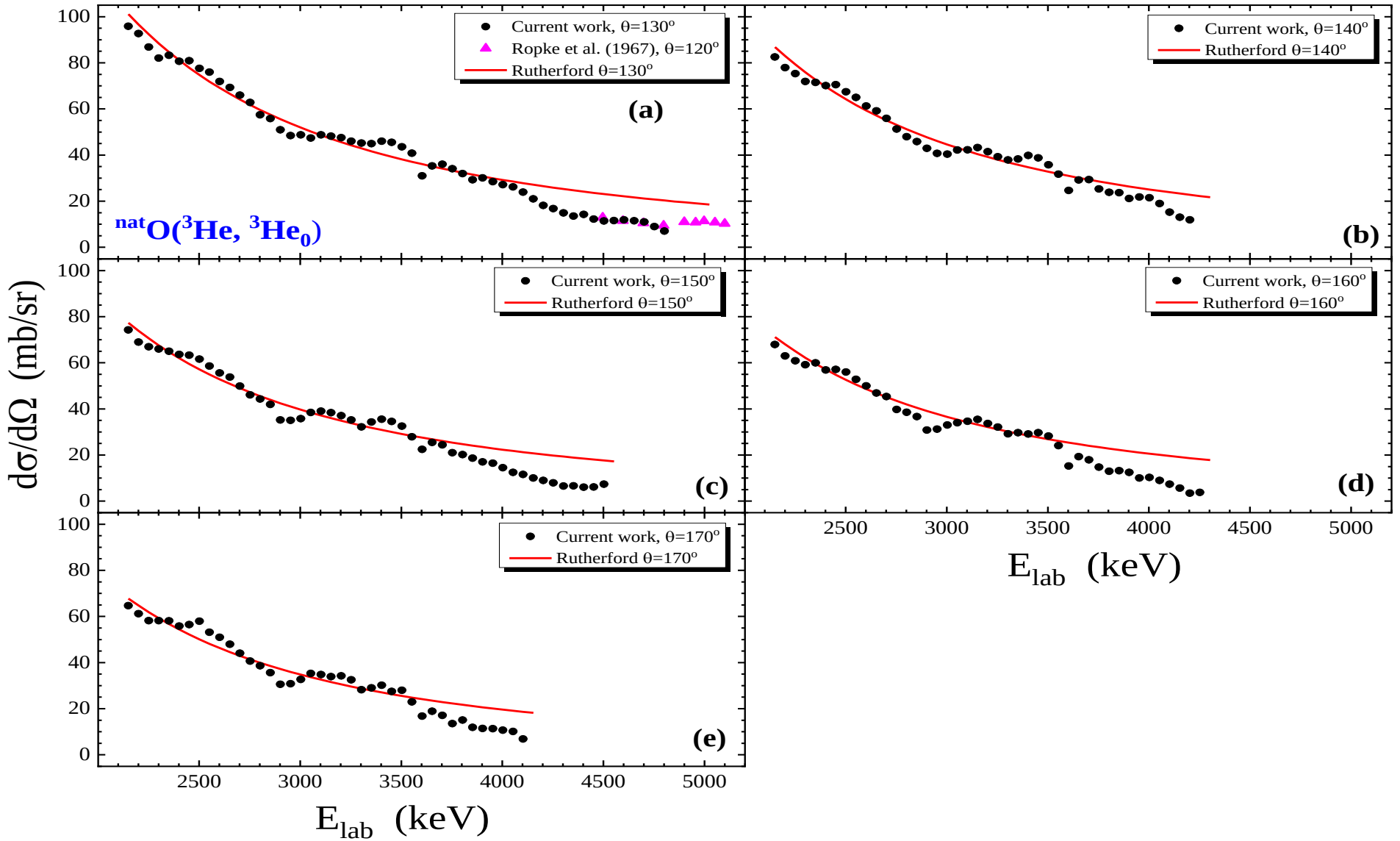
NRA using 1.15-MeV deuterium was applied

Analysis

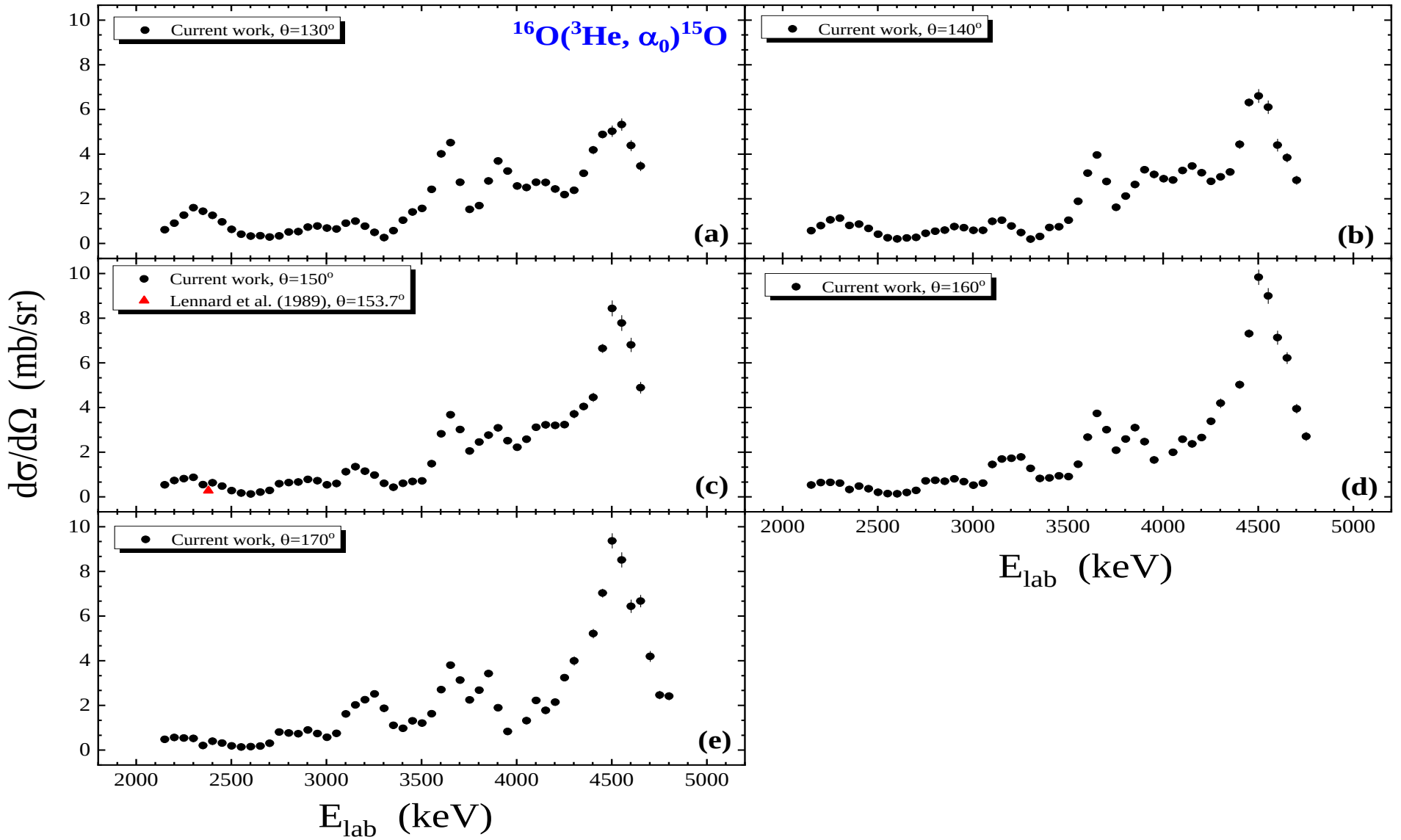


$$\frac{N_{^{197}Au}}{N_{^{16}O}} = 0.0236 \pm 0.0003$$

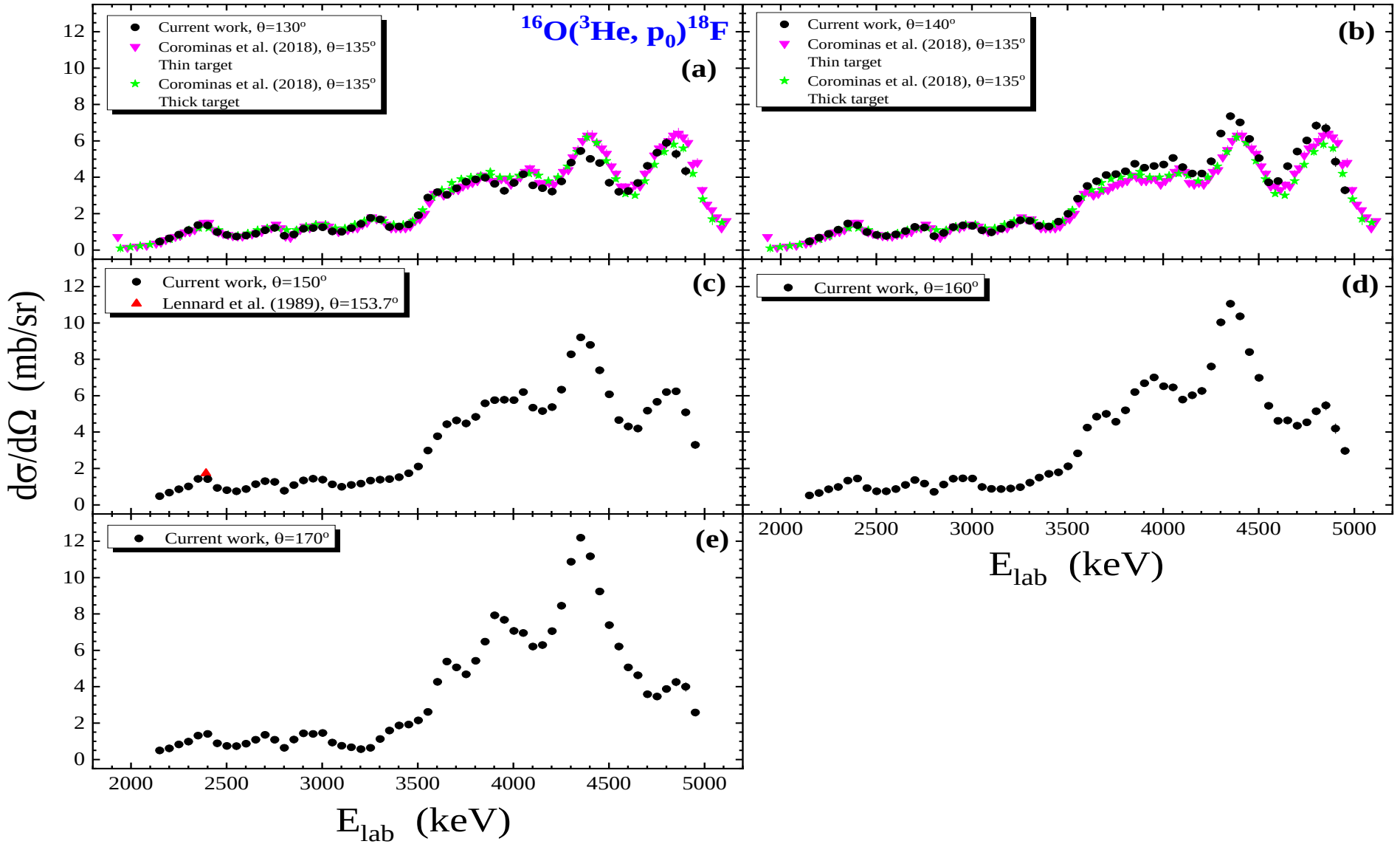
Results


Current work, θ=130°
Ropke et al. (1967), θ=120°
Rutherford θ=130°
(a)
natO(3He, 3He0)
Current work, θ=140°
Rutherford θ=140°
(b)
Current work, θ=150°
Rutherford θ=150°
(c)
Current work, θ=160°
Rutherford θ=160°
(d)
Current work, θ=170°
Rutherford θ=170°
(e)
dσ/dΩ (mb/sr)
Elab (keV)
Elab (keV)

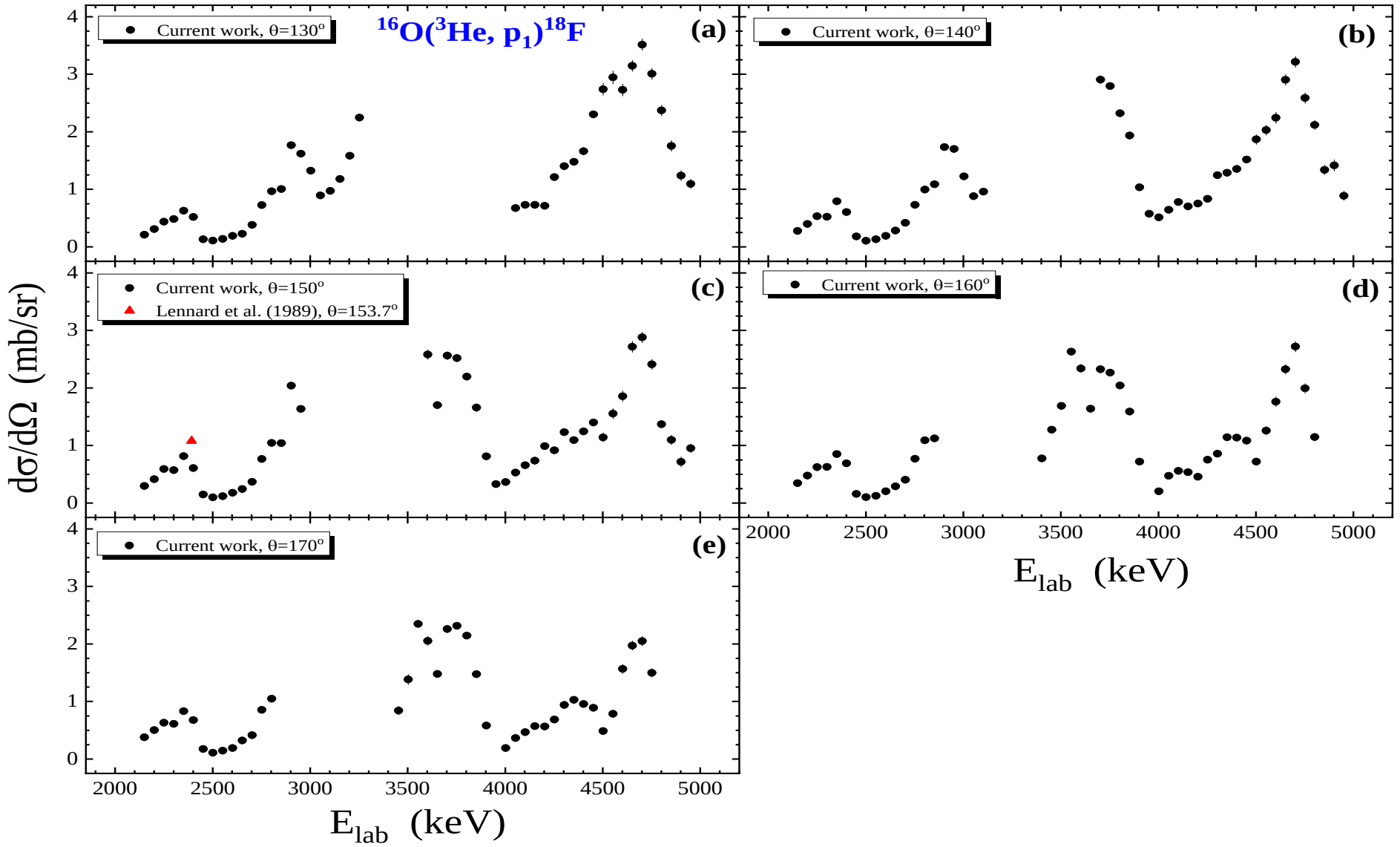
Results


$^{16}O(^{3}He, \alpha_0)^{15}O$
Current work, θ=130°
Current work, θ=140°
Current work, θ=150°
Lennard et al. (1989), θ=153.7°
Current work, θ=160°
Current work, θ=170°
(a)
(b)
(c)
(d)
(e)
dσ/dΩ (mb/sr)
E_{lab} (keV)
0
2
4
6
8
10
2000
2500
3000
3500
4000
4500
5000

Results


$^{16}O(^{3}He, p_0)^{18}F$
(a)
Current work, θ=130°
Corominas et al. (2018), θ=135° Thin target
Corominas et al. (2018), θ=135° Thick target
(b)
Current work, θ=140°
Corominas et al. (2018), θ=135° Thin target
Corominas et al. (2018), θ=135° Thick target
(c)
Current work, θ=150°
Lennard et al. (1989), θ=153.7°
(d)
Current work, θ=160°
(e)
Current work, θ=170°
dσ/dΩ (mb/sr)
E_{lab} (keV)

Results


$^{16}O(^{3}He, p_1)^{18}F$
(a)
Current work, θ=130°
(b)
Current work, θ=140°
(c)
Current work, θ=150°
Lennard et al. (1989), θ=153.7°
(d)
Current work, θ=160°
(e)
Current work, θ=170°
dσ/dΩ (mb/sr)
E_{lab} (keV)
0
1
2
3
4
2000
2500
3000
3500
4000
4500
5000

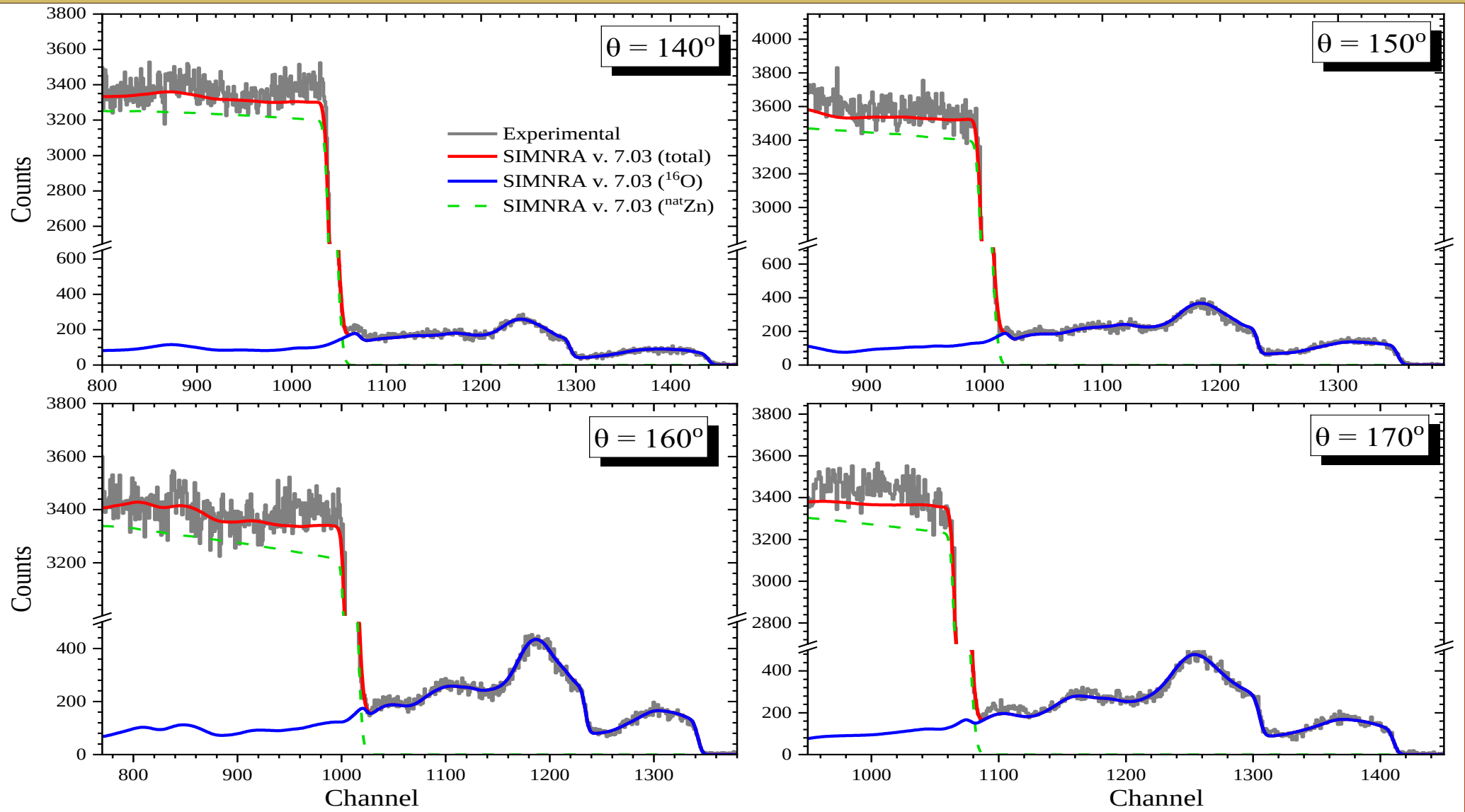
Benchmarking

Benchmarking method

Method to validate the values that we just measured

- The beam particle was $E_{^3He}$=4600 keV, suitable for checking the entire set of differential cross section that were measured.
- High-purity thick crystal ZnO as a target.
- For 4 detection angles from 140° to 170° with 10° step.

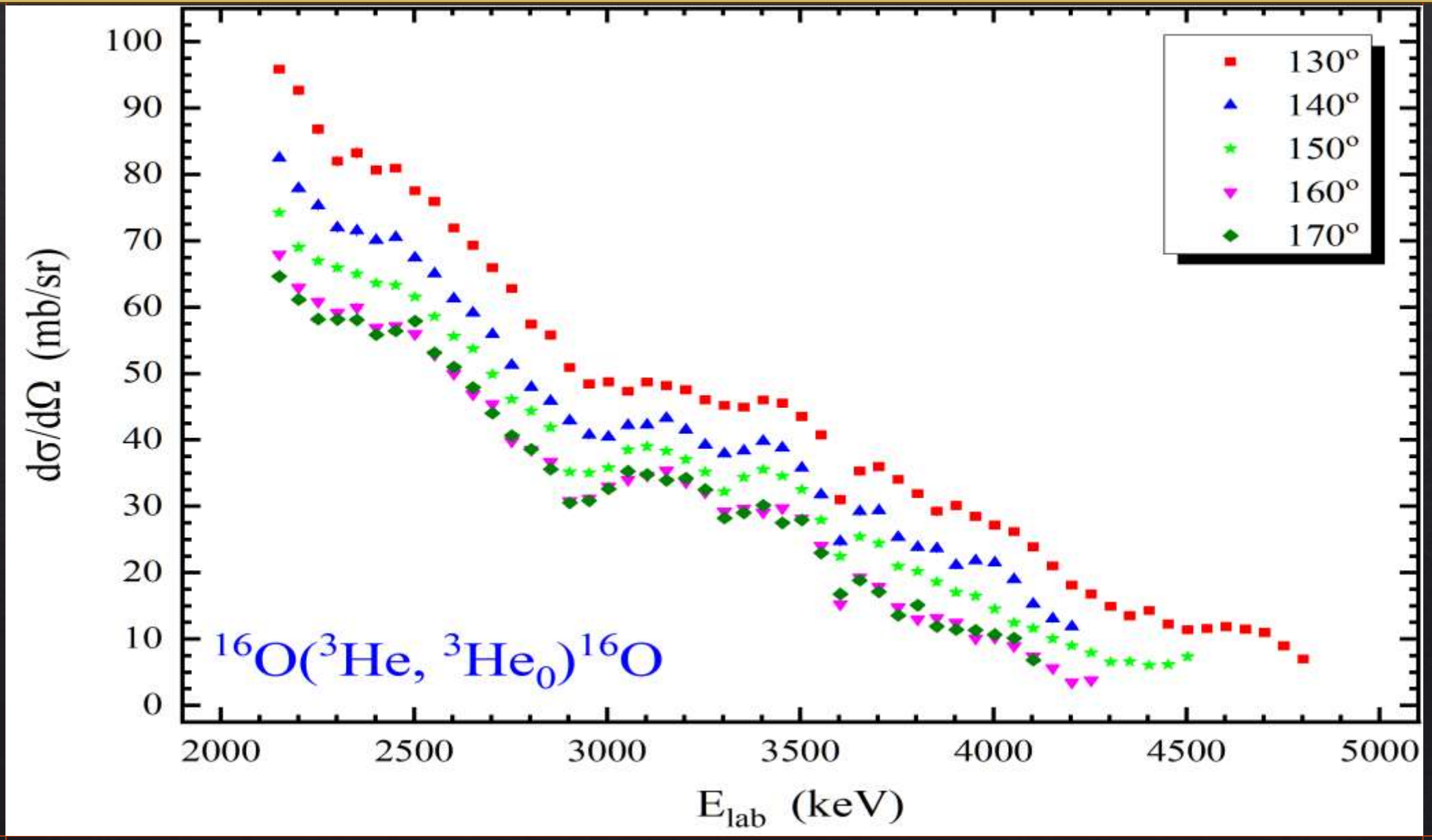
Results


θ = 140°
θ = 150°
θ = 160°
θ = 170°
Experimental
SIMNRA v. 7.03 (total)
SIMNRA v. 7.03 (16O)
SIMNRA v. 7.03 (natZn)
Counts
Channel

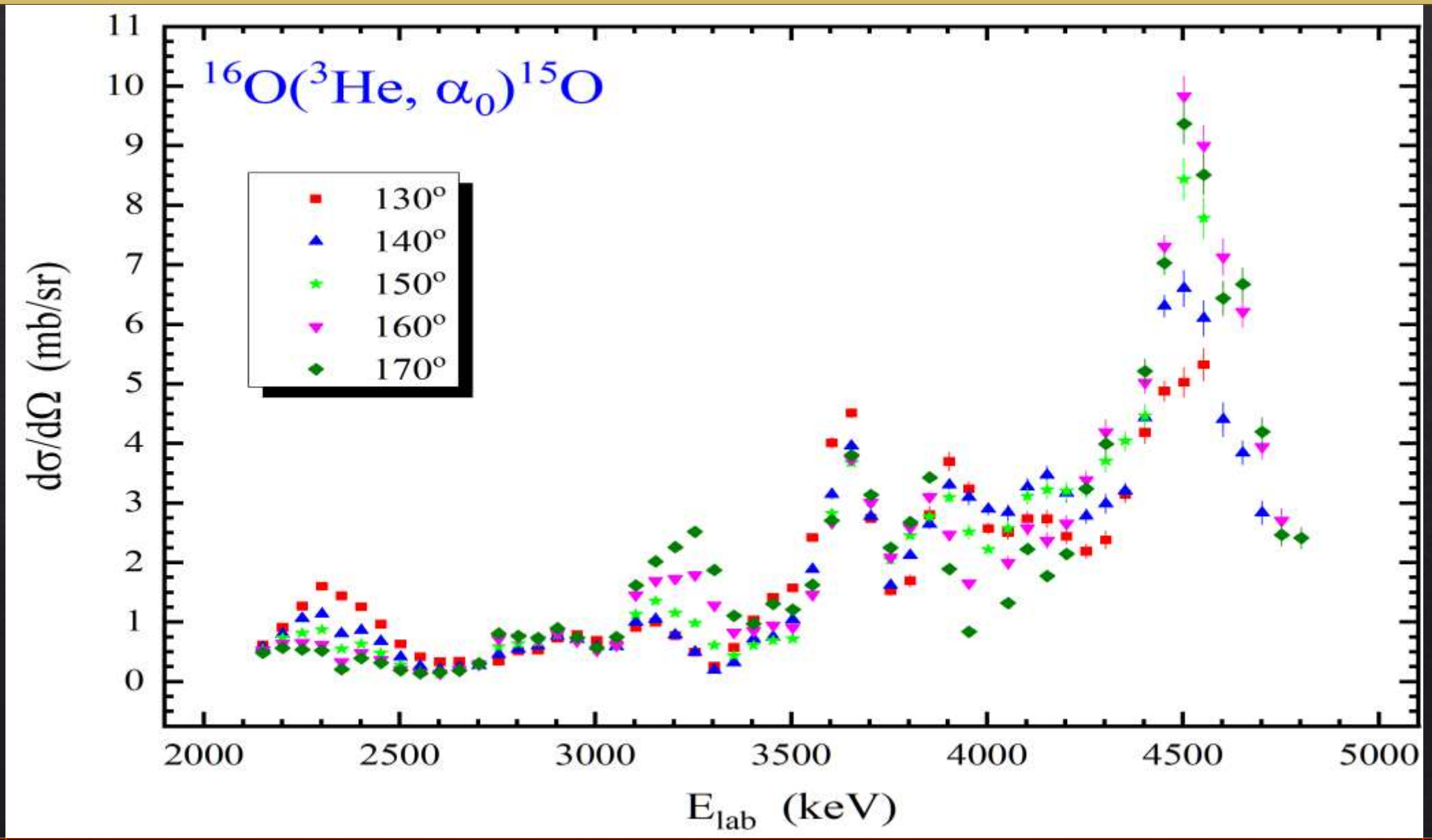
Conclusions

- The first systematic study of the reactions $^{16}O(^{3}He,\alpha_0)^{15}O$, $^{16}O(^{3}He,p_0)^{18}F$, $^{16}O(^{3}He,p_1)^{18}F$ and elastic scattering of oxygen was carried out for beam energies of 2.2-5 MeV
- The reliability of the experimental result was verified.
- The determined differential cross section are expected to be a valuable tool for the quantitative analysis and depth distribution determination of oxygen .

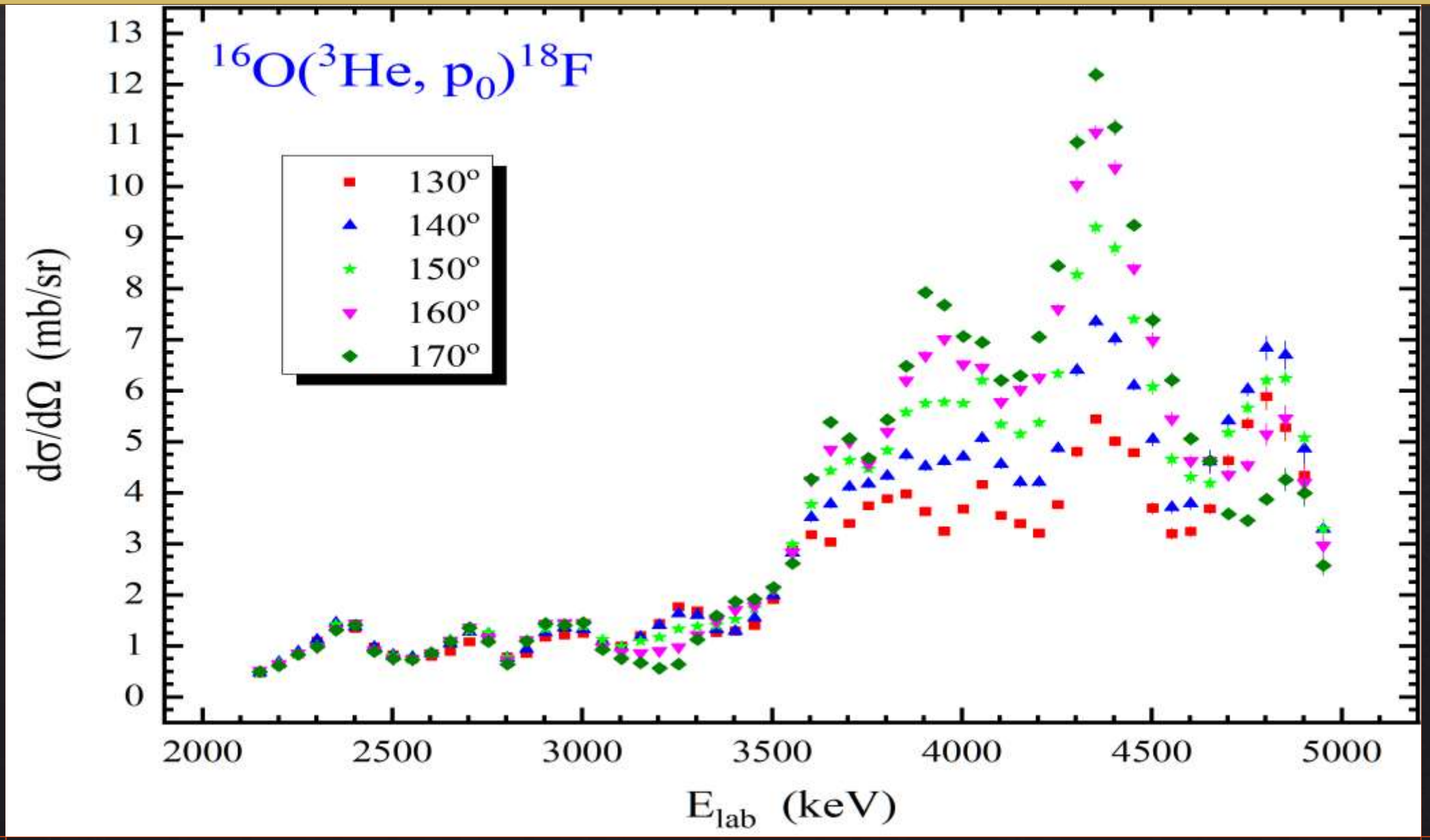
Results


130°
140°
150°
160°
170°
$^{16}O(^{3}He, ^{3}He_0)^{16}O$
dσ/dΩ (mb/sr)
E_{lab} (keV)
0
10
20
30
40
50
60
70
80
90
100
2000
2500
3000
3500
4000
4500
5000

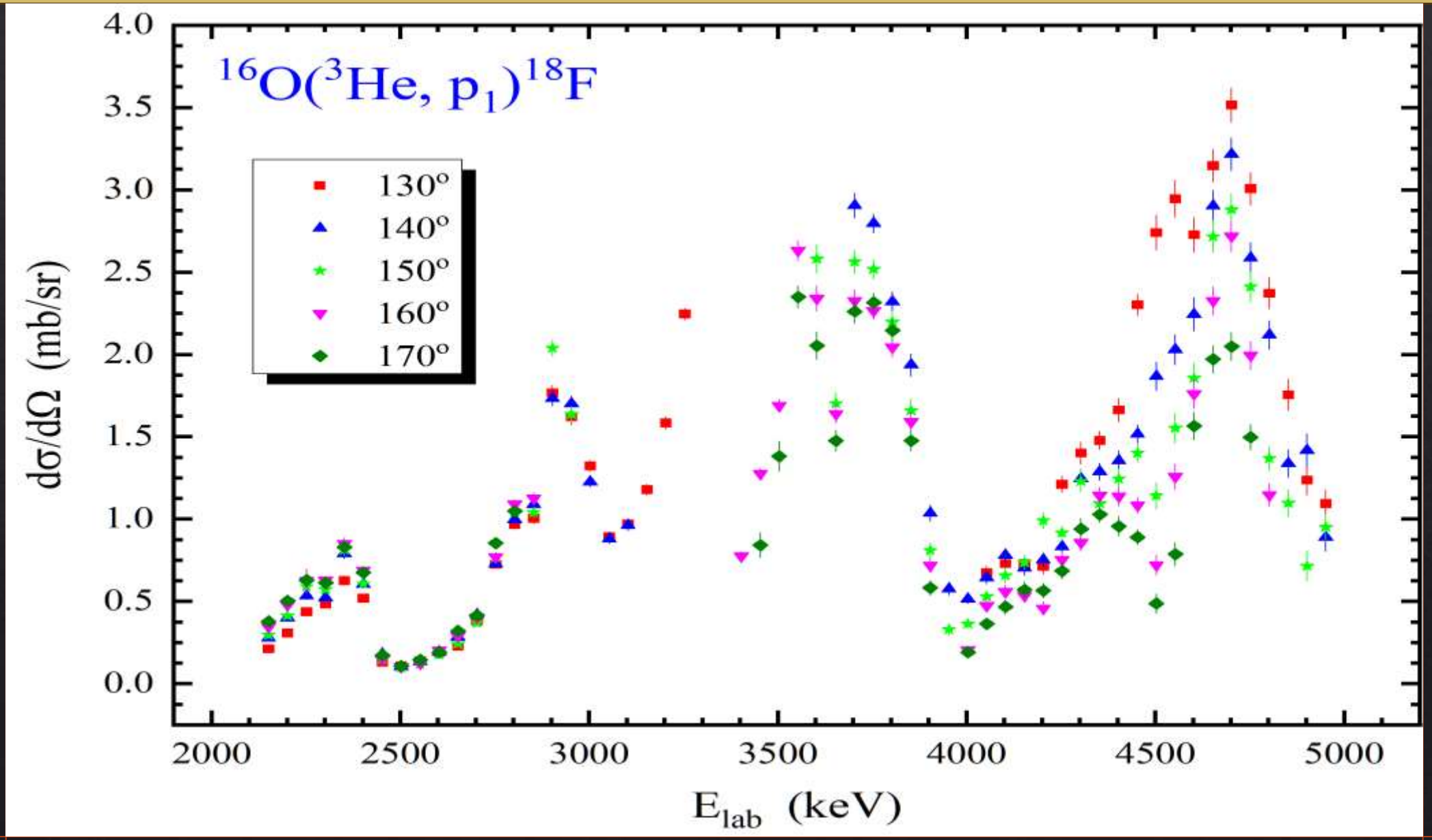
Results


$^{16}O(^{3}He, \alpha_0)^{15}O$
130°
140°
150°
160°
170°
dσ/dΩ (mb/sr)
E_{lab} (keV)
0
1
2
3
4
5
6
7
8
9
10
11
2000
2500
3000
3500
4000
4500
5000

Results


$^{16}O(^{3}He, p_0)^{18}F$
130°
140°
150°
160°
170°
dσ/dΩ (mb/sr)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
2000
2500
3000
3500
4000
4500
5000
E_{lab} (keV)

Results


$^{16}O(^{3}He, p_1)^{18}F$
130°
140°
150°
160°
170°
dσ/dΩ (mb/sr)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
2000
2500
3000
3500
4000
4500
5000
E_{lab} (keV)