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Measurements of the $^{18}O(d,\alpha_{0-3})^{16}N$ reactions differential cross sections for NRA purposes

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Motivation

- Oxygen drives chemical and technological processes, plays key role in environmental & biological systems
- ^{18}O: the practical tracer for oxygen (^{16}O: 99.738%, ^{17}O: 0.0367%, ^{18}O: 0.187%)

→ Need for detection & depth profiling

- Nuclear Reaction Analysis (NRA): High sensitivity, Least-destructive, matrix-independent, well-separated peaks
- d-NRA: excites all light isotopes in a single run, better peak identification

\+ • Only one dataset exists: (G. Amsel, 1964, θ=165°)

→ **Aim:**

Reliable $^{18}O(d,\alpha_{0\text{-}3})^{16}N$ differential cross sections

→ Amsel's data (1964) [1]:

- $^{18}O(d,\alpha_0)^{16}N$:

  $E_{d,lab}$ = 827–2001 keV

- $^{18}O(d,\alpha_1)^{16}N$:

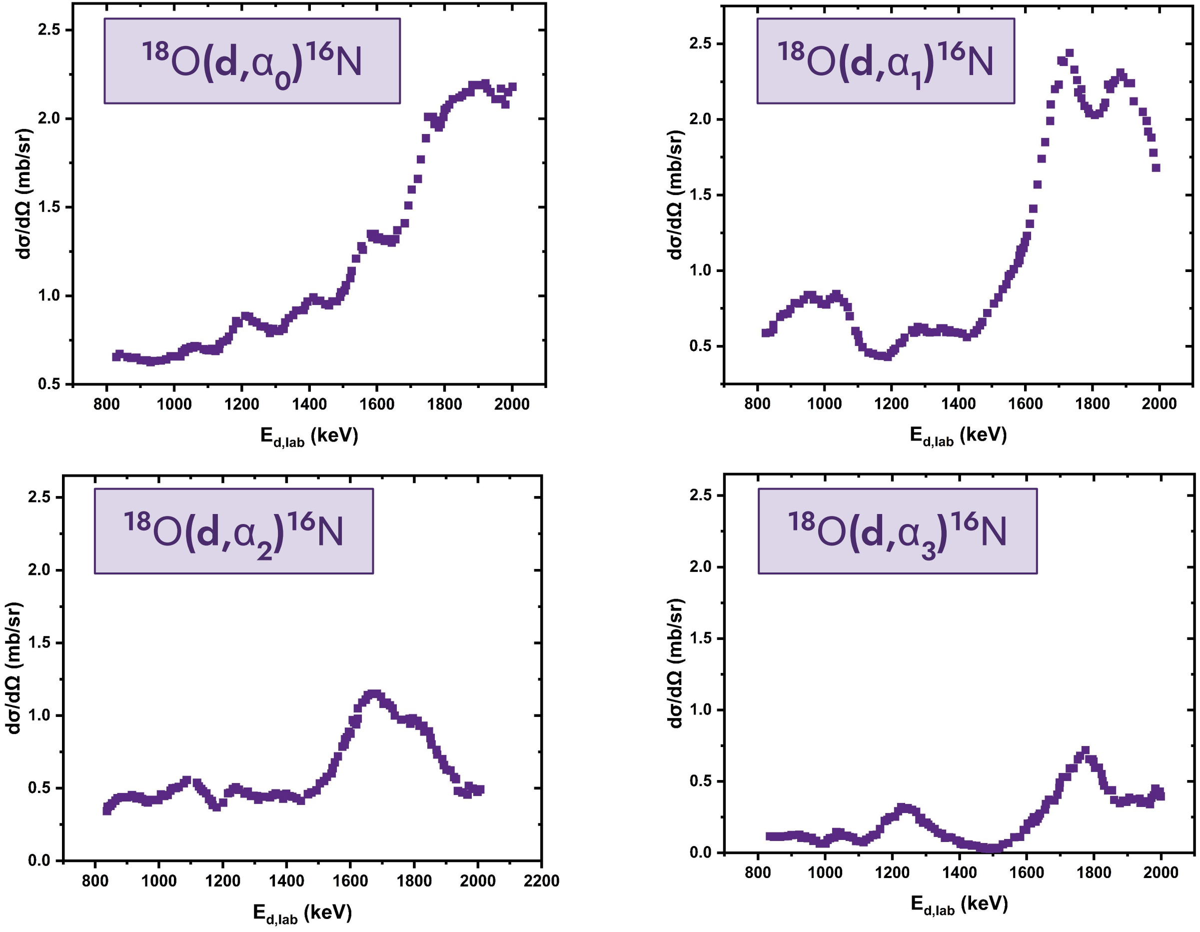
  $E_{d,lab}$ = 824–1990 keV

- $^{18}O(d,\alpha_2)^{16}N$:

  $E_{d,lab}$ = 837–2007 keV

- $^{18}O(d,\alpha_3)^{16}N$:

  $E_{d,lab}$ = 836–1999 keV



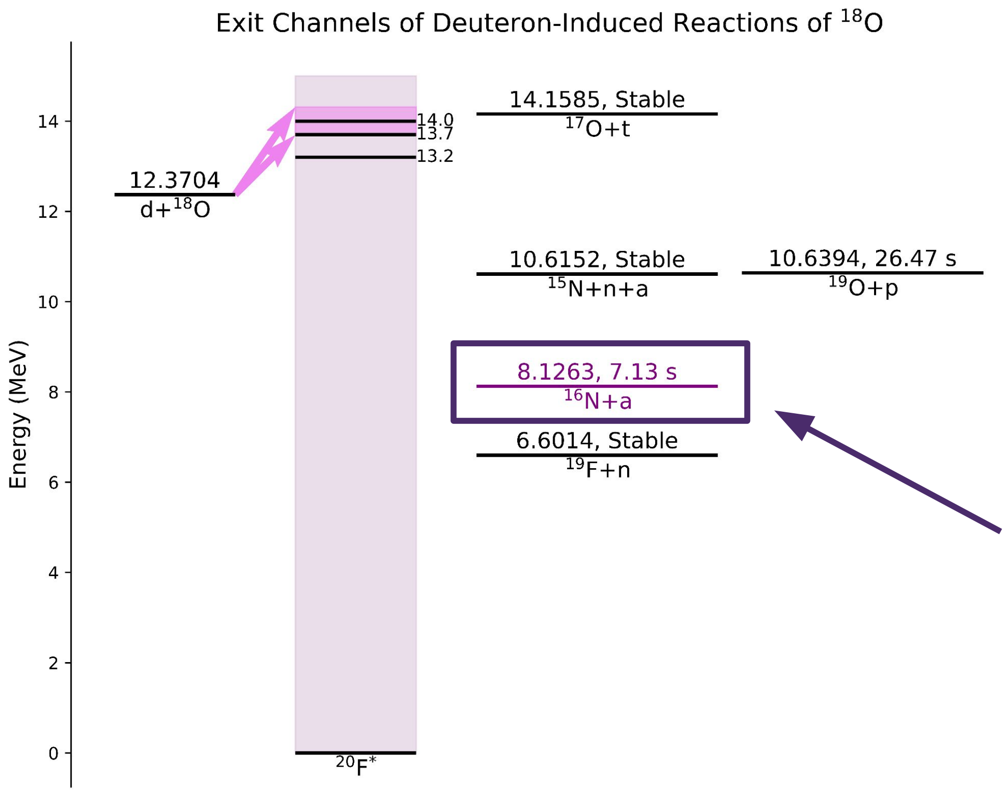
Kinematics & Energy Scheme

Q-values:

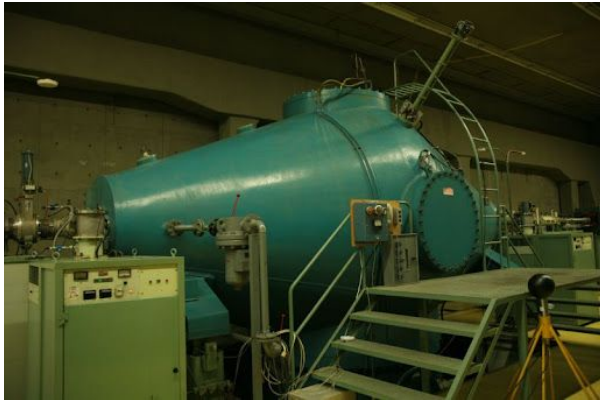
- $Q[^{18}O(d,\alpha_0)^{16}N] = 4.244$ MeV
- $Q[^{18}O(d,\alpha_1)^{16}N] = 4.124$ MeV
- $Q[^{18}O(d,\alpha_2)^{16}N] = 3.946$ MeV
- $Q[^{18}O(d,\alpha_3)^{16}N] = 3.845$ MeV

$E_{d,lab}$= 1.47–2.16 MeV

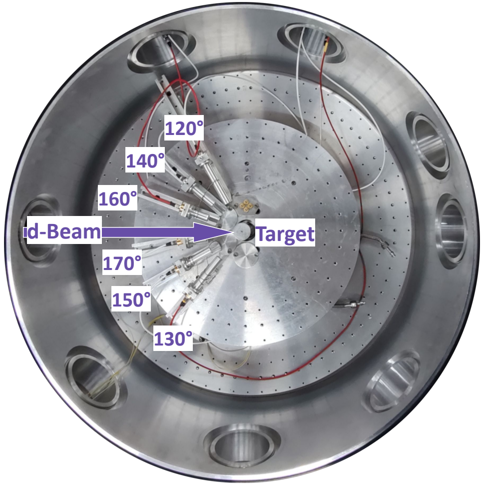
(The energy state at 14 MeV is the highest found in bibliography)



Experimental Setup

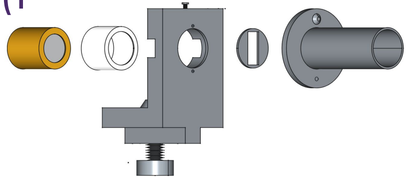


- 5.5 MV TN11 Tandem, N.C.S.R. "Demokritos"
- Deuteron beam, $E_{d,lab}$ = 1470–2160 keV
- Beam energy via NMR (precise determination)
- Cylindrical chamber, r ≈ 40 cm
- High-precision goniometer (0.1°)
- High vacuum, 10^{-6} mbar



- Thin Ta_2O_5 layer on thick Ta backing
- Prepared via controlled progressive anodization — established technique for accurate oxide layer growth
- Unknown enrichment in ^{18}O and total layer thickness
- Mounted on Al holder, perpendicular to beam

- 6 SSB detectors at θ = 120°–170°, 10° steps
- Distances to target: 11–15 cm
- Orthogonal slits ~4×8 mm² → δθ = ±0.45°–±1.14°
- Cylindrical shielding tubes against multiple scattering
- MSI-8 preamp/shaper (1 μs shaping)
- ADC/MCA acquisition, dead-time < 10%, I_{beam}<80 nA



Analysis: Differential Cross Section

$$\frac{d\sigma(E,\theta)}{d\Omega} = \frac{Y(E,\theta)}{Q \times \Omega \times N_t} \text{ (mb/sr)}$$

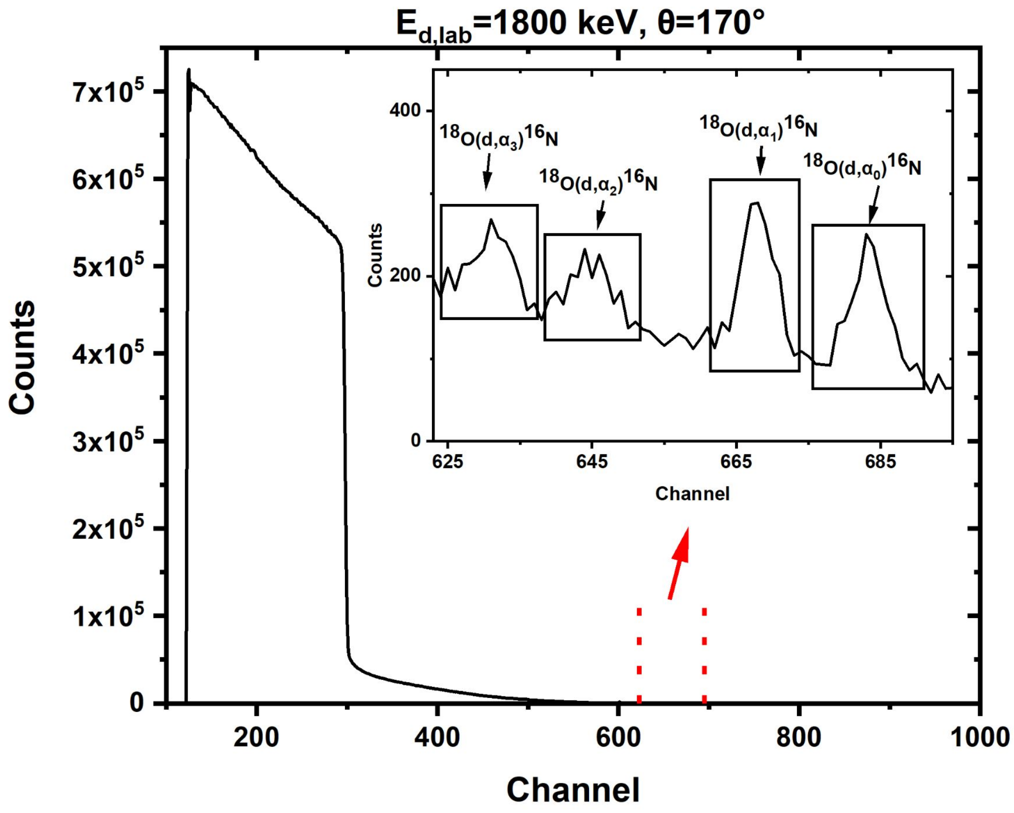
Where:

- $Y(E,\theta)$: the yield of the particles detected with kinetic energy E at angle θ
- Q: the number of incident deuterons (integrated beam charge divided by the elementary charge)
- Ω: the detector solid angle (sr)
- N_t: the target surface density (at/cm^2)

The deuteron beam energy was corrected for energy loss at the middle of the target using SRIM 2013

Analysis: Y(E,θ)

- The TV code was used to identify and integrate/fit the peaks of the understudy reactions
- Statistical error 2%–11%
- Pile-up due to Ta backing → third-degree polynomial background



Analysis: QxΩ

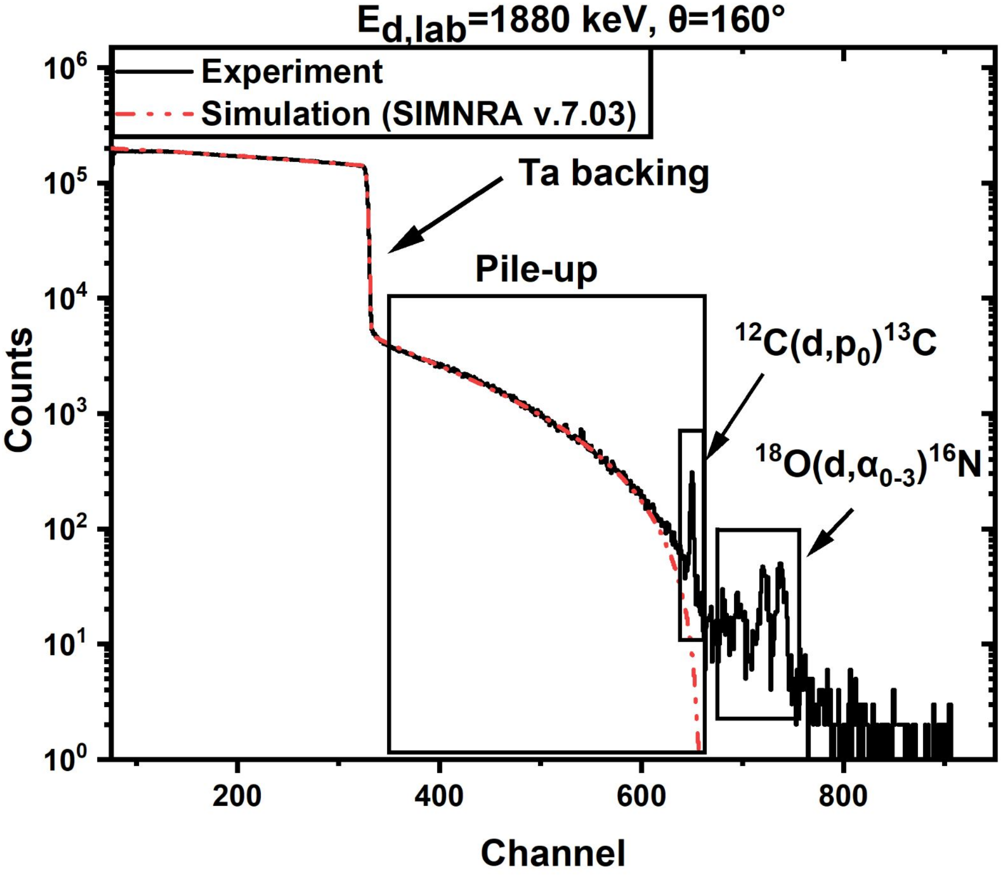
The QxΩ product was determined via SIMNRA simulations:

- Normalization on the Ta backing ($^{181}Ta(d,d_0)^{181}Ta$ elastic, RBS)
- Pile-up model incorporated in the SIMNRA code

Pile-up model: fast vs accurate:

- Fast (Jeynes): for Pile-up rejector (PUR) + near-simultaneous pulses
- Accurate (Wielopolski–Gardner): no PUR or short pulses ($T_P < 1$ μs)

⟶ Accurate model applied in this work



Analysis: Q x Ω

Calculation Method:

- Q·Ω tuned at 160° → simulation matches experiment within 1% (Ta peak + pile-up region)
- Adopted as the true $Q \cdot \Omega_{160°}$
- Cross-check: repeated without pile-up model → difference = $\delta(Q \cdot \Omega_{160°})$
- Other angles: scaled from ratios to 160°
- $\delta(Q \cdot \Omega_{160°})$ & std. dev. of ratios → final uncertainty
- Propagated $\delta(Q \cdot \Omega) < 3.3\%$ at every angle

Analysis: target: ^{18}O areal density - framework

- Initial spectra revealed $^{12}C(d,p_0)^{13}C$ & $^{16}O(d,p_0)^{17}O$ peaks → carbon contamination in target
- Both reactions evaluated (SigmaCalc 2.0): $^{12}C(d,p_0)$ [890–1900 keV], $^{16}O(d,p_0)$ [500–1700 keV]
- ^{12}C + ^{16}O areal density → indirect ^{18}O determination

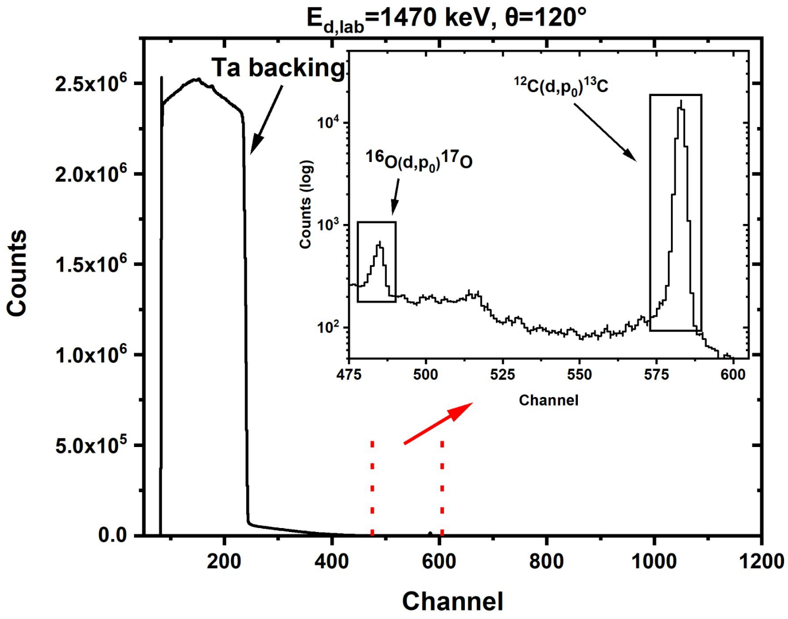
Working assumptions:

- Carbon accumulated throughout the Ta_2O_5 layer during anodization
- Constant stoichiometry: $N_{Ta} = 0.4 \cdot N_O$ (A. Caciolli et al, 2012)
- Negligible ^{13}C (0.96%) and ^{17}O (0.0384%) →

$$N_O = N_{16\text{-}O} + N_{18\text{-}O} \quad \& \quad N_C = N_{12\text{-}C}$$

In situ, indirect target characterization according to:

$$N_{18\text{-}O} = \frac{N_t - N_{12\text{-}C}}{1.4} - N_{16\text{-}O}$$



Analysis: target:
N_t & $N_{12\text{-}c}$ determination

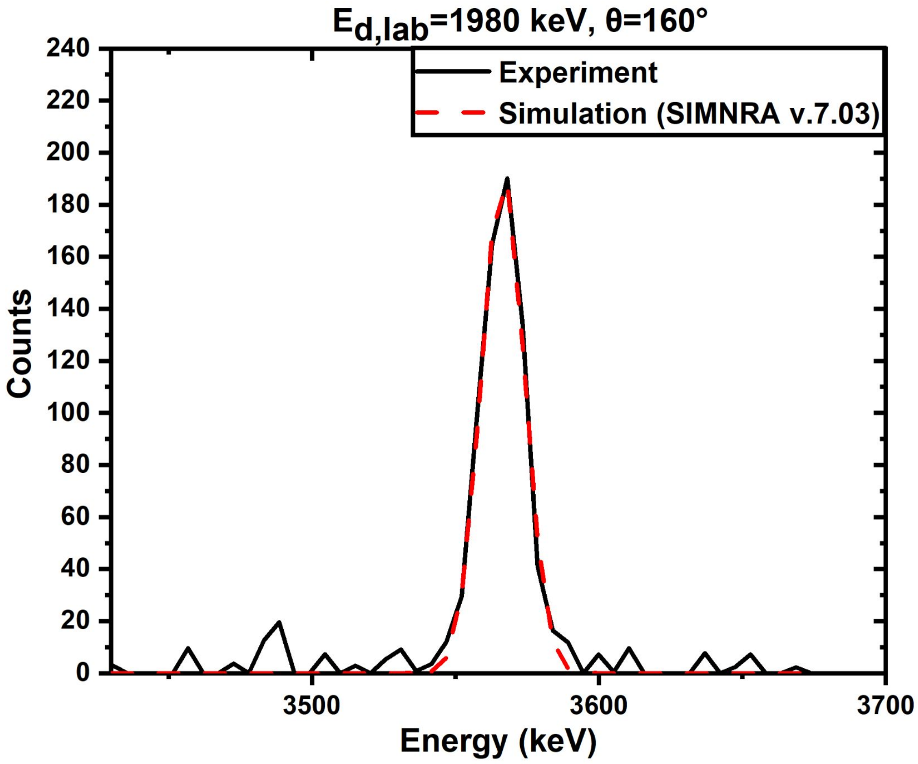
The $^{12}C(d,p)^{13}C$ peak (Q-value = 2.722 MeV) simulated for 5 of the first spectra, at $E_{d,lab}$= 1960 and 1980 keV and θ = 150°, 160°, 170°, before build-up occurrence (NRA):

- Fitting peak width → N_t

$N_t \pm \delta N_t$ = (606±5)×10^{15} at/cm^2

- Matching simulation and experiment yield→ $N_{12\text{-}C}$

$N_{12\text{-}C} \pm \delta N_{12\text{-}C}$ = (60±5)×10^{15} at/cm^2



Analysis: target: $N_{16\text{-}O}$ & $N_{18\text{-}O}$ determination

The $^{16}O(d,p)^{17}O$ peak (Q-value = 1.918 MeV) simulated for 7 spectra, at:

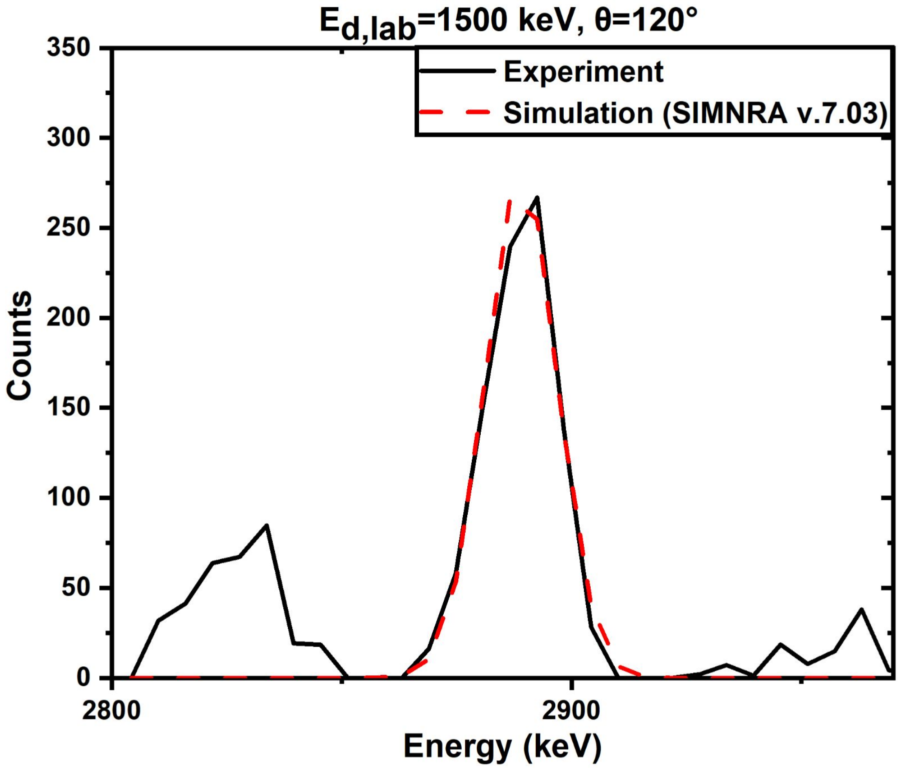
- $E_{d,lab}$= 1.47, 1.50, 1.54, 1.58, 1.62, 1.66, 1.70 MeV
- θ = 120° (NRA):

Yielding for $N_{16\text{-}O}$:

$$N_{16\text{-}O} \pm \delta N_{16\text{-}O} = (61 \pm 6) \times 10^{15}\ at/cm^2$$

So for $N_{18\text{-}O}$:

$$N_{18\text{-}O} \pm \delta N_{18\text{-}O} = (329 \pm 8) \times 10^{15}\ at/cm^2$$

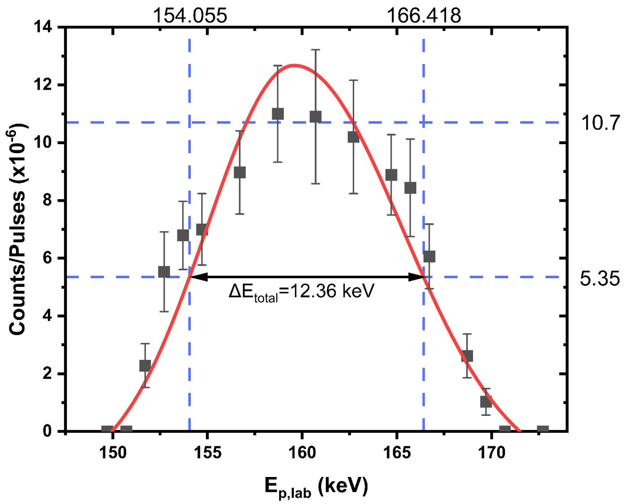


✔ Agreement with nominal (326×10^{15} at/cm^2)

Analysis: target:
Results cross-check

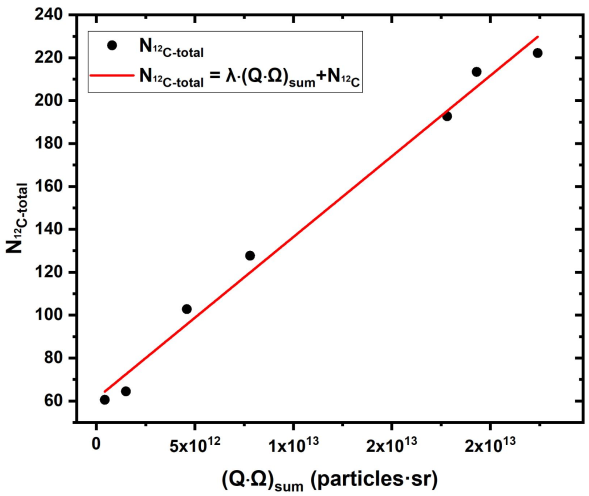
Narrow resonance $^{18}O(p,\alpha)^{15}N$ at ~150 keV, measured in Rurh University, Bochum:

$N_t \pm \delta N_t$ = (610±30)×10^{15} at/cm^2 ✔

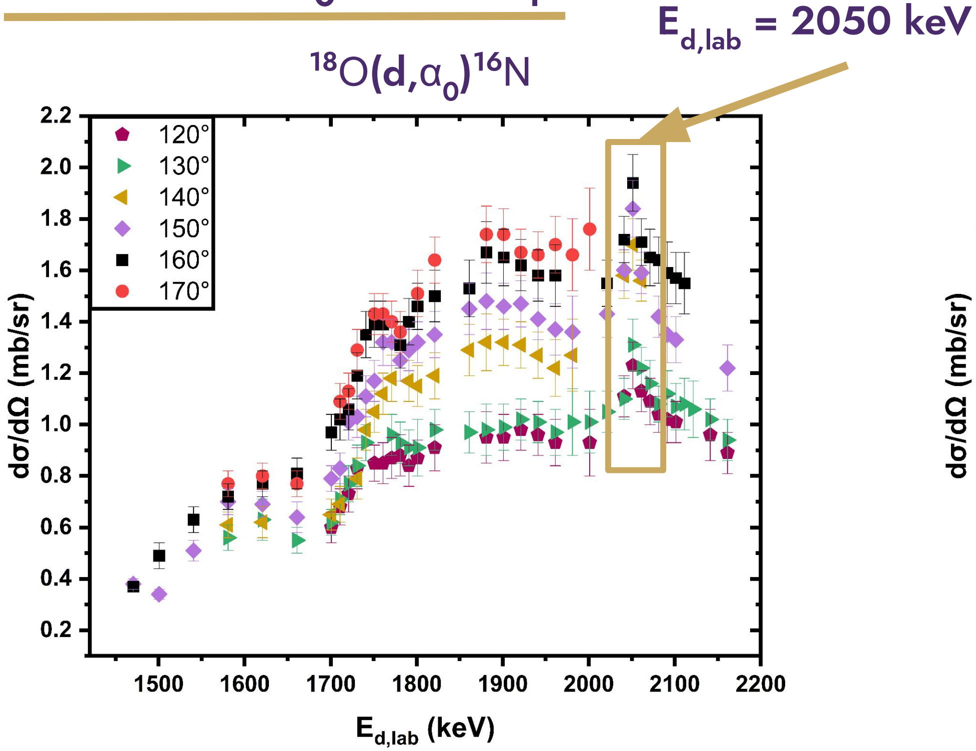


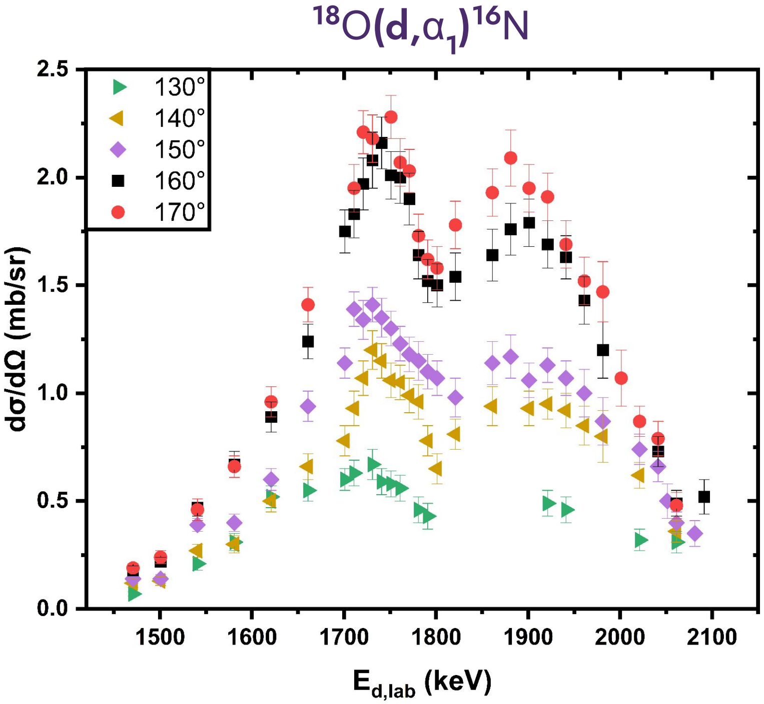
Linear carbon build-up model:

$N_C \pm \delta N_C$ = (61±4)×10^{15} at/cm^2 ✔



Results: (d,α_0) & (d,α_1)

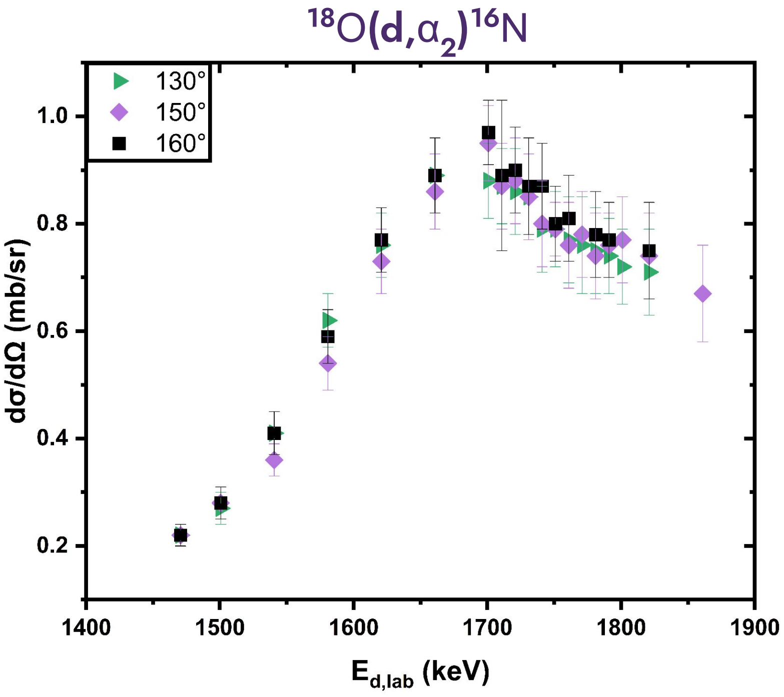


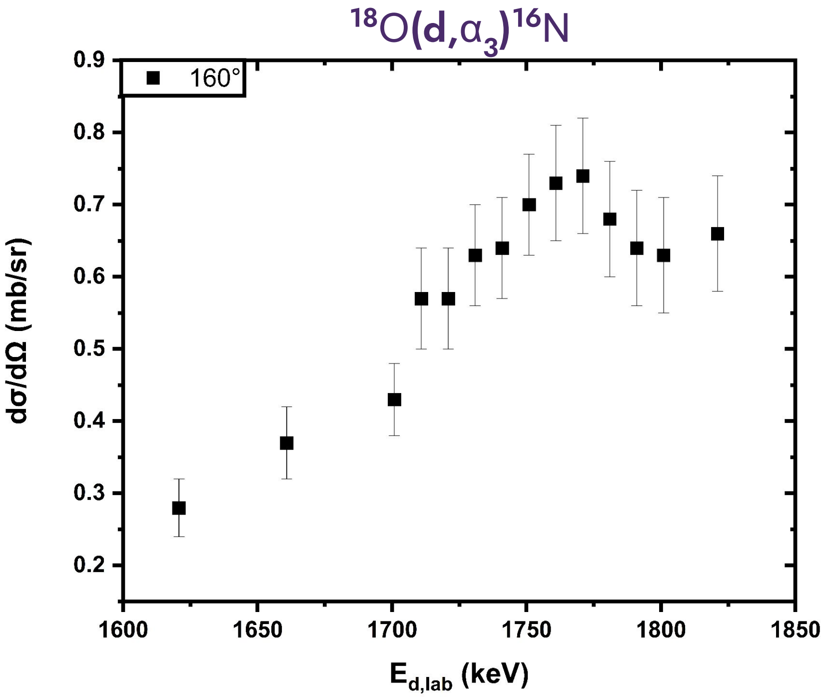


- 1470-2160 keV energy range
- six detection angles
- δE ~ 3 keV

- 1470-2100 keV energy range
- five detection angles
- δE ~ 3 keV

Results: (d,α_2) & (d,α_3)

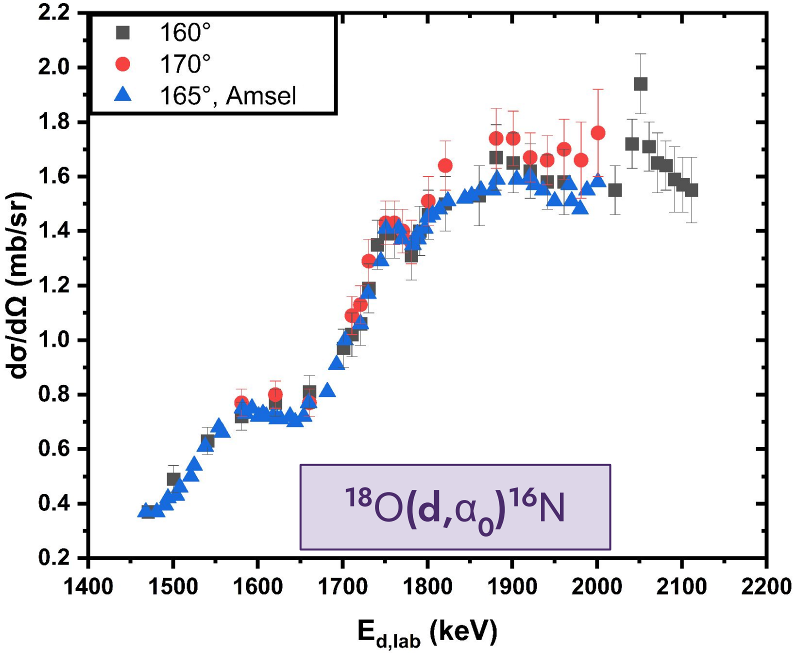


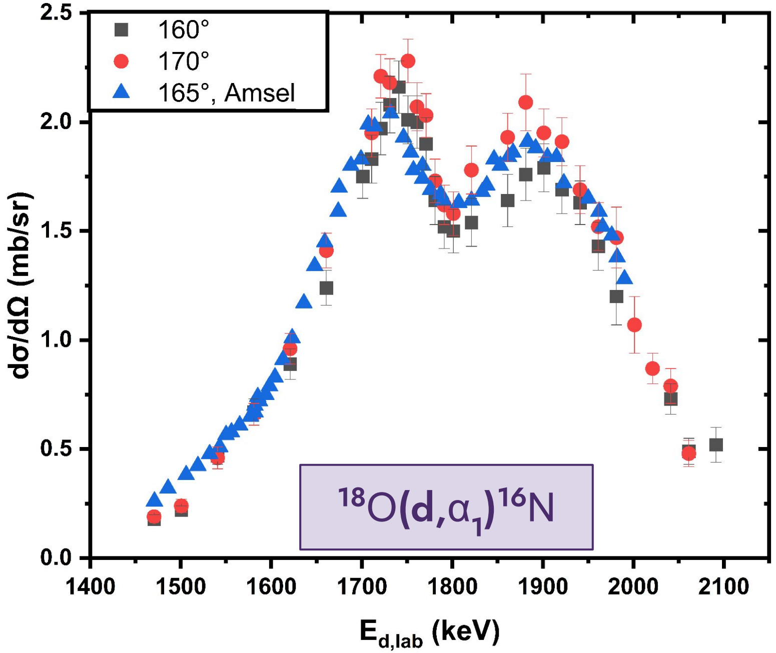


- 1470-1860 keV energy range
- three detection angles
- δE ~ 3 keV

- 1580-1840 keV energy range
- one detection angles
- δE ~ 3 keV

Discussion: (d,α_0) & (d,α_1)

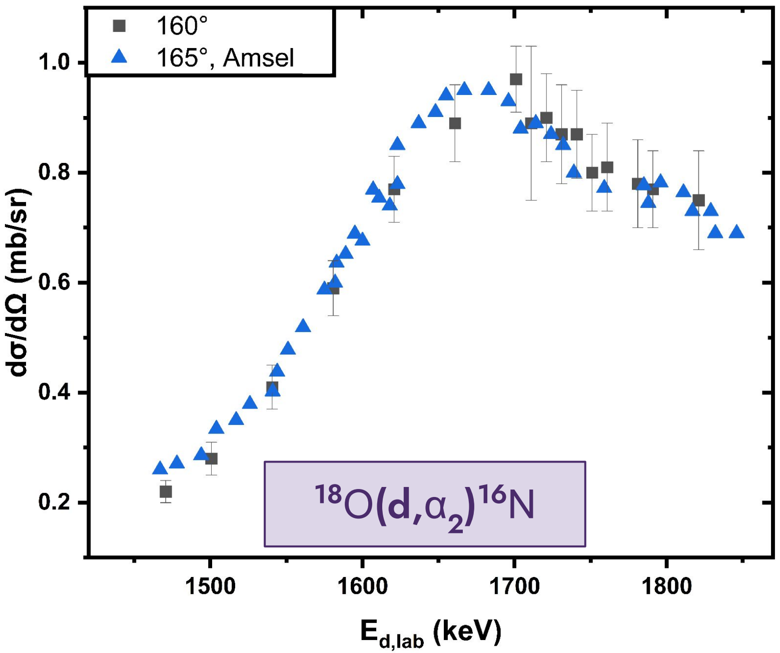


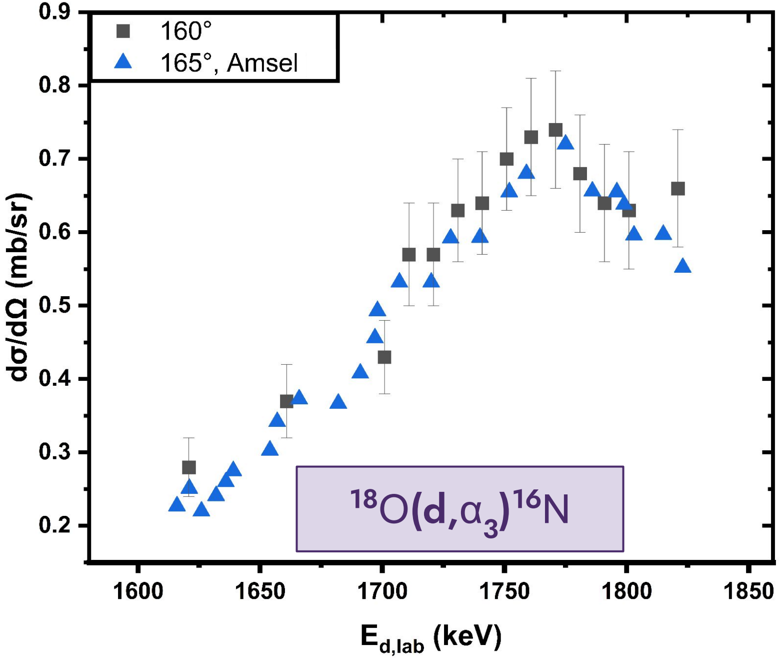


- 160°: excellent agreement over full overlapping range
- 170°: same shape, systematically above Amsel by 0.1–0.15 mb/sr for $E_{d,lab} \geq 1800$ keV
- consistent with angular dependence in the results figure within experimental uncertainty

- Both 160° and 170° reproduce the double-peak structure
- Below 1700 keV: 160° ≈ 170°, both ~0.05–0.10 mb/sr below Amsel — within uncertainties
- Above 1800 keV: angular separation develops — 170° above Amsel, 160° below — consistent with Fig

Discussion: (d,α_2) & (d,α_3)





- After removing the +0.2 mb/sr (α_2) visualization offset from Amsel's data
- α_2: excellent agreement across all measured angles within uncertainties
- α_3: excellent agreement within uncertainties over the 1620–1820 keV overlap range

Conclusions & Future Perspectives

- Measured $^{18}O(d,\alpha_{0\text{-}3})^{16}N$: $E_{d,lab}$ = 1470–2160 keV, θ = 120°–170°, unc. 5–17%
- Target characterised *in situ*; validated two independent ways
- Clear angular dependence for α_0, α_1; none for α_2
- Good agreement with corrected Amsel data
- First data above 2000 keV and at 120°–150°
- IBANDL offset identified and corrected

- R-matrix investigation and further study of the possible resonance of $^{18}O(d,\alpha_0)^{16}N$ at $E_{d,lab}$= 2050 keV
- Pending results for the proton induced ^{18}O reactions
- Extension of our study to other tracers such as ^{13}C

Thank you for your time!