ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

# Neutrons @ FOOT

**Cristian Massimi for INFN Bologna**

Department of Physics and Astronomy

# Outline

## A close look up to the netron data in the literature

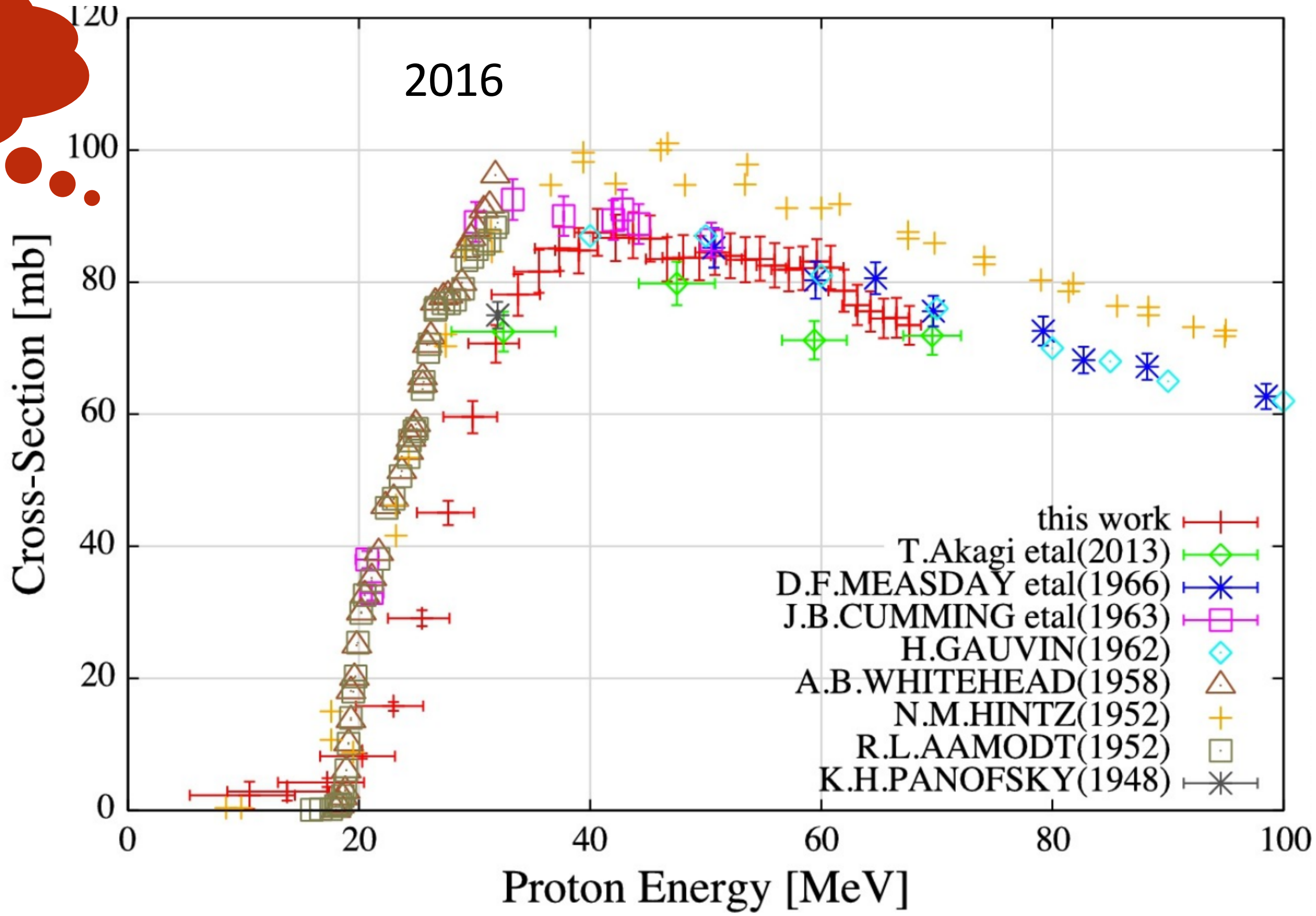
- **Neutron** production in **THIN** targets: cross sections, angular distribution, … as **input to MC**
  - ➢ Proton-induced reactions: inclusive Vs exclusive cross section
  - ➢ Light-ion induced reactions

- **Neutron** production in **THICK** targets: **comparison/benchmark** with MC simulations
  - ➢ Proton- and Carbon-induced reactions on homogeneous target: measurement of **secondary neutron yields**
  - ➢ Proton- and Carbon-induced reactions on clinical phantom

# Thin target, proton-induced reactions

Example: **exclusive** cross section data for **$^{12}C(p,pn)^{11}C$**

Total cross section

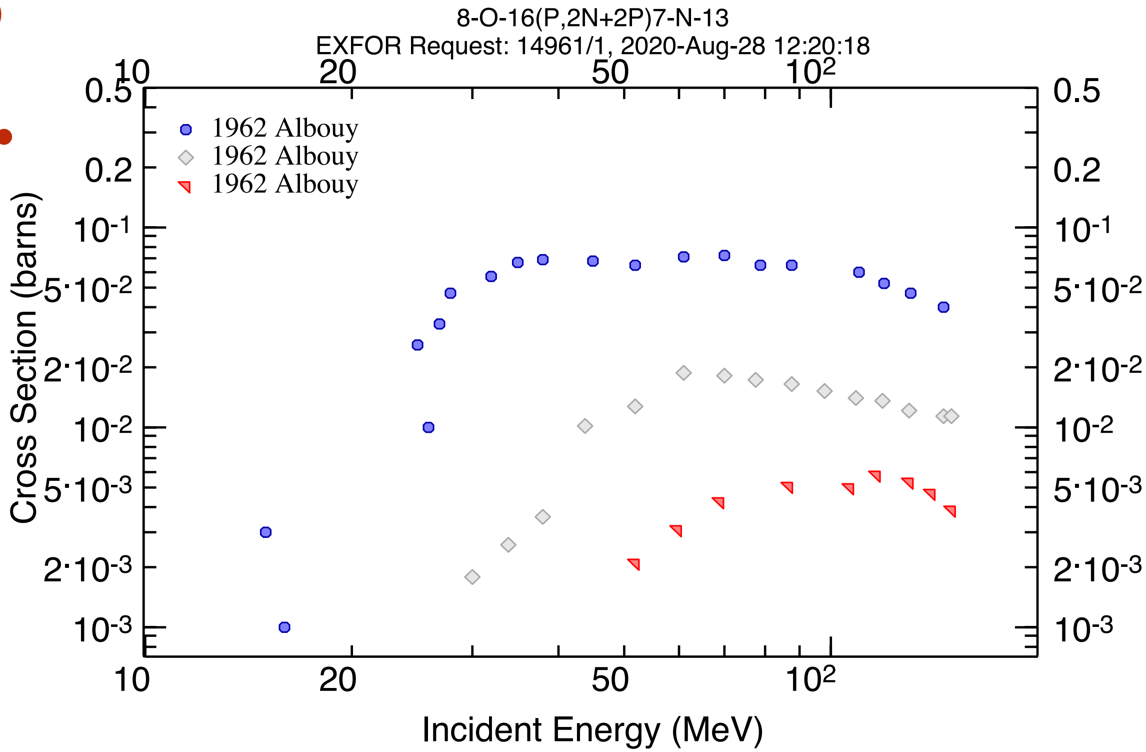



K. Matsushita et al., Nuclear Physics A 946 (2016) 104–116

# Thin target, proton-induced reactions

Example: **exclusive** cross section data for **$^{16}O(p,n)$, $^{16}O(p,2n)$, $^{16}O(p,3n)$**

Total cross section




Data retrieved from the EXFOR database

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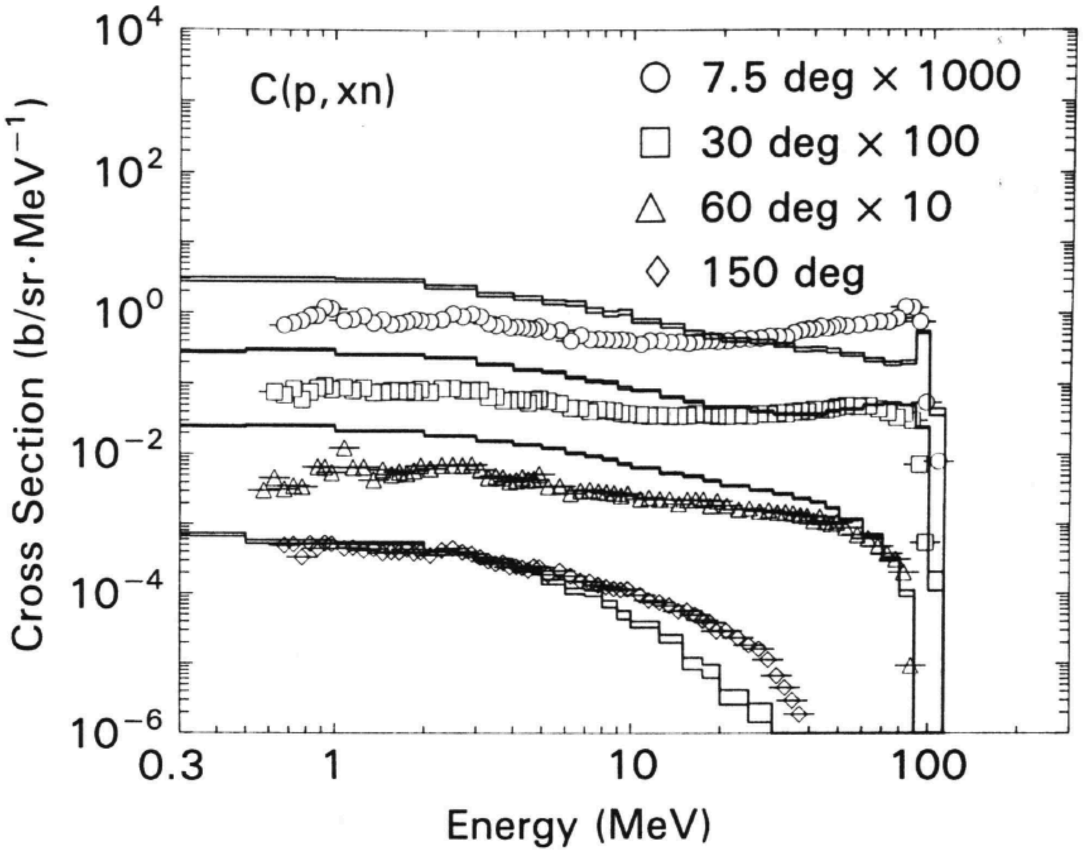
# Thin target, proton-induced reactions (p,nx)

p + C
@ 113 MeV

Example: **inclusive** cross section data for **C(p,xn) @ 113 MeV**

Differential cross section



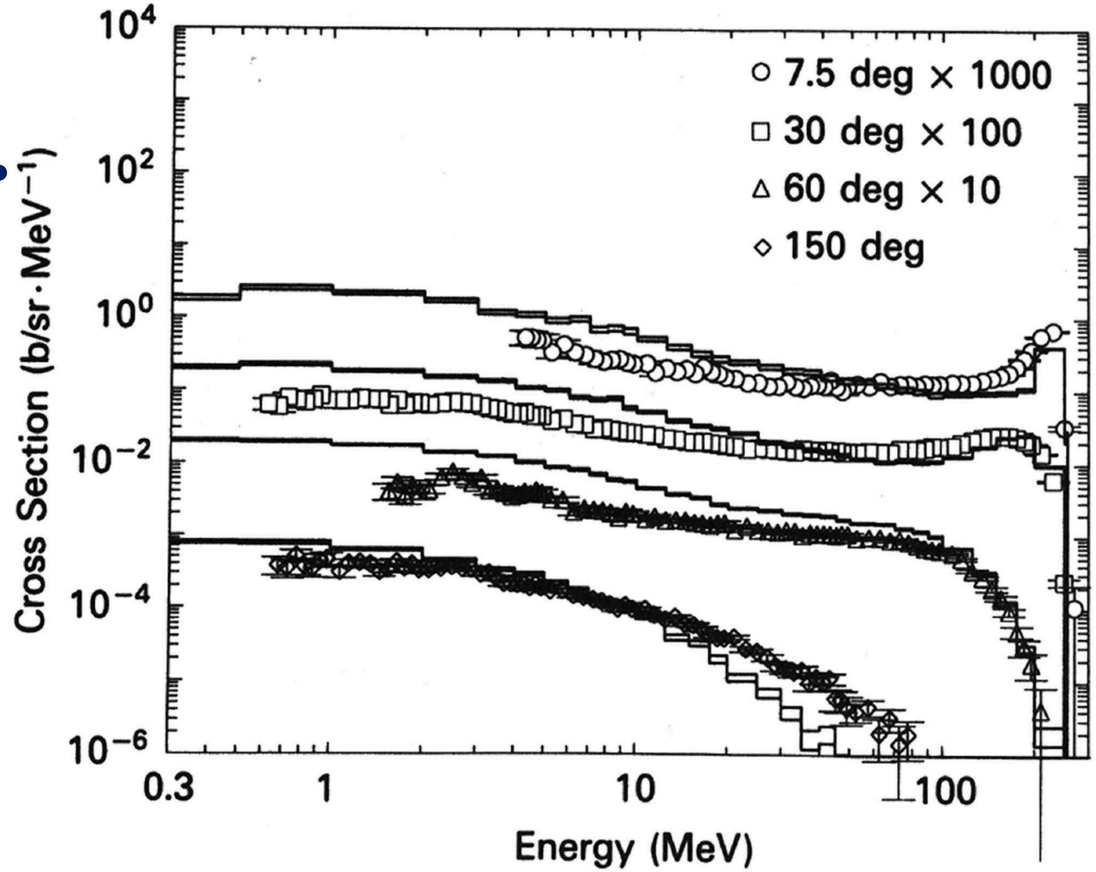

NUCLEAR SCIENCE AND ENGINEERING: 102, 310-321 (1989)

# Thin target, proton-induced reactions (p,nx)

p + C
@ 256 MeV

Example: **inclusive** cross section data for **C(p,xn) @ 256 MeV**

Differential cross section



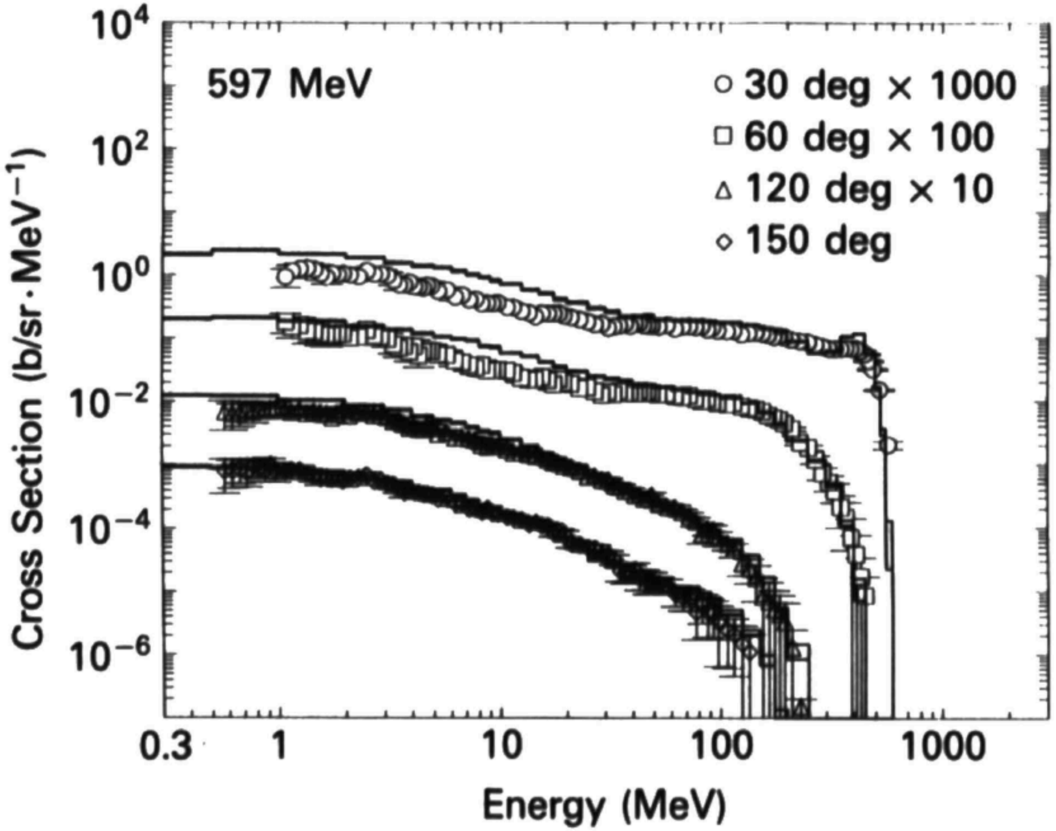

NUCLEAR SCIENCE AND ENGINEERING: 110, 289-298 (1992)

# Thin target, proton-induced reactions (p,nx)

p + C
@ 597 MeV

Example: **inclusive** cross section data for **C(p,xn)** **@ 597 MeV**

Differential cross section




(c) C(*p*,*xn*)

NUCLEAR SCIENCE AND ENGINEERING: 115, 1 - 1 2 (1993)

# Thin target, proton-induced reactions (p,nx)

p + C
@ 800 MeV

Example: **inclusive** cross section data for **C(p,xn)** **@ 800 MeV**

Differential cross section

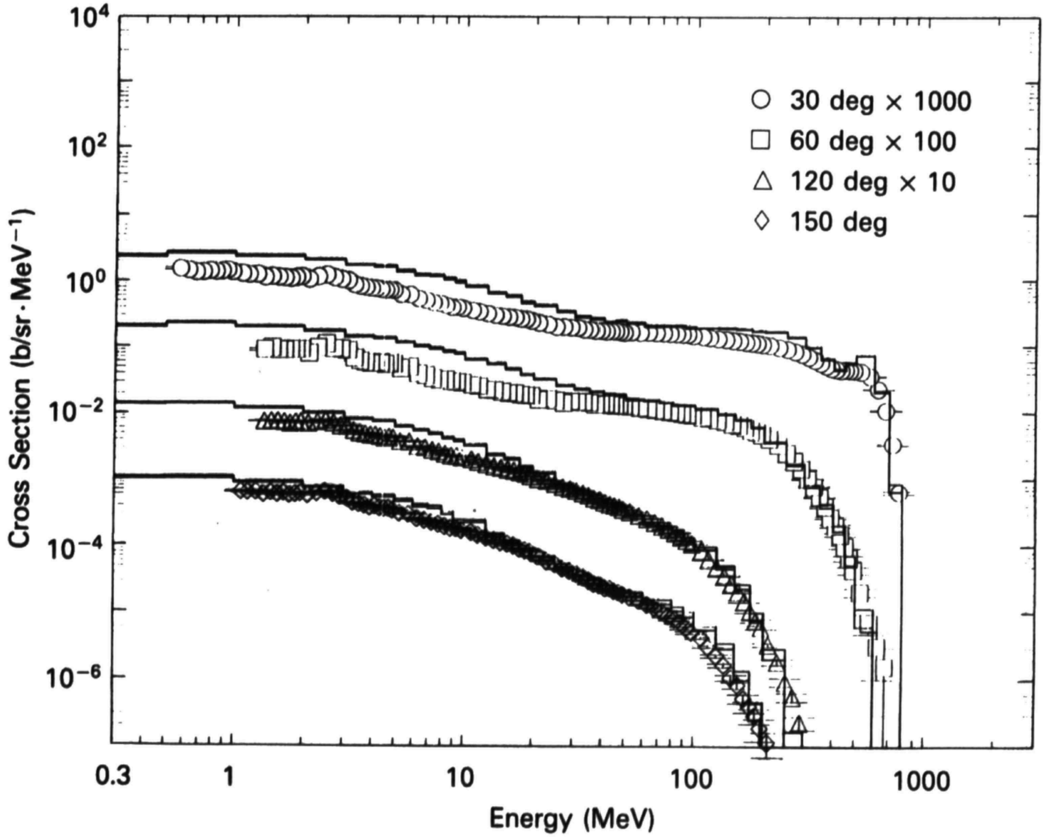



Fig. 3. Experimental differential cross sections for carbon compared with HETC calculations.

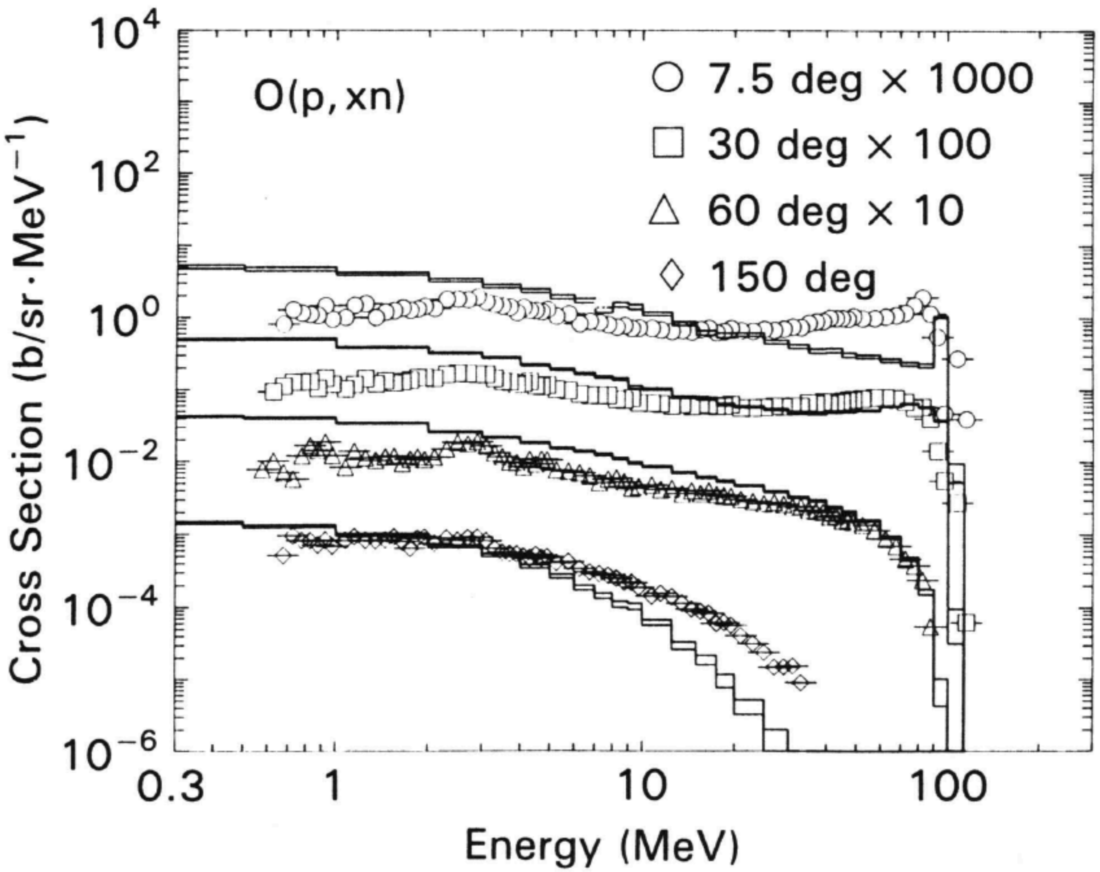
NUCLEAR SCIENCE AND ENGINEERING: 112, 78-86 (1992)

# Thin target, proton-induced reactions (p,nx)

p + O
@ 113 MeV

Example: **inclusive** cross section data for **O(p,xp) @ 113 MeV**

Differential cross section



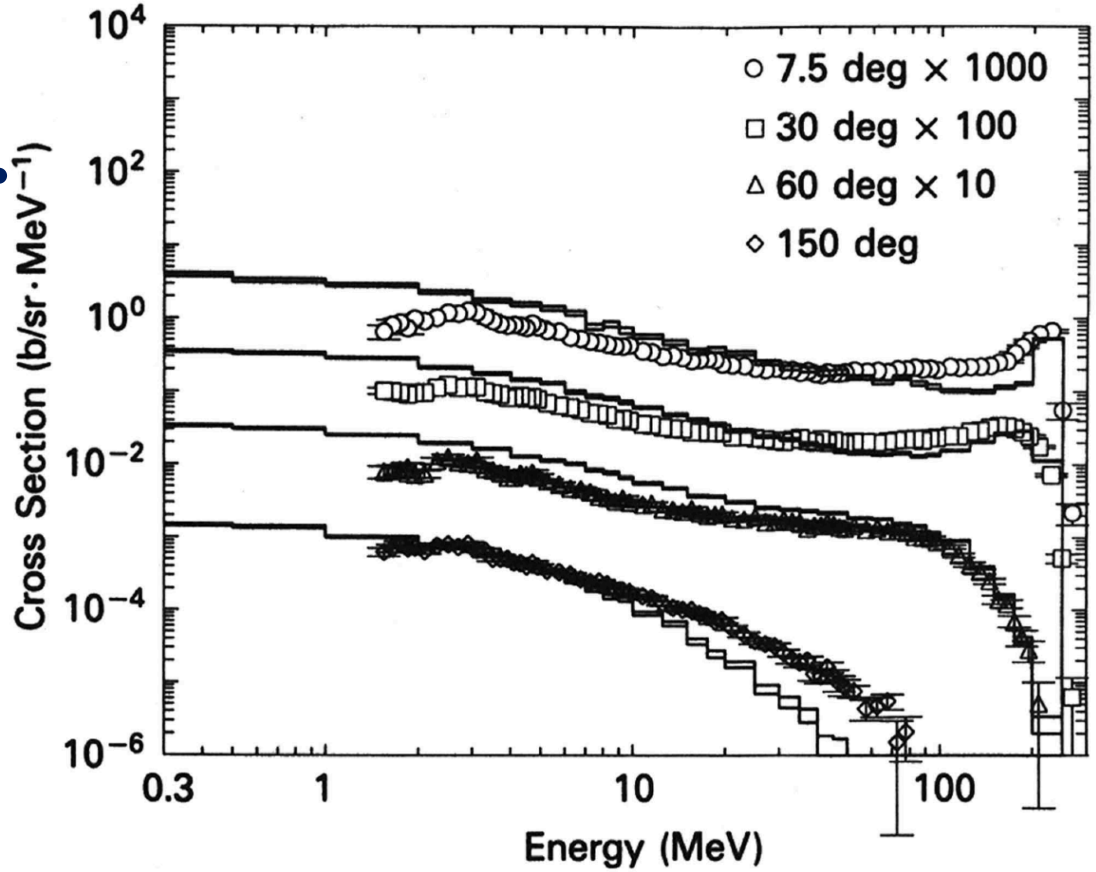

NUCLEAR SCIENCE AND ENGINEERING: 102, 310-321 (1989)

# Thin target, proton-induced reactions (p,nx)

p + O
@ 256 MeV

Example: **inclusive** cross section data for **O(p,xp)** **@ 256 MeV**

Differential cross section



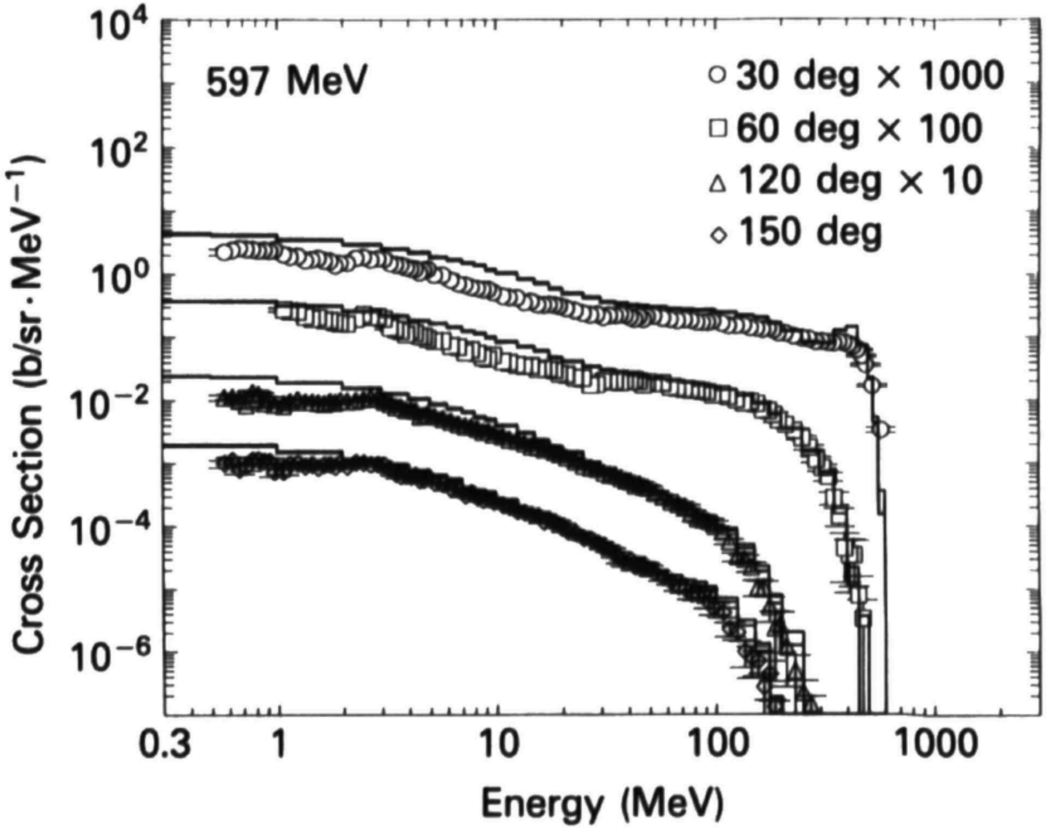

NUCLEAR SCIENCE AND ENGINEERING: 110, 289-298 (1992)

# Thin target, proton-induced reactions (p,nx)

p + O
@ 597 MeV

Example: **inclusive** cross section data for **O(p,xp) @ 597 MeV**

Differential cross section




(e) O(*p*,*xn*) (BeO Target)

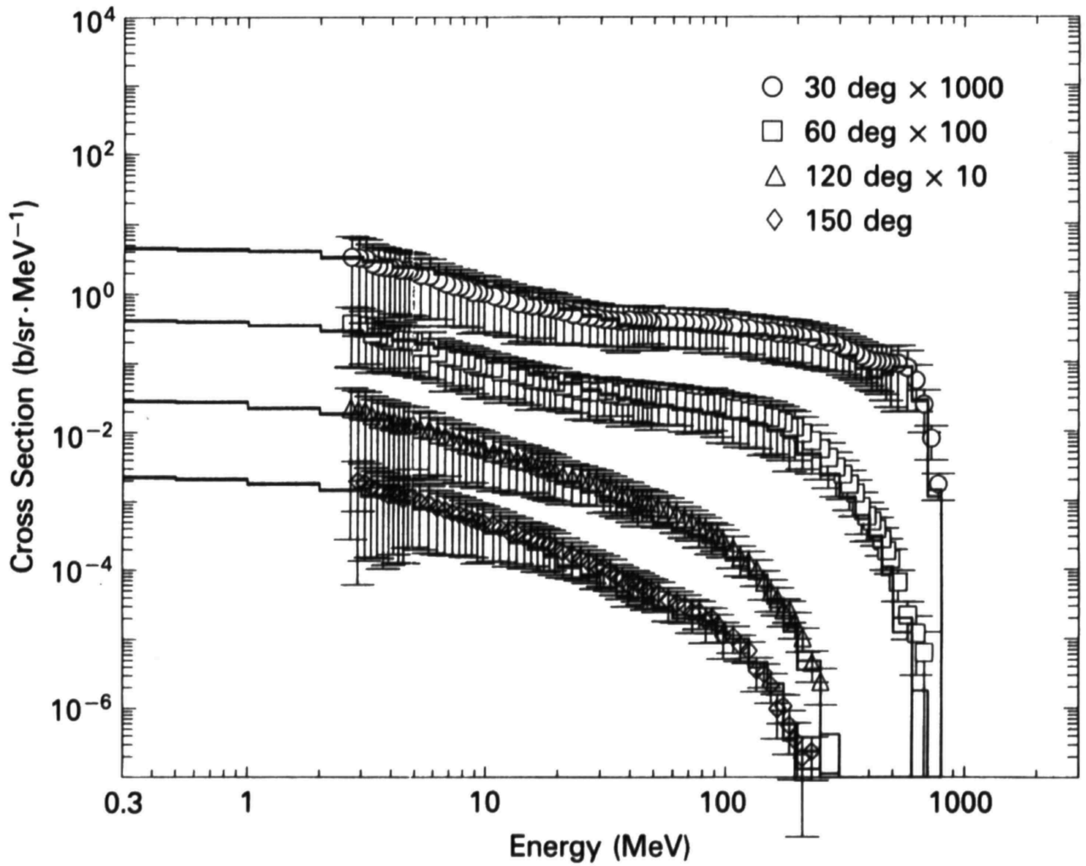
NUCLEAR SCIENCE AND ENGINEERING: 115, 1 - 1 2 (1993)

# Thin target, proton-induced reactions (p,nx)

p + O
@ 800 MeV

Example: **inclusive** cross section data for **O(p,xp) @ 800 MeV**

Differential cross section




NUCLEAR SCIENCE AND ENGINEERING: 112, 78-86 (1992)

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# Thin target, proton-induced reactions (p,nx)

TOF technique

Inclusive cross sections

Target:

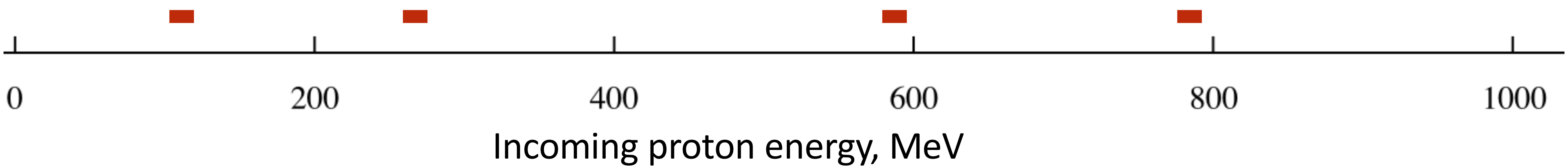
**Be, B, C, N, Al, Fe, Pb, U**

Energy:

**113, 256, 597, 800 MeV**

Angle:

**7.5°, 30°, 60°, 150° LE & 30°, 60°, 120°,150° HE**





NUCLEAR SCIENCE AND ENGINEERING: 102, 310-321 (1989)
NUCLEAR SCIENCE AND ENGINEERING: 110, 289-298 (1992)
NUCLEAR SCIENCE AND ENGINEERING: 112, 78-86 (1992)
NUCLEAR SCIENCE AND ENGINEERING: 115, 1 - 1 2 (1993)

## Thin target, proton-induced reactions (p,nx)

TOF technique

Inclusive cross sections

UNCERTAINTIES

| Factor/Correction | Magnitude | Uncertainty |
|---|---|---|
| Time-Independent Background | < 1% | 5% |
| Time-Dependent Background | < 5% | 20% |
| Shadowbar Background | < 5% | < 3% |
| Air Attenuation | < 2.2% | < 2.5% |
| Efficiency | 3 - 20% | 5 - 20% |
| Dead Time | < 20% | < 5% |
| Charge Normalization | 1.0% | 5% |

NUCLEAR SCIENCE AND ENGINEERING: 102, 310-321 (1989)
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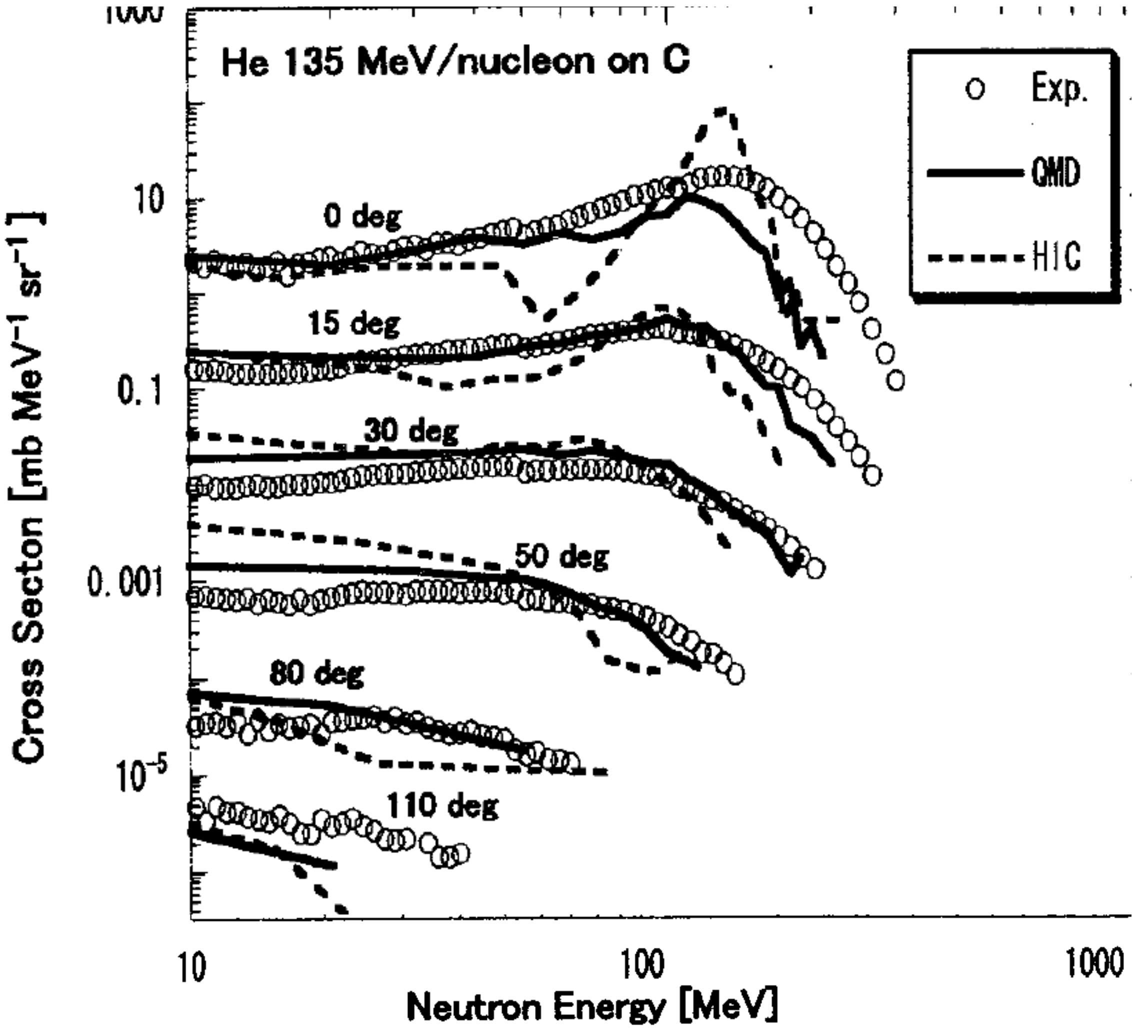
# Thin target, heavy-Ion induced reactions

@ 135 MeV/u

Example: **inclusive cross section**

| Target and thickness (mm) | Projectile type and energy (MeV/nucleon) |
|---|---|
| C (1.0) | He (135) |
| | C (135) |
| | Ne (135) |
| | Ar (95) |
| Al (0.6) | He (135) |
| | C (135) |
| | Ne (135) |
| | Ar (95) |
| Cu (0.3) | He (135) |
| | C (135) |
| | Ne (135) |
| | Ar (95) |
| Pb (0.3) | He (135) |
| | C (135) |
| | Ne (135) |
| | Ar (95) |
| Polyethylene (1.0) | He (135) |

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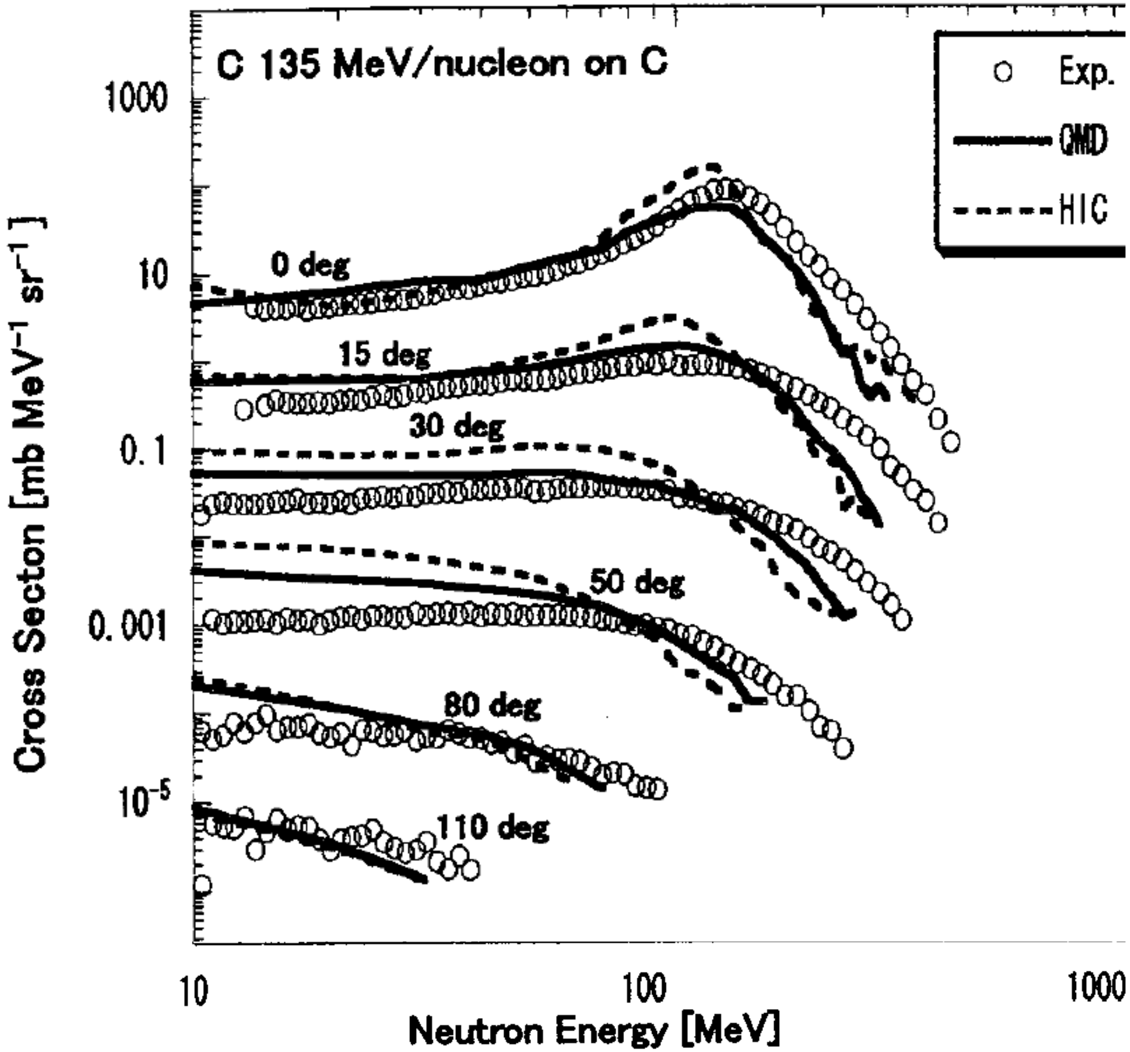
# Thin target, heavy-Ion induced reactions

@ 135 MeV/u

Example: **inclusive cross section**

| Target and thickness (mm) | Projectile type and energy (MeV/nucleon) |
|---|---|
| C (1.0) | He (135) |
| | C (135) |
| | Ne (135) |
| | Ar (95) |
| Al (0.6) | He (135) |
| | C (135) |
| | Ne (135) |
| | Ar (95) |
| Cu (0.3) | He (135) |
| | C (135) |
| | Ne (135) |
| | Ar (95) |
| Pb (0.3) | He (135) |
| | C (135) |
| | Ne (135) |
| | Ar (95) |
| Polyethylene (1.0) | He (135) |

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# Thin target, heavy-Ion induced reactions

@ 135 MeV/u

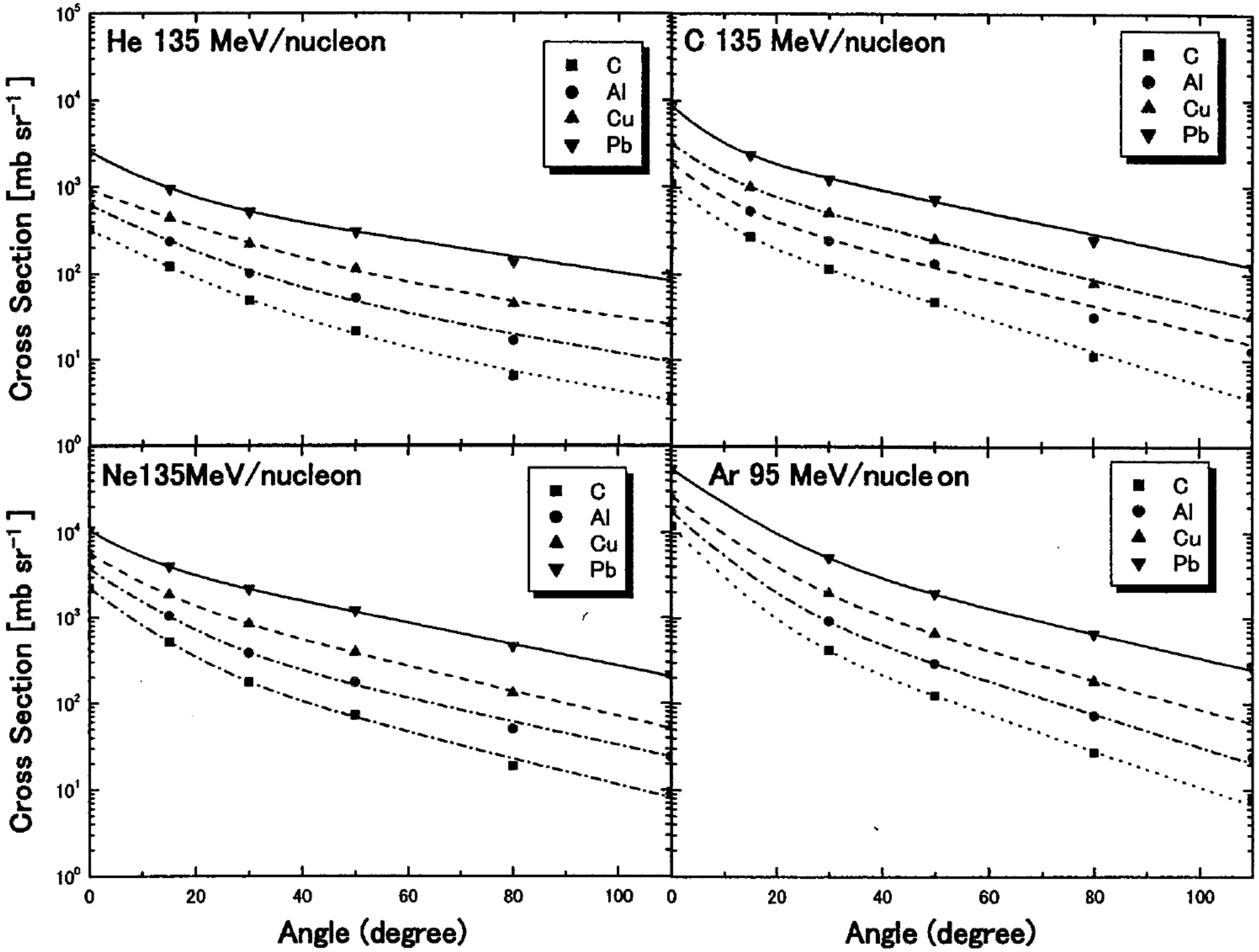


FIG. 8. Angular distributions of neutron production cross sections integrated above 20 MeV.

Angular distribution

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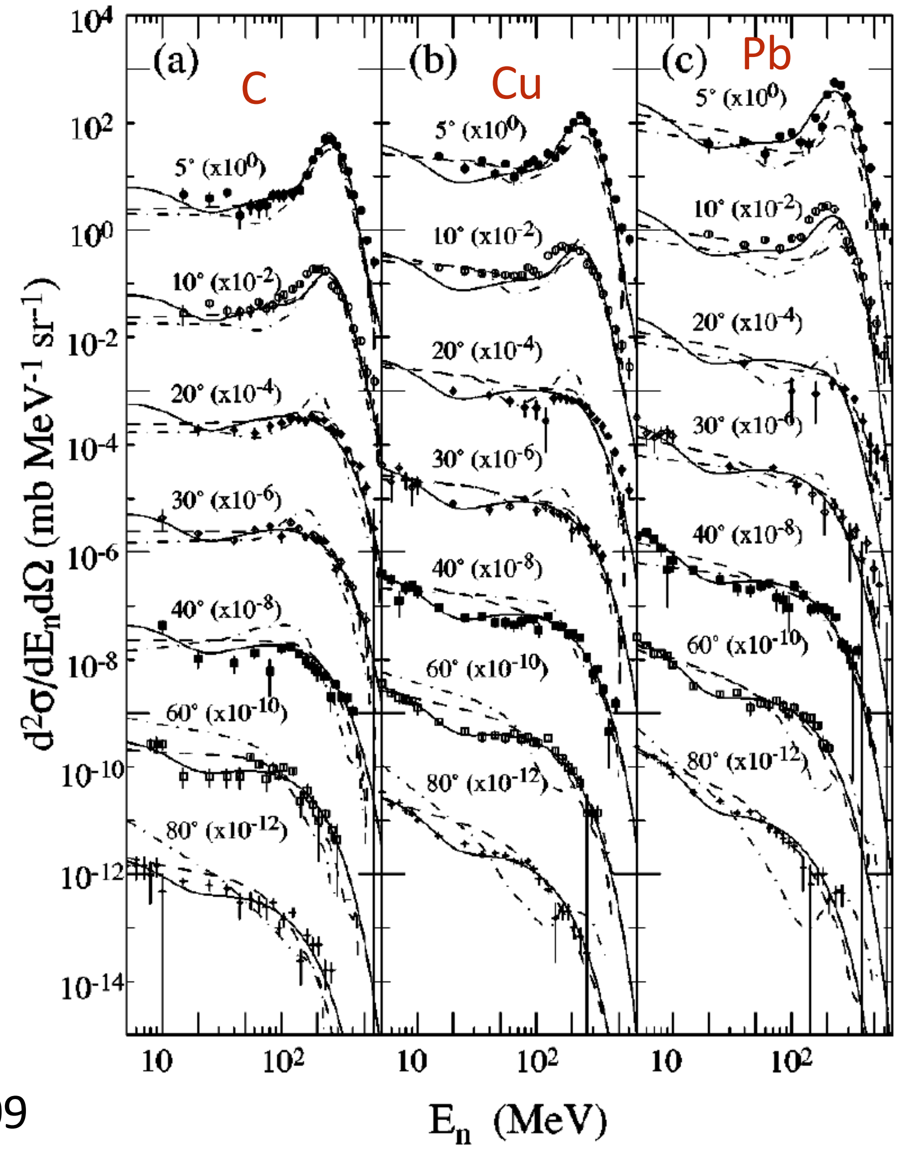
# Thin target, heavy-Ion induced reactions

@ 290 MeV/u
@ 400 MeV/u
@ 600 MeV/u

Example: **inclusive cross section**

TABLE II. Summary of the beams and targets used in the experiment.

| Beam (MeV) | Thickness (g/cm$^2$) C target | Cu target | Pb target |
|---|---|---|---|
| C at $E/A = 290$ | 1.80 | 4.47 | 2.27 |
| C at $E/A = 400$ | 9.00 | 13.4 | 9.08 |
| Ne at $E/A = 400$ | 1.80 | 4.47 | 2.27 |
| Ne at $E/A = 600$ | 3.60 | 4.47 | 4.54 |
| Ar at $E/A = 400$ | 0.720 | 1.34 | 1.70 |
| Ar at $E/A = 560$ | 1.08 | 1.79 | 2.27 |




Differential cross section

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# Thin target, heavy-Ion induced reactions

@ 290 MeV/u
@ 400 MeV/u
@ 600 MeV/u

Example: **inclusive cross section**

TABLE II. Summary of the beams and targets used in the experiment.

| Beam (MeV) | Thickness ($g/cm^2$) C target | Cu target | Pb target |
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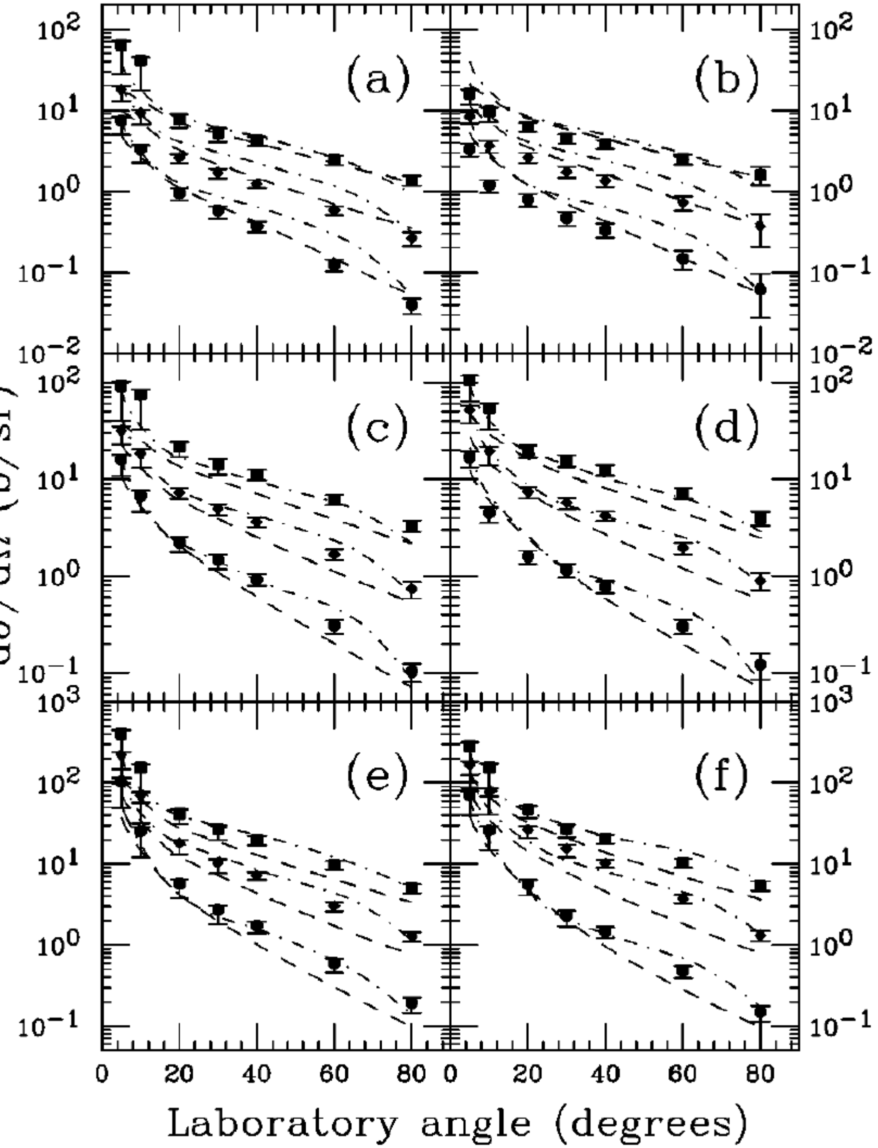
| Ne at $E/A=400$ | 1.80 | 4.47 | 2.27 |
| Ne at $E/A=600$ | 3.60 | 4.47 | 4.54 |
| Ar at $E/A=400$ | 0.720 | 1.34 | 1.70 |
| Ar at $E/A=560$ | 1.08 | 1.79 | 2.27 |

Angular distribution

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# Thin target, heavy-Ion induced reactions

@ 230 MeV/u
@ 400 MeV/u
@ 500 MeV/u
@ 600 MeV/u

Example: **inclusive cross section**

| Beam (Energy) (MeV/nucleon) | Target | Thickness ($g/cm^2$) |
|---|---|---|
| He (230) | Al | 5.40 (2.0 cm) |
| | Cu | 5.38 (0.6 cm) |
| N (400) | C | 1.78 (1.0 cm) |
| | Cu | 2.69 (0.3 cm) |
| Si (600) | C | 1.80 (1.0 cm) |
| | Cu | 3.58 (0.4 cm) |
| | Pb | 4.54 (0.4 cm) |
| Fe (500) | Li | 0.903 (1.7 cm) |
| | $CH_2$ | 0.957 (1.05 cm) |
| | Al | 1.285 (0.476 cm) |
| Kr (400) | Li | 0.47 (0.885 cm) |
| | C | 0.55 (0.3 cm) |
| | $CH_2$ | 0.46 (0.5 cm) |
| | Al | 0.54 (0.2 cm) |
| | Cu | 0.90 (0.1 cm) |
| | Pb | 1.02 (0.09 cm) |
| Xe (400) | Li | 0.48 (0.9 cm) |
| | C | 0.27 (0.15 cm) |
| | $CH_2$ | 0.20 (0.22 cm) |
| | Al | 0.26 (0.095 cm) |
| | Cu | 0.45 (0.05 cm) |
| | Pb | 0.57 (0.05 cm) |

Differential cross section

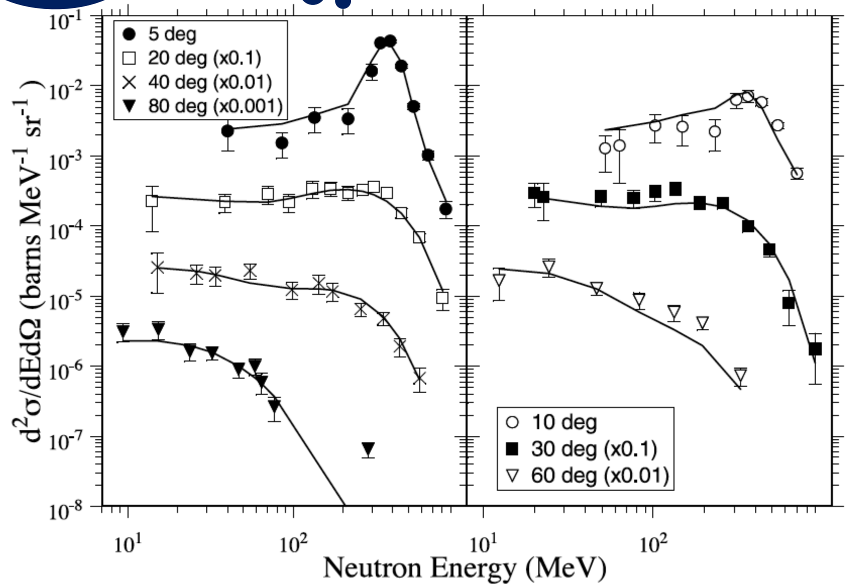


Fig. 5. Double-differential spectra from 400 MeV/nucleon N interacting in a C target. The spectra at each laboratory angle are offset by the indicated factors of 10. The lines come from a moving-source fit described in the text.

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# Thin target, heavy-Ion induced reactions

**Handbook on Secondary Particle Production And Transport by High-energy Heavy Ions**

by Nakamura and Heilbronn

| Beam ion and energy (MeV/nucleon) | Targets | Measured spectra | θ (deg) | Emin (MeV) | Facility |
|---|---|---|---|---|---|
| He (135) | C, Al, Cu, Pb | ddx, n/dΩ total | 0, 15, 30, 50, 80, 110 | 10 (all angles) | RIKEN |
| He (230) | Al, Cu | ddx, n/dΩ total | 5, 10, 20, 30, 40, 60, 80 | 5.5, 5, 4, 3.5, 3.5, 3 | HIMAC (PH2) |
| C (135) | C, Al, Cu, Pb | ddx, n/dΩ total | 0, 15, 30, 50, 80, 110 | 10 (all angles) | RIKEN |
| C (290) | C, Cu, Pb, marsbar | ddx, n/dΩ total | 5, 10, 20, 30, 40, 60, 80 | 10, 3, 3, 7, 4, 3, 3 | HIMAC (SB3) |
| C (400) | Li, C, $CH_2$, Al, Cu, Pb | ddx, n/dΩ total | 5, 10, 20, 30, 40, 60, 80 | 8.5, 5, 3.5, 3, 3, 3 | HIMAC (PH2 and SB3) |
| N (400) | C, Cu | ddx, n/dΩ total | 5, 10, 20, 30, 40, 60, 80 | 6, 6, 5, 5.5, 5.5, 5 | HIMAC (PH2) |
| Ne (135) | C, Al, Cu, Pb | ddx, n/dΩ total | 0, 15, 30, 50, 80, 110 | 10 (all angles) | RIKEN |
| Ne (337) | C, Al, Cu, U | ddx total | 30, 45, 60, 90 | 12 (all angles) | LBL Bevalac |
| Ne (400) | C, Cu, Pb, ISS wall | ddx, n/dΩ total | 5, 10, 20, 30, 40, 60, 80 | 9,6, 3.5, 3.5, 3, 3 | HIMAC (SB3) |
| Ne (600) | Li, C, $CH_2$, Al, Cu, Pb, marsbar | ddx, n/dΩ total | 5, 10, 20, 30, 40, 60, 80 | 6, 5.5, 4, 3, 3, 3 | HIMAC (PH2 and SB3) |
| Ar (95) | C, Al, Cu, Pb | ddx, n/dΩ total | 0, 30, 50, 80, 110 | 10 (all angles) | RIKEN |
| Ar (400) | C, Cu, Pb | ddx, n/dΩ total | 5, 10, 20, 30, 40, 60, 80 | 10, 7, 3.5, 3.5, 3, 3 | HIMAC (PH2 and SB3) |
| Ar (560) | C, Cu, Pb, marsbar | ddx, n/dΩ total | 5, 10, 20, 30, 40, 60, 80 | 10, 7, 3.5, 3.5, 3, 3 | HIMAC (PH2) |
| Fe (500) | Li, $CH_2$, Al | ddx, n/dΩ total | 5, 10, 20, 30, 40, 60, 80 | 12, 11, 7, 4, 3, 3 | HIMAC (PH2) |
| Kr (400) | Li, C, $CH_2$, Al, Cu, Pb | ddx, n/dΩ total | 5, 10, 20, 30, 40, 60, 80 | 20 (all angles) | HIMAC (PH2) |

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# Thin target, heavy-Ion induced reactions

TOF technique

Inclusive cross sections

Target:

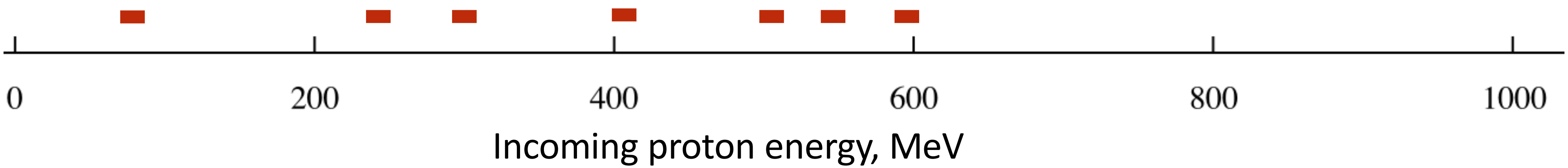
**Li, C, Al, Cu, Pb, U and $CH_2$**

Beams:

**He, C, N, Ne, Ar, Si, Fe, Kr, Xe**

Energy:

**135, 230, 290, 400, 500, 560, 600 MeV/u**




**Handbook on Secondary Particle Production And Transport by High-energy Heavy Ions** by Nakamura and Heilbronn

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# Thin target, heavy-Ion induced reactions

TOF technique

Inclusive cross sections

Target:

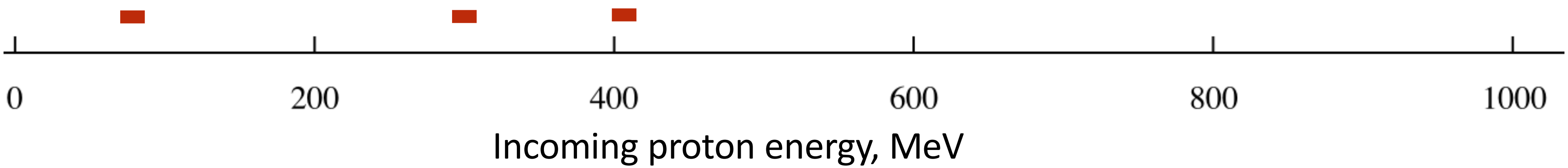
**C** **and $CH_2$**

Beams:

**He, C, N**

Energy:

**135 290, 400, MeV/u**

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# Homogeneous THIK target, charged-particle induced reactions

## Handbook on Secondary Particle Production And Transport by High-energy Heavy Ions

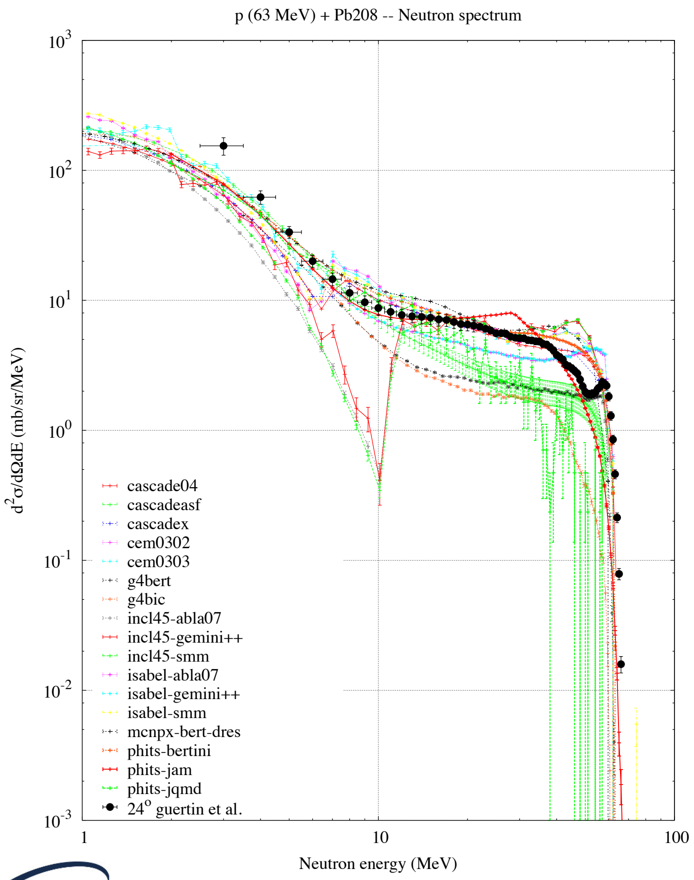
by Nakamura and Heilbronn

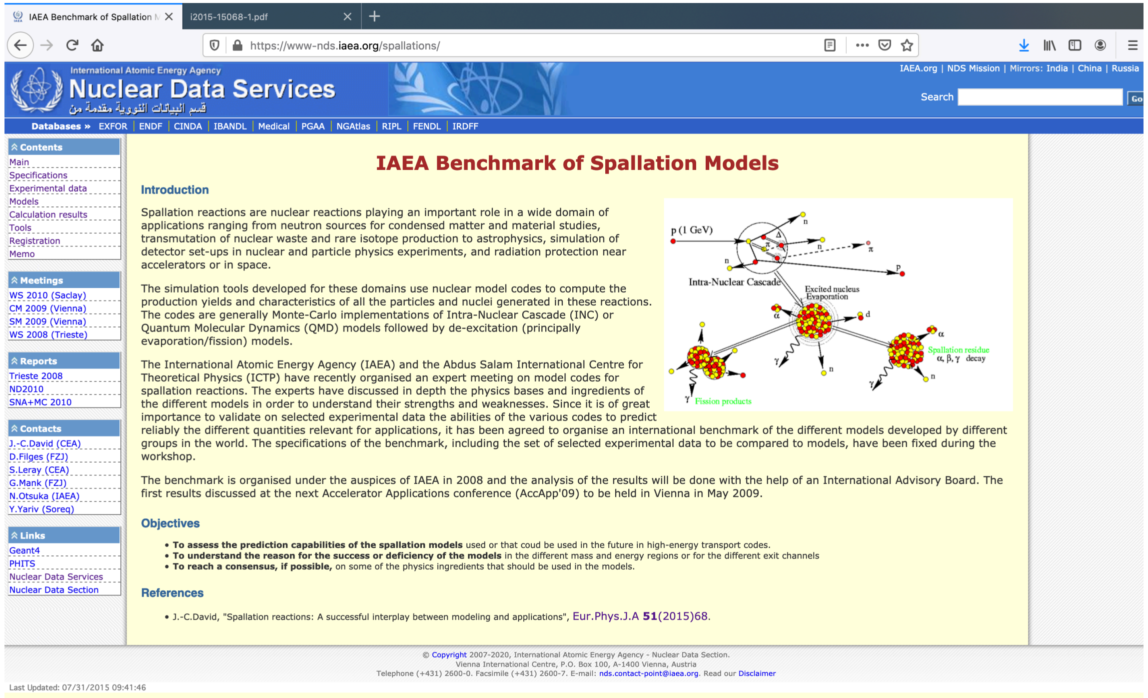
| Beam ion and energy (MeV/nucleon) | Targets (cm) | Measured spectra | θ (deg) | Emin (MeV) | Facility |
|---|---|---|---|---|---|
| He (100) | C (5.0)<br>Al (4.0)<br>Cu (1.5)<br>Pb (1.5) | TTY<br>n/dΩ<br>total | 0, 7.5, 15, 30, 60, 90 | 5.5, 5, 4, 3.5, 3.5, 3 | HIMAC |
| He (155) | Al (8.26) | TTY<br>n/dΩ<br>total | 10, 30, 45, 60, 90, 125, 160 | 10, 3, 3, 7, 4, 3, 3 | NSCL |
| He (160) | Pb (3.937) | TTY<br>Total | 0, 45, 90, 120, 150 | 10, 3, 13, 13, 13 | SREL |
| He (177.5) | C (14.73)<br>$H_2O$ (22.86)<br>Steel (4.445)<br>Pb (3.937) | TTY<br>Total | 0, 6, 15, 30, 45, 60, 90, 120, 135, 150 | 3, 10, 11, 11, 3, 10, 3, 13, 3, 13 | SREL |

| Beam ion and energy (MeV/nucleon) | Targets (cm) | Measured spectra | θ (deg) | Emin (MeV) | Facility |
|---|---|---|---|---|---|
| He (180) | C (16.0)<br>Al (12.0)<br>Cu (4.5)<br>Pb (5.0) | TTY<br>n/dΩ<br>total | 0, 7.5, 15, 30, 60, 90 | 17, 11, 5.5, 6.5, 3.5, 3.5 | HIMAC |
| C (100) | C (2.0)<br>Al (1.0)<br>Cu (0.5)<br>Pb (0.5) | TTY<br>n/dΩ<br>total | 0, 7.5, 15, 30, 60, 90 | 4, 4, 3.5, 3.5, 3, 3 | HIMAC |
| C (155) | Al (8.26) | TTY<br>n/dΩ<br>total | 10, 30, 45, 60, 90, 125, 160 | 10, 3, 3, 7, 4, 3, 3 | NSCL |
| C (180) | C (6.0)<br>Al (4.0)<br>Cu (1.5)<br>Pb (1.5) | TTY<br>n/dΩ<br>total | 0, 7.5, 15, 30, 60, 90 | 5.5, 5.5, 3.5, 2.5, 3, 2.5 | HIMAC |
| C (400) | C (20.0)<br>Al (15.0)<br>Cu (5.0)<br>Pb (5.0) | TTY<br>n/dΩ<br>total | 0, 7.5, 15, 30, 60, 90 | 8.5, 5, 3.5, 3, 3, 3 | HIMAC |
| Ne (100) | C (1.0)<br>Al (1.0)<br>Cu (0.5)<br>Pb (0.5) | TTY<br>n/dΩ<br>total | 0, 7.5, 15, 30, 60, 90 | 6, 6, 5, 5.5, 5.5, 5 | HIMAC |
| Ne (180) | C (4.0)<br>Al (3.0)<br>Cu (1.0)<br>Pb (1.0) | TTY<br>n/dΩ<br>total | 0, 7.5, 15, 30, 60, 90 | 9,6, 3.5, 3.5, 3, 3 | HIMAC |
| Ne (400) | C (11.0)<br>Al (9.0)<br>Cu (3.0)<br>Pb (3.0) | TTY<br>n/dΩ<br>total | 0, 7.5, 15, 30, 60, 90 | 6, 5.5, 4, 3, 3, 3 | HIMAC |
| Si (800) | C (23.0)<br>Cu (6.5) | TTY<br>n/dΩ<br>total | 0, 7.5, 15, 30, 60, 90 | 11, 8, 8, 4, 3.5, 3.5 | HIMAC |
| Ar (400) | C (7.0)<br>Al (5.5)<br>Cu (2.0)<br>Pb (2.0) | TTY<br>n/dΩ<br>total | 0, 7.5, 15, 30, 60, 90 | 10, 7, 3.5, 3.5, 3, 3 | HIMAC |

# Homogeneous THIK target, charged-particle induced reactions

**IAEA Benchmark of Spallation Models** available online: https://www-nds.iaea.org/spallations/



Nuclear Data Services

## IAEA Benchmark of Spallation Models

### Introduction

Spallation reactions are nuclear reactions playing an important role in a wide domain of applications ranging from neutron sources for condensed matter and material studies, transmutation of nuclear waste and rare isotope production to astrophysics, simulation of detector set-ups in nuclear and particle physics experiments, and radiation protection near accelerators or in space.

The simulation tools developed for these domains use nuclear model codes to compute the production yields and characteristics of all the particles and nuclei generated in these reactions. The codes are generally Monte-Carlo implementations of Intra-Nuclear Cascade (INC) or Quantum Molecular Dynamics (QMD) models followed by de-excitation (principally evaporation/fission) models.

The International Atomic Energy Agency (IAEA) and the Abdus Salam International Centre for Theoretical Physics (ICTP) have recently organised an expert meeting on model codes for spallation reactions. The experts have discussed in depth the physics bases and ingredients of the different models in order to understand their strengths and weaknesses. Since it is of great importance to validate on selected experimental data the abilities of the various codes to predict reliably the different quantities relevant for applications, it has been agreed to organise an international benchmark of the different models developed by different groups in the world. The specifications of the benchmark, including the set of selected experimental data to be compared to models, have been fixed during the workshop.

The benchmark is organised under the auspices of IAEA in 2008 and the analysis of the results will be done with the help of an International Advisory Board. The first results discussed at the next Accelerator Applications conference (AccApp'09) to be held in Vienna in May 2009.

### Objectives

- **To assess the prediction capabilities of the spallation models** used or that coud be used in the future in high-energy transport codes.
- **To understand the reason for the success or deficiency of the models** in the different mass and energy regions or for the different exit channels
- **To reach a consensus, if possible,** on some of the physics ingredients that should be used in the models.

### References

- J.-C.David, "Spallation reactions: A successful interplay between modeling and applications", Eur.Phys.J.A **51**(2015)68.



## Double differential cross section (neutron)

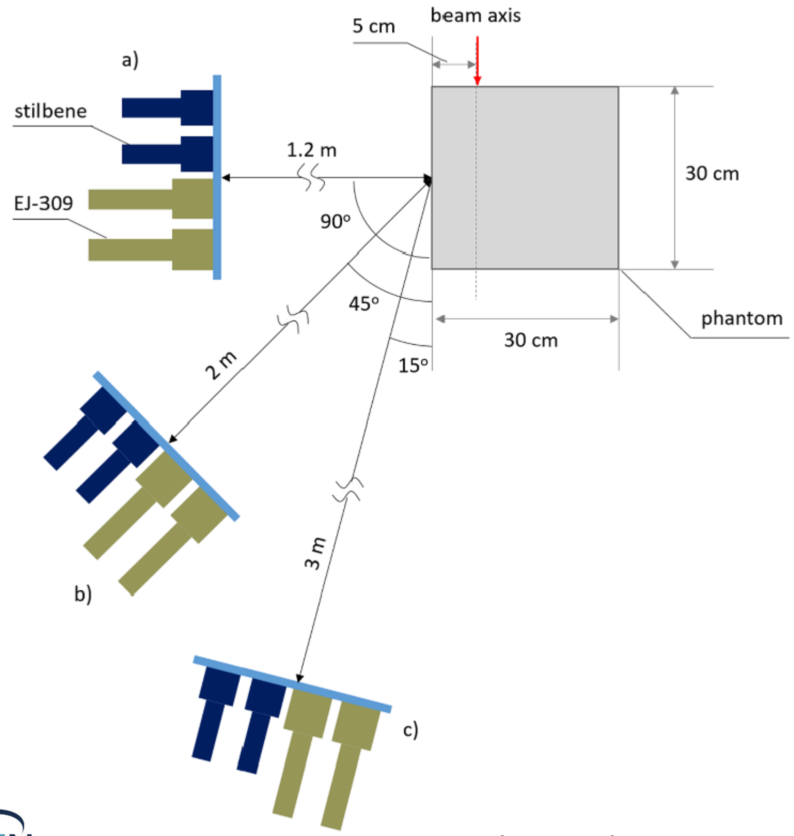
| Proj. | Targ. | E (MeV) | Reference | Lab. | EXFOR | Figure |
|---|---|---|---|---|---|---|
| n | natFe | 65 | E.L.Hjort et al., Phys.Rev.C.53(1996)237 | UC Davis, USA | 13522 | [fig] |
| p | natFe | 800 | W.B.Amian et al., Nucl.Sci.Eng.112(1992)78 | LANL, USA | C0170 | [fig] |
| p | natFe | 800 | S.Leray et al., Phys.Rev.C65(2002)044621 | Saturn, France | O0977 | [fig] |
| p | natFe | 1200 | S.Leray et al., Phys.Rev.C65(2002)044621 | Saturn, France | O0977 | [fig] |
| p | natFe | 1600 | S.Leray et al., Phys.Rev.C65(2002)044621 | Saturn, France | O0977 | [fig] |
| p | natFe | 3000 | K.Ishibashi et al., J.Nucl.Sci.Tech.34(1997)529 | KEK, Japan | E1762 | [fig] |
| p | natPb | 256 | M.M.Meier et al., Nucl.Sci.Eng.110(1992)289 | LANL, USA | C0168 | [fig] |
| p | natPb | 800 | W.B.Amian et al., Nucl.Sci.Eng.112(1992)78 | LANL, USA | C0170 | [fig] |
| p | natPb | 800 | S.Leray et al., Phys.Rev.C65(2002)044621 | Saturn, France | O0977 | [fig] |
| p | natPb | 1200 | S.Leray et al., Phys.Rev.C65(2002)044621 | Saturn, France | O0977 | [fig] |
| p | natPb | 1600 | S.Leray et al., Phys.Rev.C65(2002)044621 | Saturn, France | O0977 | [fig] |
| p | natPb | 3000 | K.Ishibashi et al., J.Nucl.Sci.Tech.34(1997)529 | KEK, Japan | E1762 | [fig] |
| p | 208Pb | 63 | A.Guertin et al., Eur.Phys.J.A23(2005)49 | Louvain, Belgium | O1146 | [fig] |

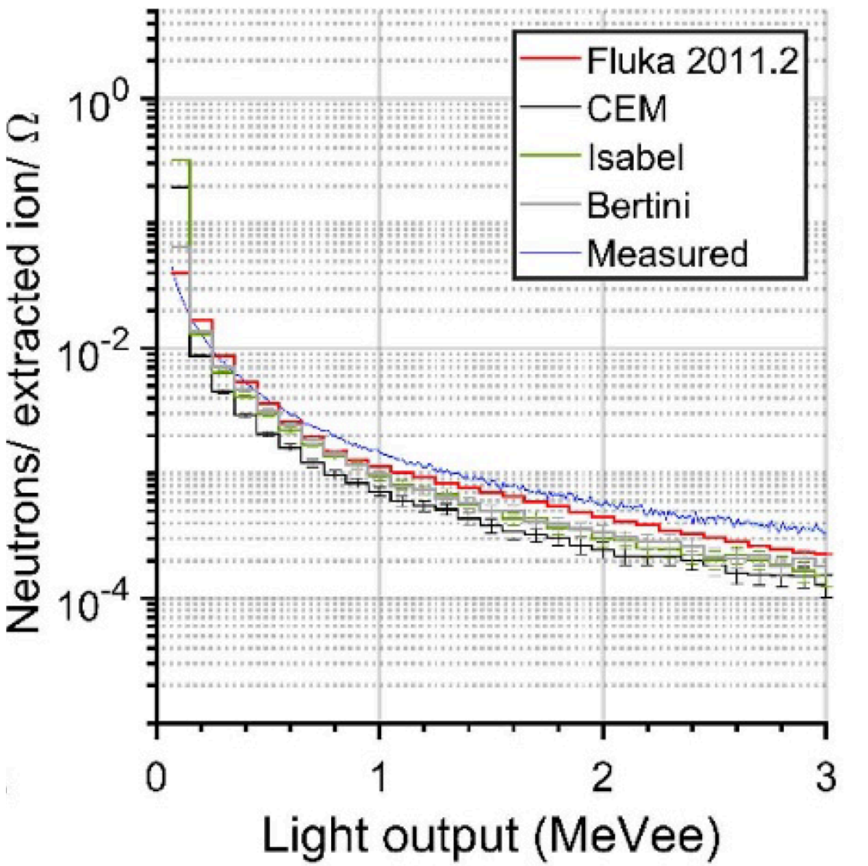
# THICK target: non homogenous target (clinical phantom)

@ CNAO

| | FWHM x (mm) | FWHM y (mm) |
|---|---|---|
| Protons, 155 MeV $u^{-1}$ | 9.46 | 9.69 |
| Protons, 200.28 MeV $u^{-1}$ | 7.66 | 7.80 |
| Carbon ions, 292.96 MeV $u^{-1}$ | 5.51 | 4.41 |
| Carbon ions, 387.78 MeV $u^{-1}$ | 4.23 | 3.72 |

BW3 phantom: 30 cm x 30 cm x 15 cm (thick enough to stop the proton and carbon-ion beams)

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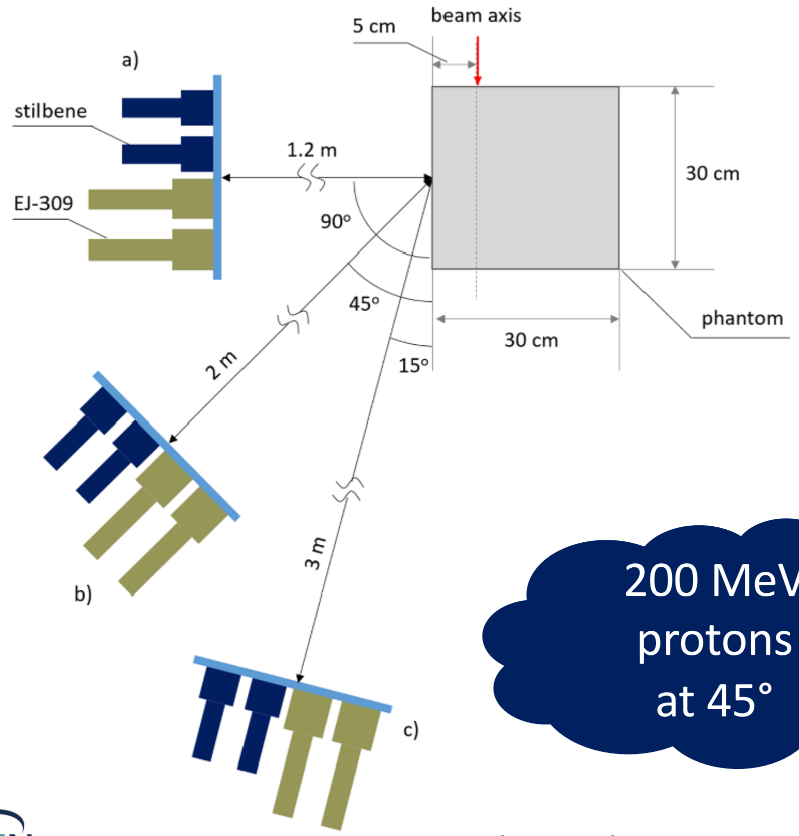
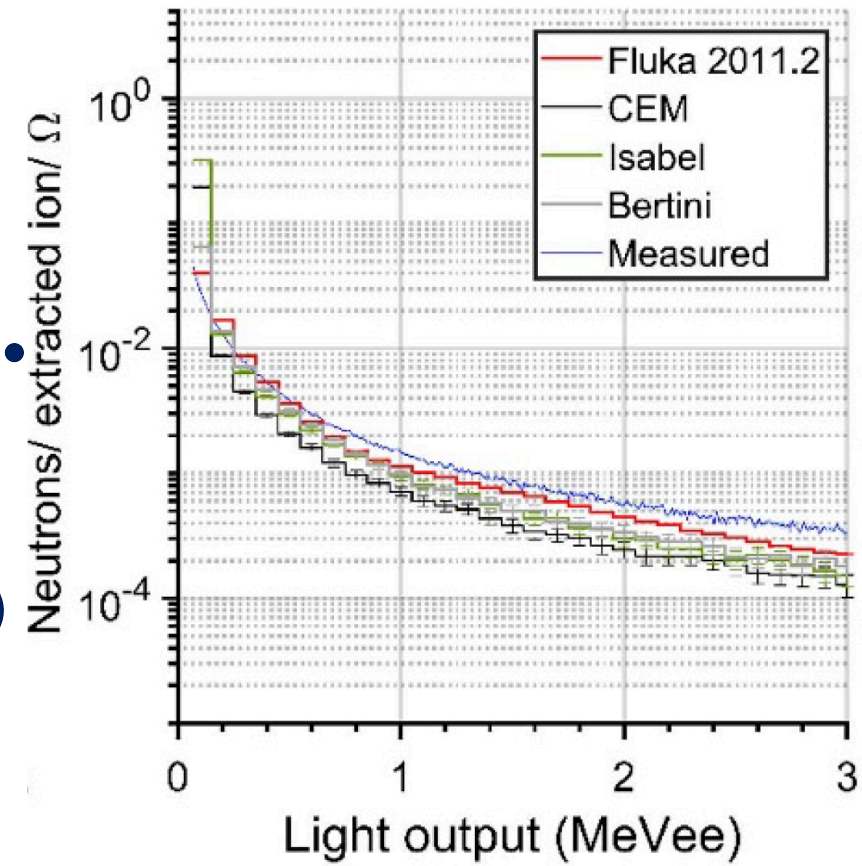



200 MeV protons at 45°

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@ CNAO

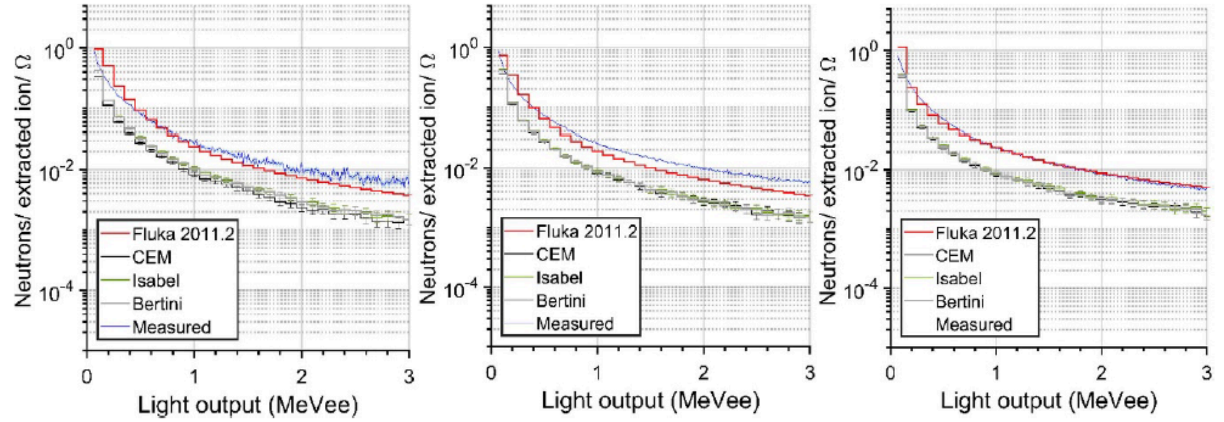


**Figure 8.** Comparison between simulated and measured EJ-309 pulse height distributions, for 293 MeV $u^{-1}$ carbon-ion irradiation, at measurement locations of 15°, 45° and 90° (left to right) with respect to the beam axis.

293 MeV/u
&
388 MeV/u
Carbon

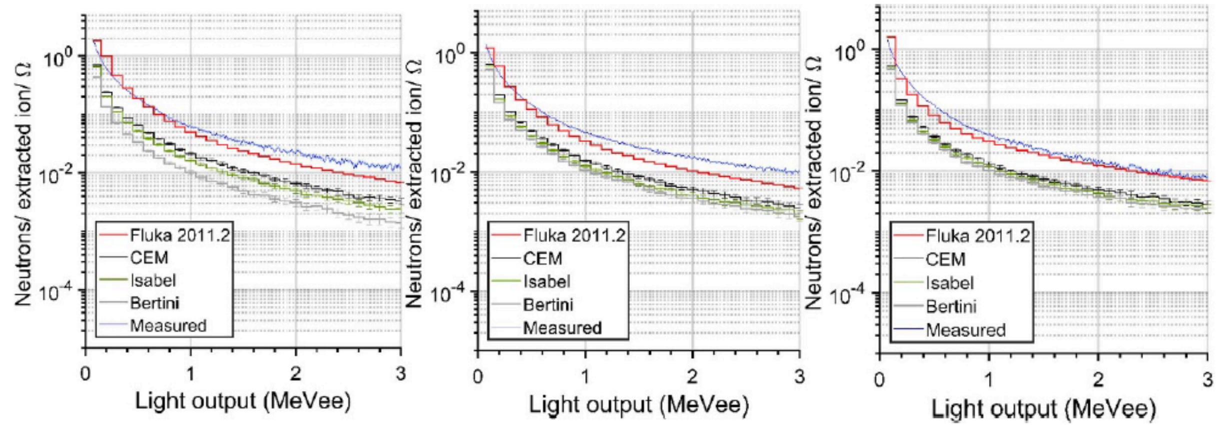


**Figure 9.** Comparison between simulated and measured EJ-309 pulse height distributions, for 387.78 MeV $u^{-1}$ carbon-ion irradiation, at measurement locations of 15°, 45° and 90° (left to right) with respect to the beam axis.



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## Conclusions

- Large number of **experimental data** sets but **often not** made **available** on nuclear reaction databases.

- A few **exclusive cross section** measurements on p + $^{12}C$ and + $^{16}O$, respectively. **Very challenging experiments** and most valuable data(?)

- Inclusive differential cross sections on **thin targets** for p + $^{12}C$ and $^{16}O$ available at several angles and energies.

- **No neutron data** for the **$^{12}C$ + $^{16}O$** reaction. Few neutron data for **$^{12}C$ + $^{12}C$**.

- Experiments on thick targets, show the **need for more accurate neutron data**.

Worth investigating feasibility @ FOOT ?

$d^2\sigma/dEd\Omega$ could be improved and perhaps cross-checked?

Similar experiments could be performed @ FOOT?

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# backup

- **Handbook on Secondary Particle Production And Transport by High-energy Heavy Ions**, by Nakamura and Heilbronn
- **IAEA Benchmark of Spallation Models** available online: https://www-nds.iaea.org/spallations/