



ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Neutrons @ FOOT

Cristian Massimi for INFN Bologna

Department of Physics and Astronomy

Outline

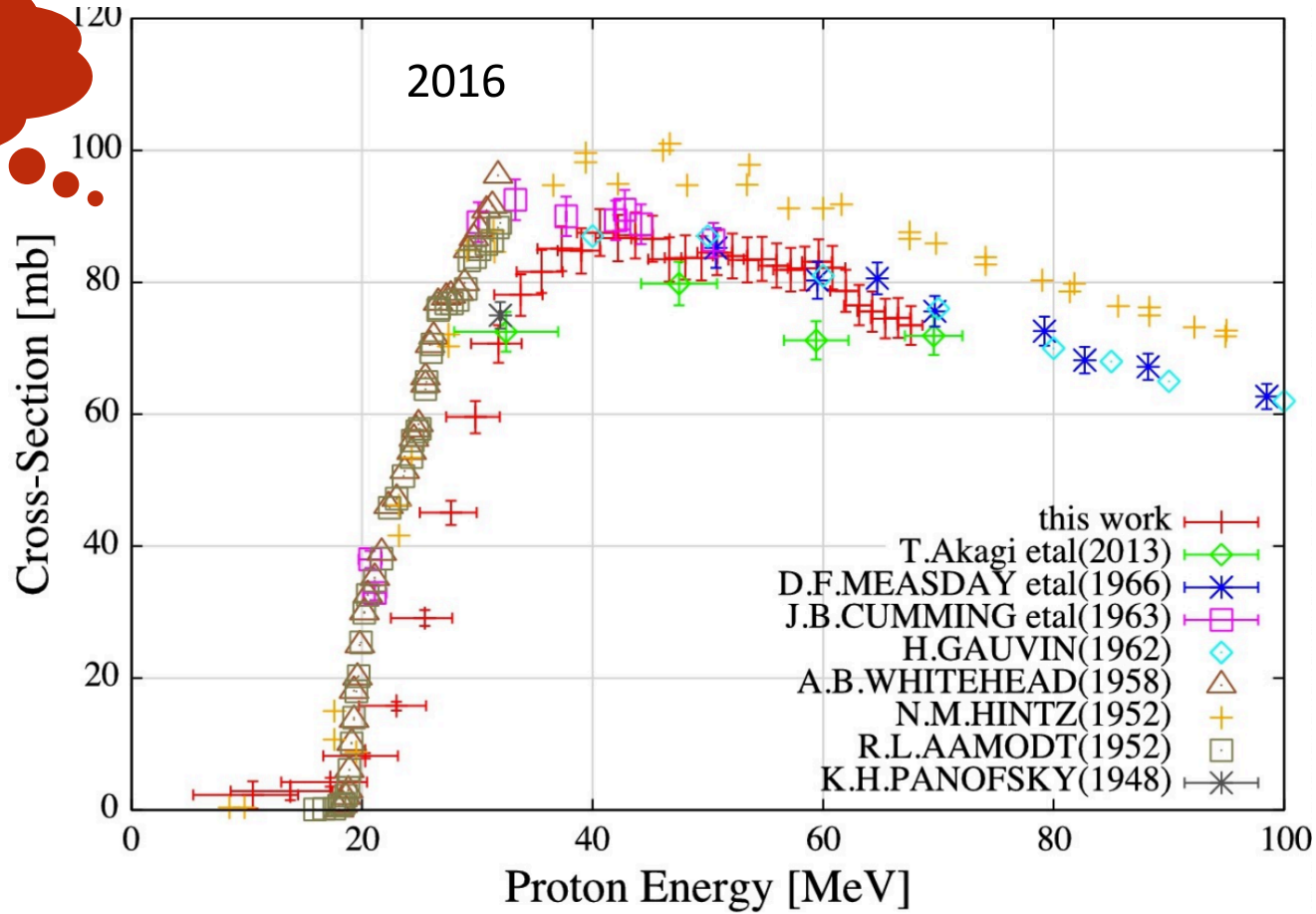
A close look up to the neutron data in the literature

- **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 $^{12}\text{C}(p, pn)^{11}\text{C}$

Total cross section

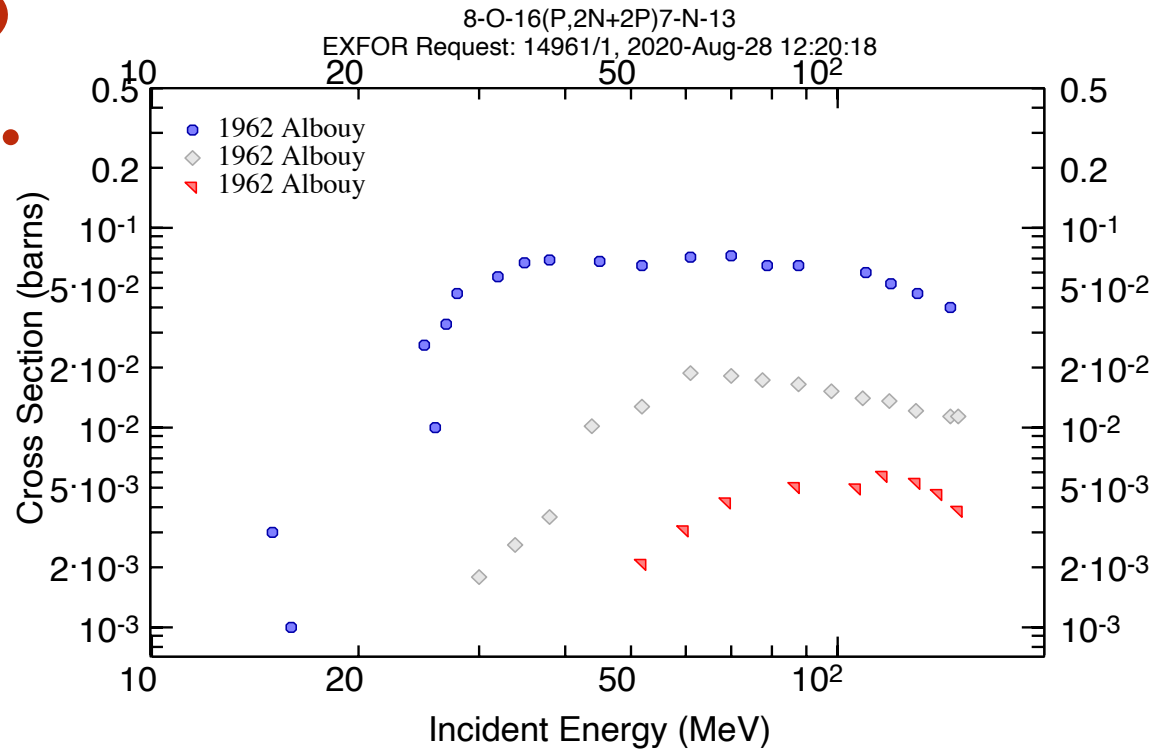


K. Matsushita et al., Nuclear Physics A 946 (2016) 104–116

Thin target, proton-induced reactions

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

Total cross section



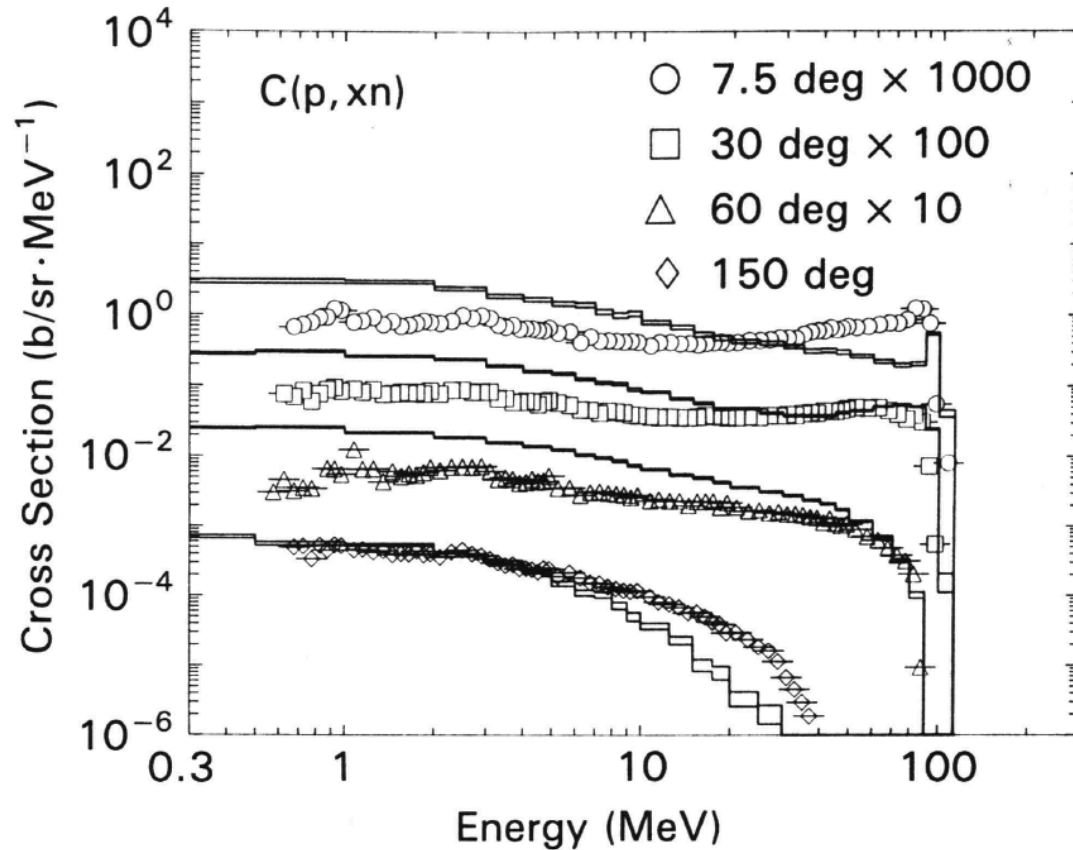
Data retrieved from the EXFOR database

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

p + C
@ 113 MeV

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

Differential cross section

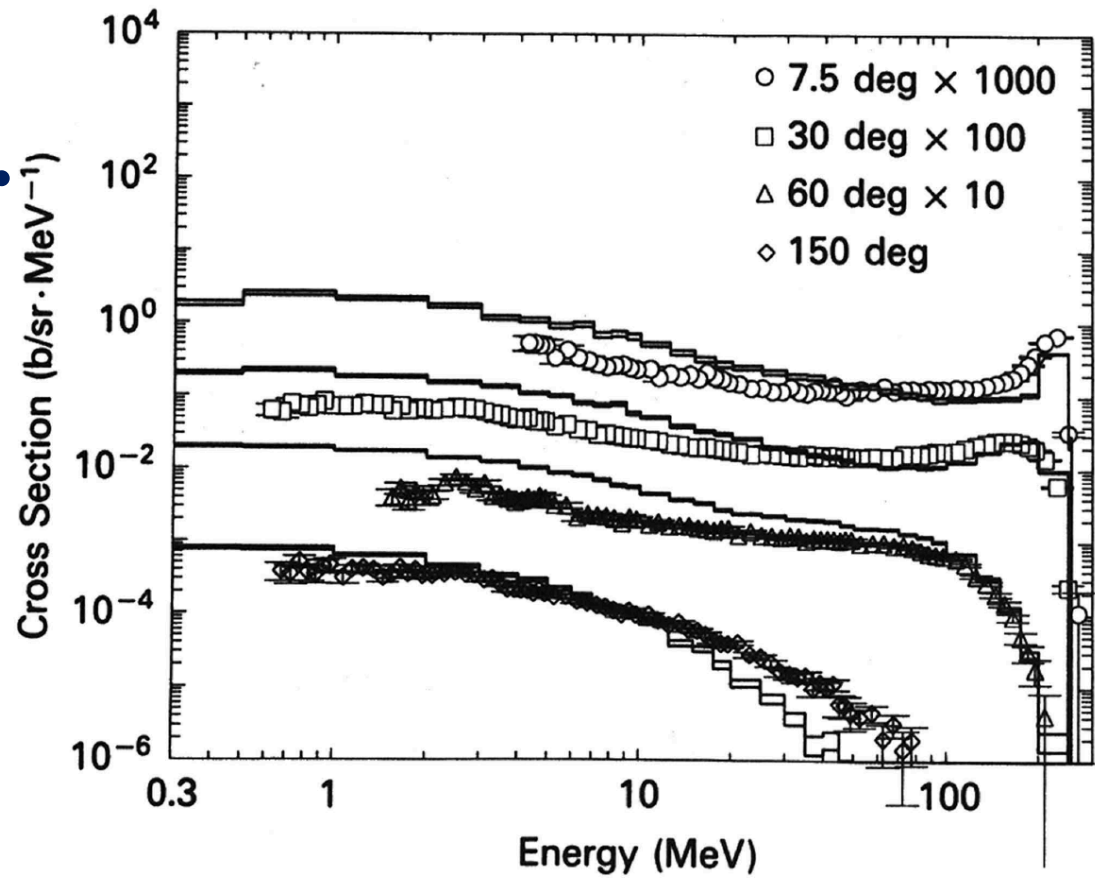


Thin target, proton-induced reactions (p,nx)

p + C
@ 256 MeV

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

Differential
cross section

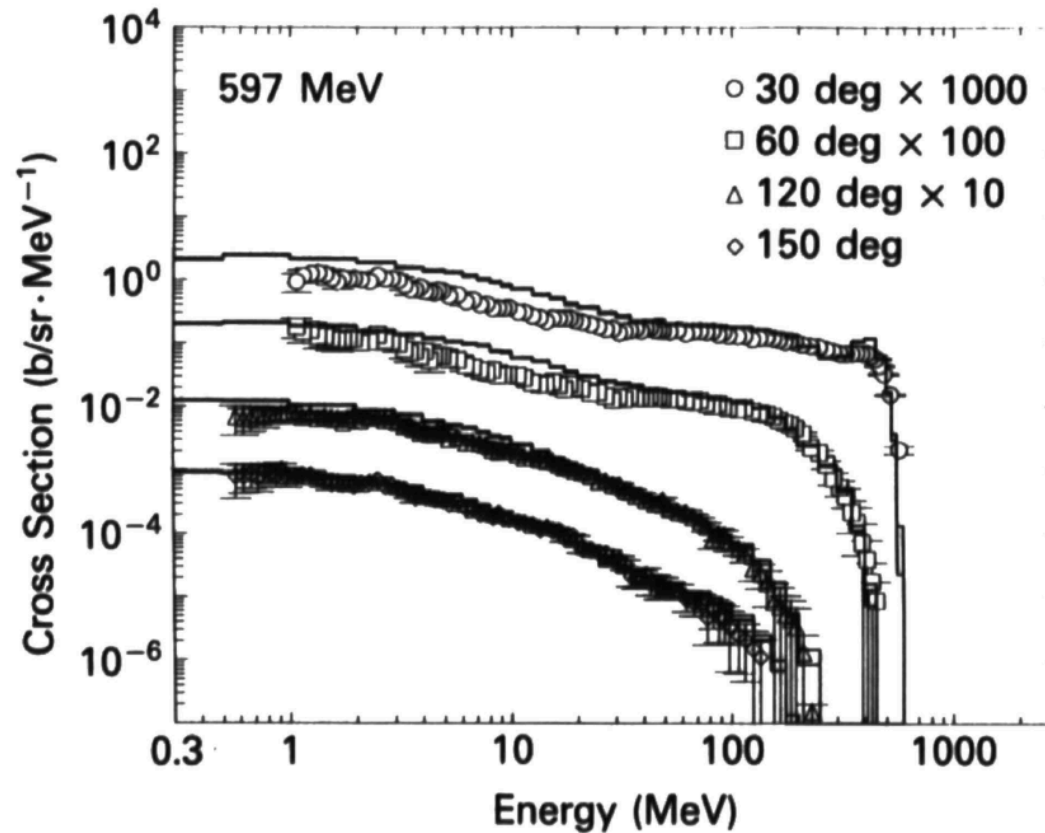


Thin target, proton-induced reactions (p,nx)

p + C
@ 597 MeV

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

Differential cross section



(c) C(p,xn)

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

p + C
@ 800 MeV

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

Differential cross section

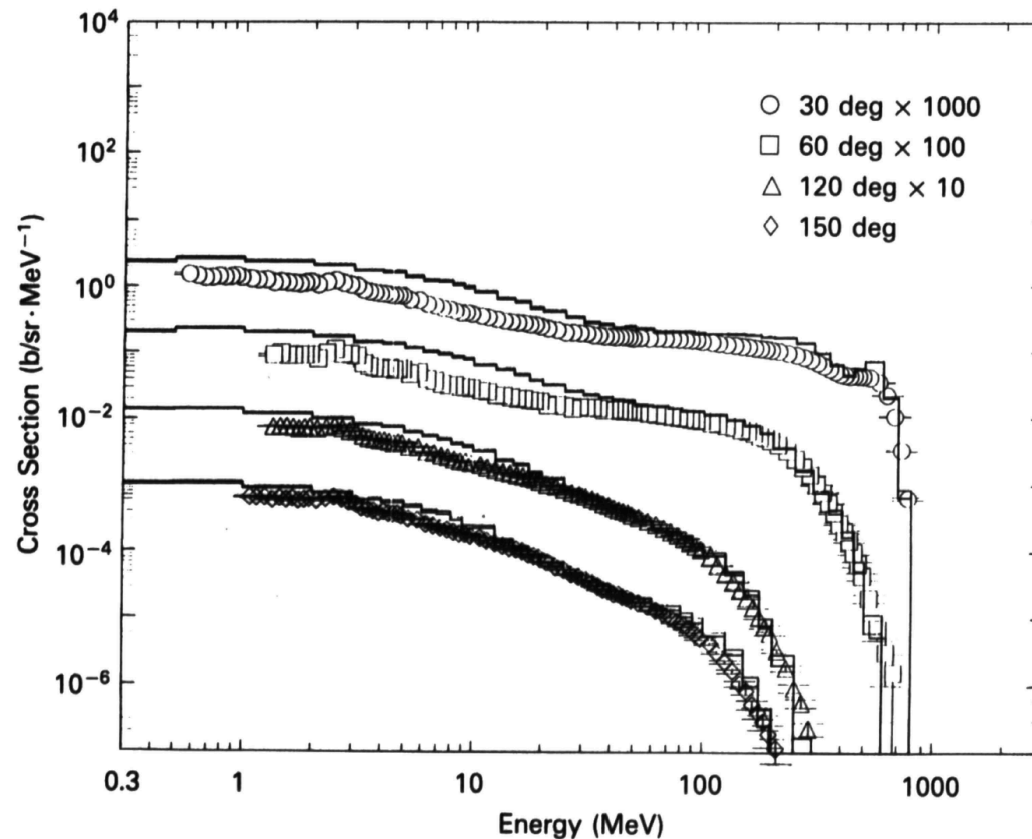


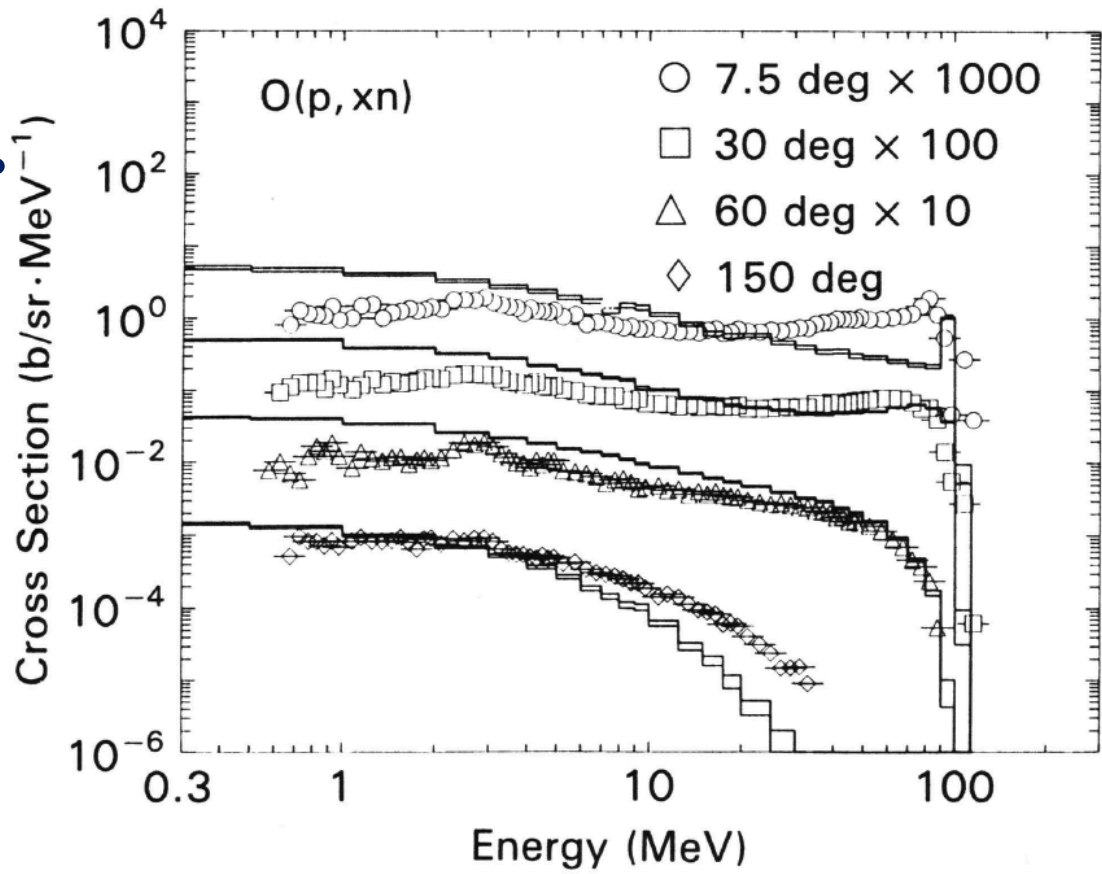
Fig. 3. Experimental differential cross sections for carbon compared with HETC calculations.

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

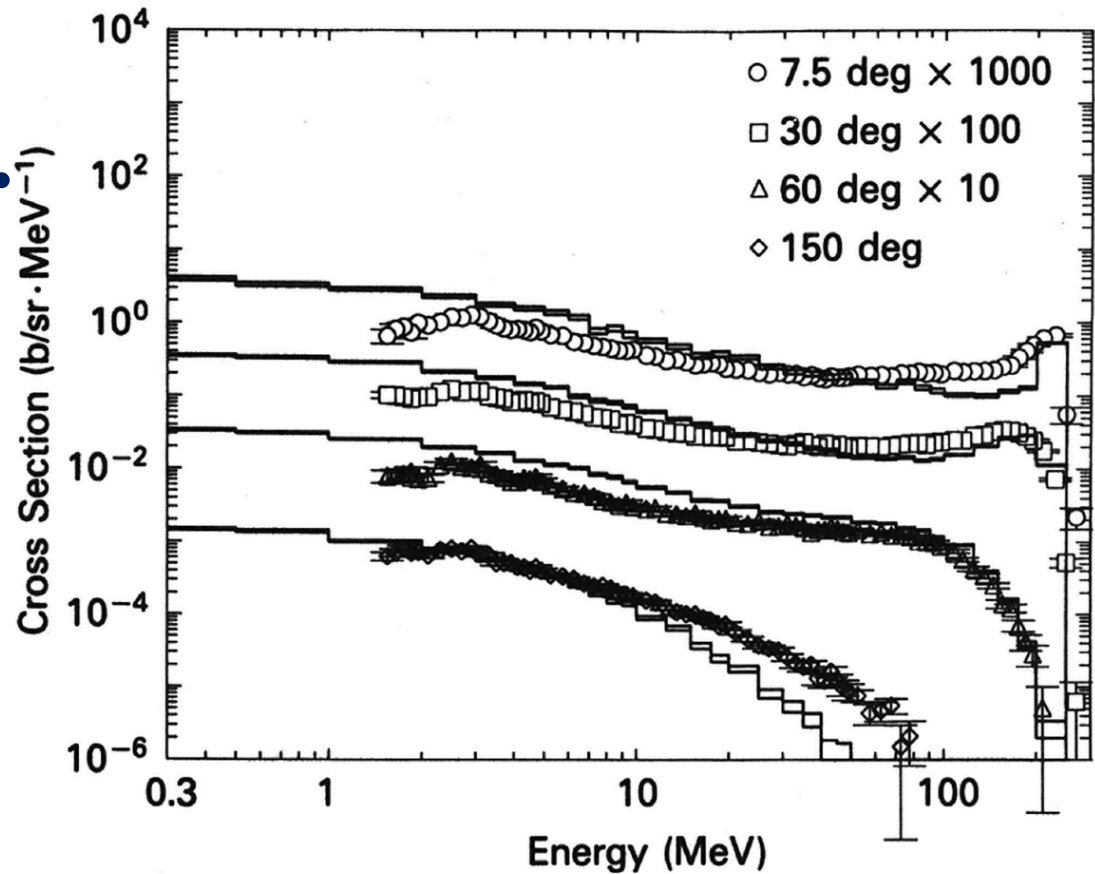


Thin target, proton-induced reactions (p,nx)

p + 0
@ 256 MeV

Example: **inclusive** cross section data for **0(p,xp) @ 256 MeV**

Differential cross section

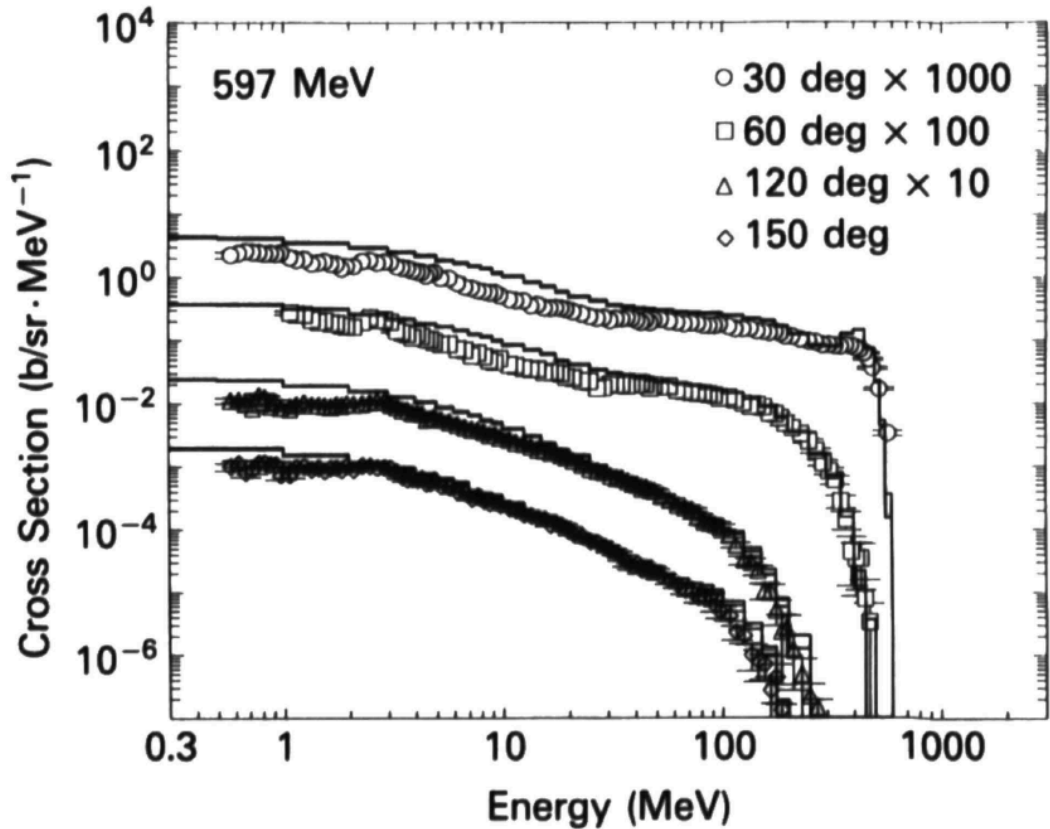


Thin target, proton-induced reactions (p,nx)

p + O
@ 597 MeV

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

Differential cross section



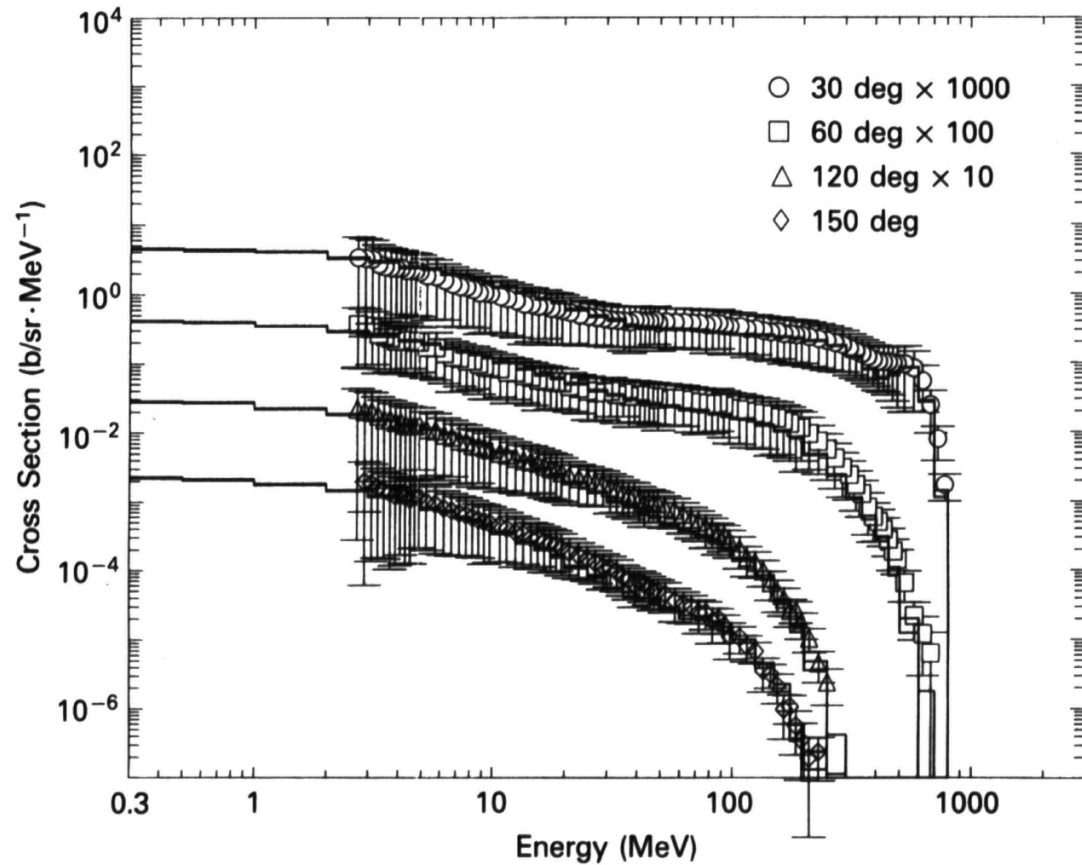
(e) O(p,xn) (BeO Target)

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

p + 0
@ 800 MeV

Example: **inclusive** cross section
data for **0(p,xp) @ 800 MeV**

Differential
cross section



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

TOF
technique

UNCERTAINTIES

Inclusive cross
sections

<u>Factor/Correction</u>	<u>Magnitude</u>	<u>Uncertainty</u>
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)

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

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

NUCLEAR SCIENCE AND ENGINEERING: 115, 1 - 12 (1993)

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

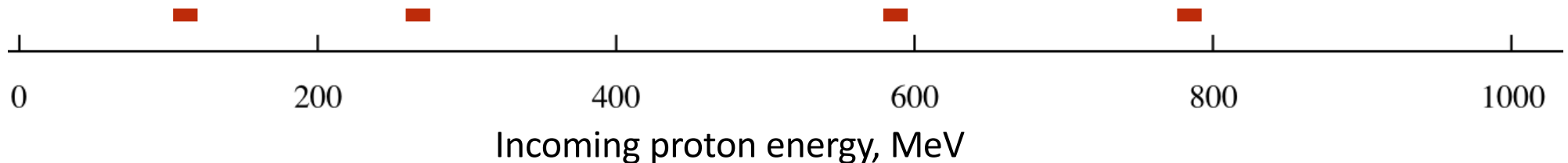
TOF
technique

Target:
Be, B, C, N, Al, Fe, Pb, U

Inclusive cross
sections

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)

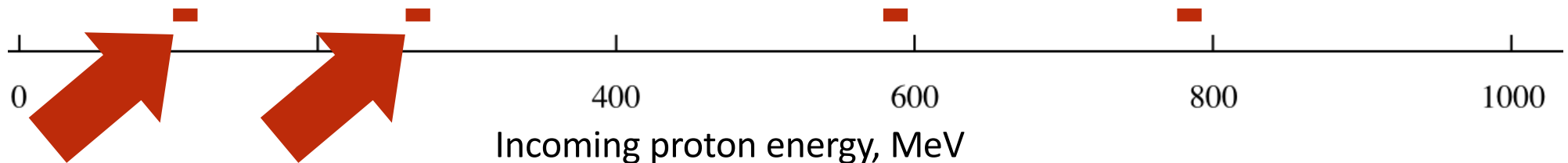
TOF
technique

Target:
Be, B, C, N, Al, Fe, Pb, U

Inclusive cross
sections

Energy:
113, 256, 597, 800 MeV

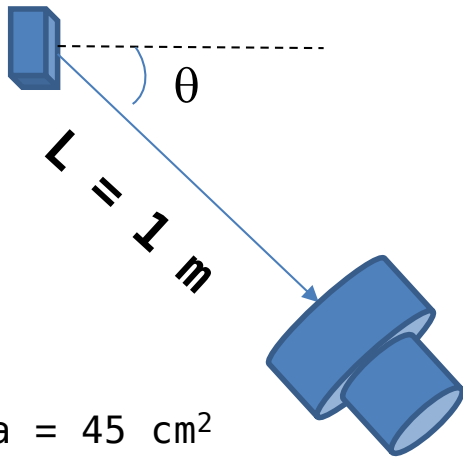
Angle:
7.5°, 30°, 60°, 150° LE & 30°, 60°, 120°, 150° HE



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 - 12 (1993)

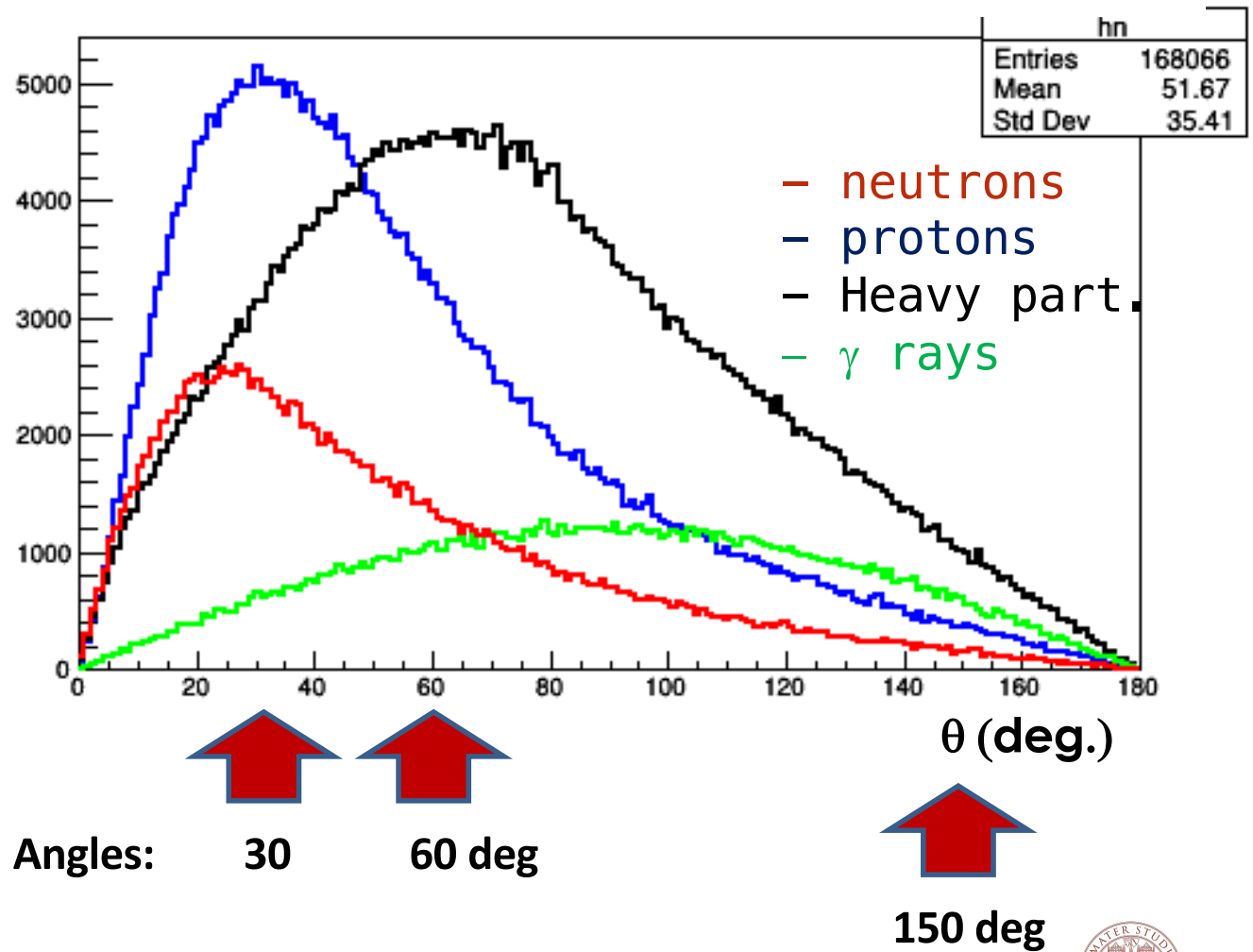
MC simulations – particles from target (5-mm thick)

$^1\text{H} + \text{C}_2\text{H}_4$ @200MeV/u (newgeom) statistics: 5×10^7 primaries



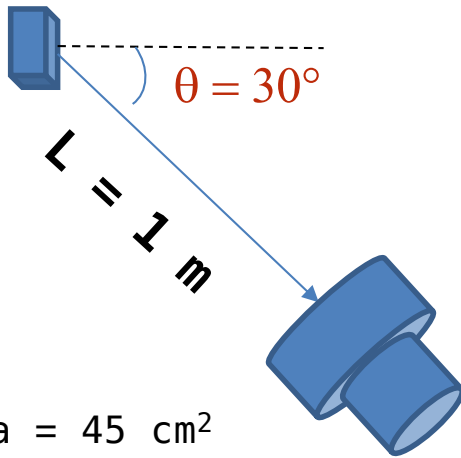
Area = 45 cm²
 $\Delta\theta \sim 2$ deg.

E_n	TOF
1 MeV	72 ns
10 MeV	23 ns
50 MeV	10.6 ns
100 MeV	7.8 ns
200 MeV	5.9 ns



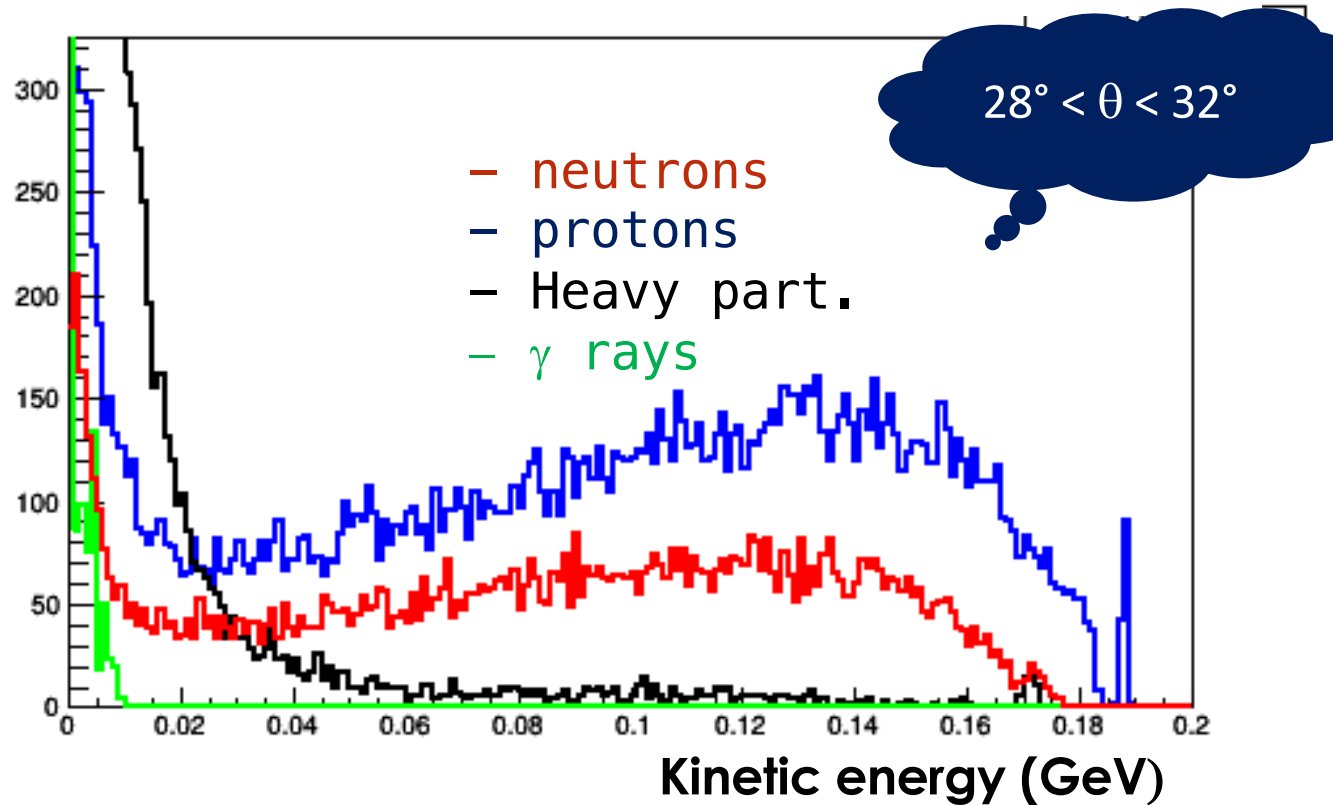
MC simulations – particles from target (5-mm thick)

$^1\text{H} + \text{C}_2\text{H}_4$ @200MeV/u (newgeom) statistics: 5×10^7 primaries



Area = 45 cm²
 $\Delta\theta \sim 2$ deg.
 Geometric eff. $\sim 1\%$
 of the ring

E_n	TOF
1 MeV	72 ns
10 MeV	23 ns
50 MeV	10.6 ns
100 MeV	7.8 ns
200 MeV	5.9 ns



~ 10000 neutrons

Geometric efficiency $\sim 1\%$

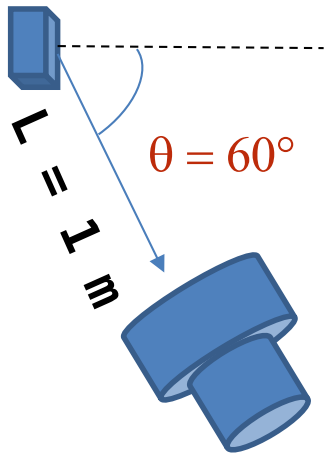
Detection efficiency $\sim 10\%$

$\rightarrow 10$ events in the detector for 5×10^7 primaries

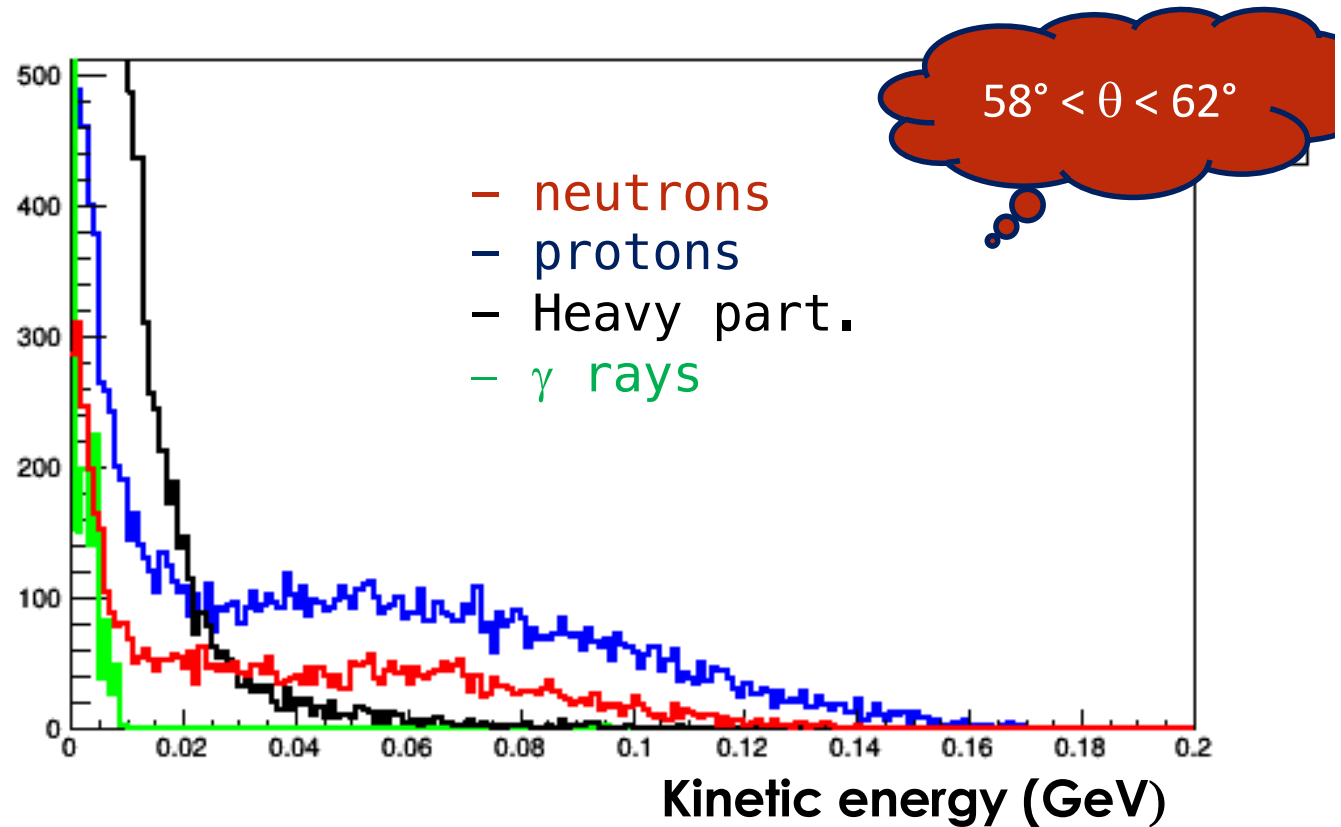


MC simulations – particles from target (5-mm thick)

$^1\text{H} + \text{C}_2\text{H}_4$ @200MeV/u (newgeom) statistics: 5×10^7 primaries



E_n	TOF
1 MeV	72 ns
10 MeV	23 ns
50 MeV	10.6 ns
100 MeV	7.8 ns
200 MeV	5.9 ns



~ 550 neutrons

Geometric efficiency ~ 1%

Detection efficiency ~ 10 %

→ < 1 events in the detector for 5×10^7 primaries

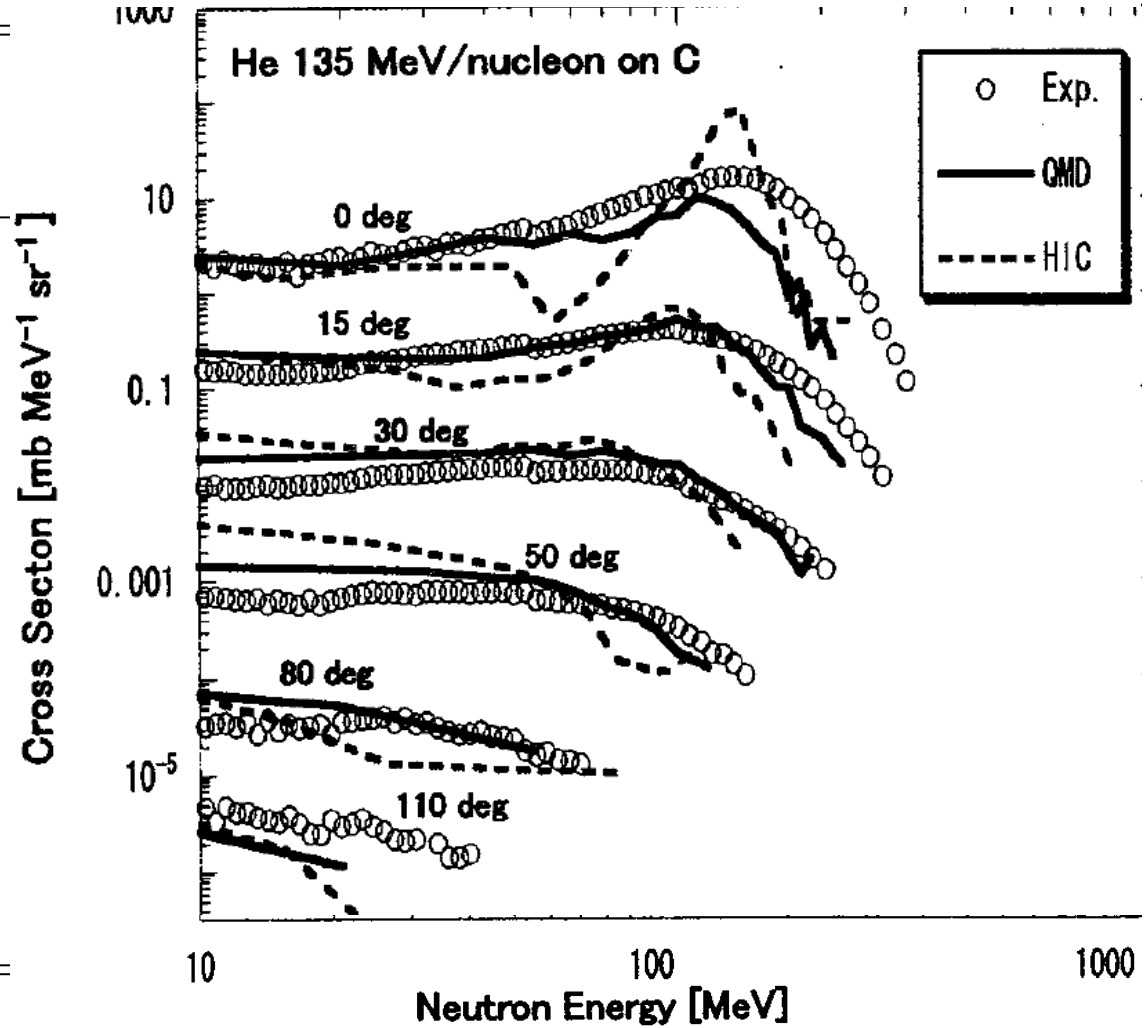


Thin target, heavy-ion induced reactions

@ 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)

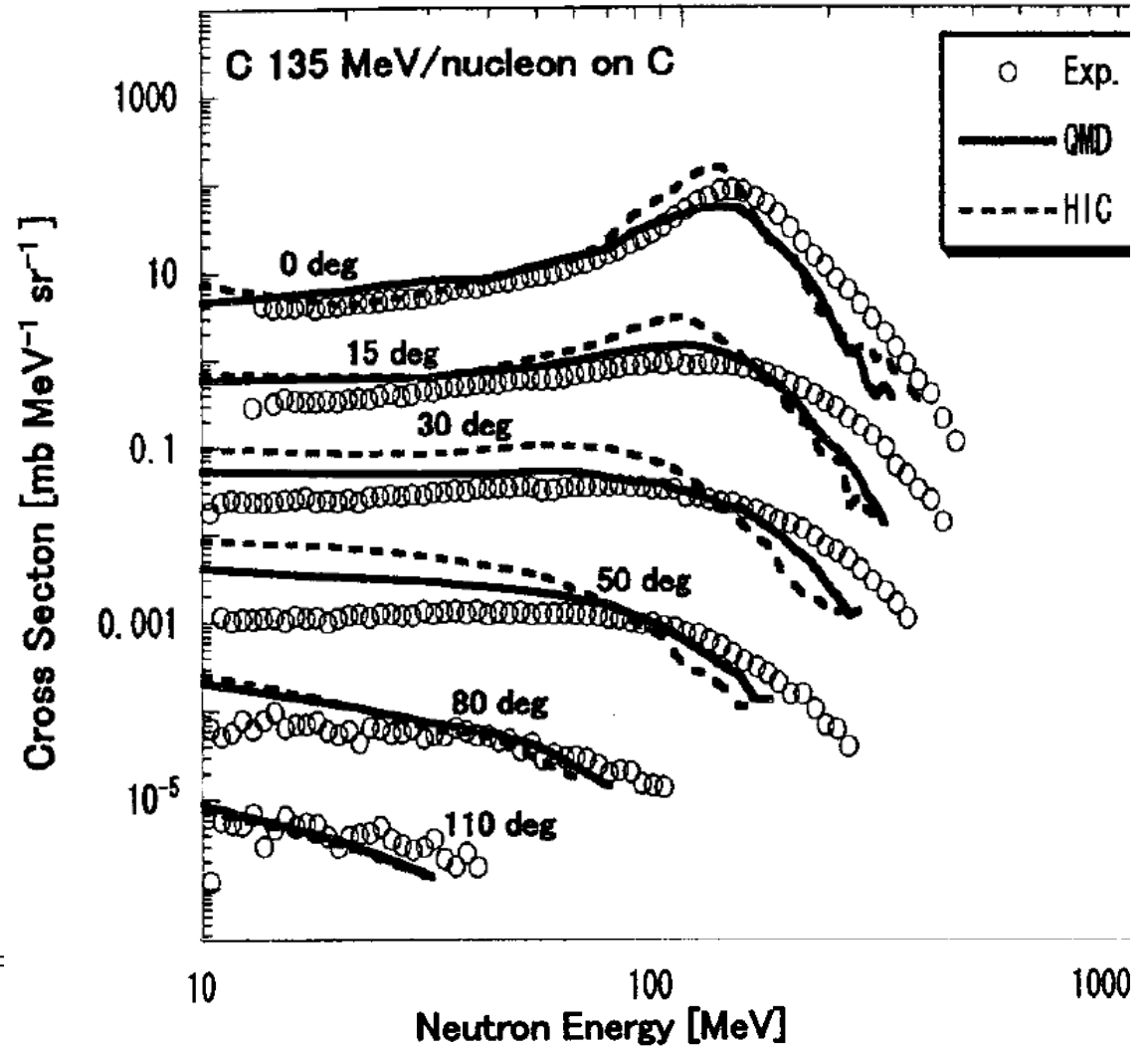


Thin target, heavy-ion induced reactions

@ 135 MeV/u

Example: inclusive cross section

Target and thickness (mm)	Projectile type and energy (MeV/nucleon)
C (1.0)	He (135)
	<u>C (135)</u>
	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)



Thin target, heavy-ion induced reactions

@ 135 MeV/u

Angular distribution

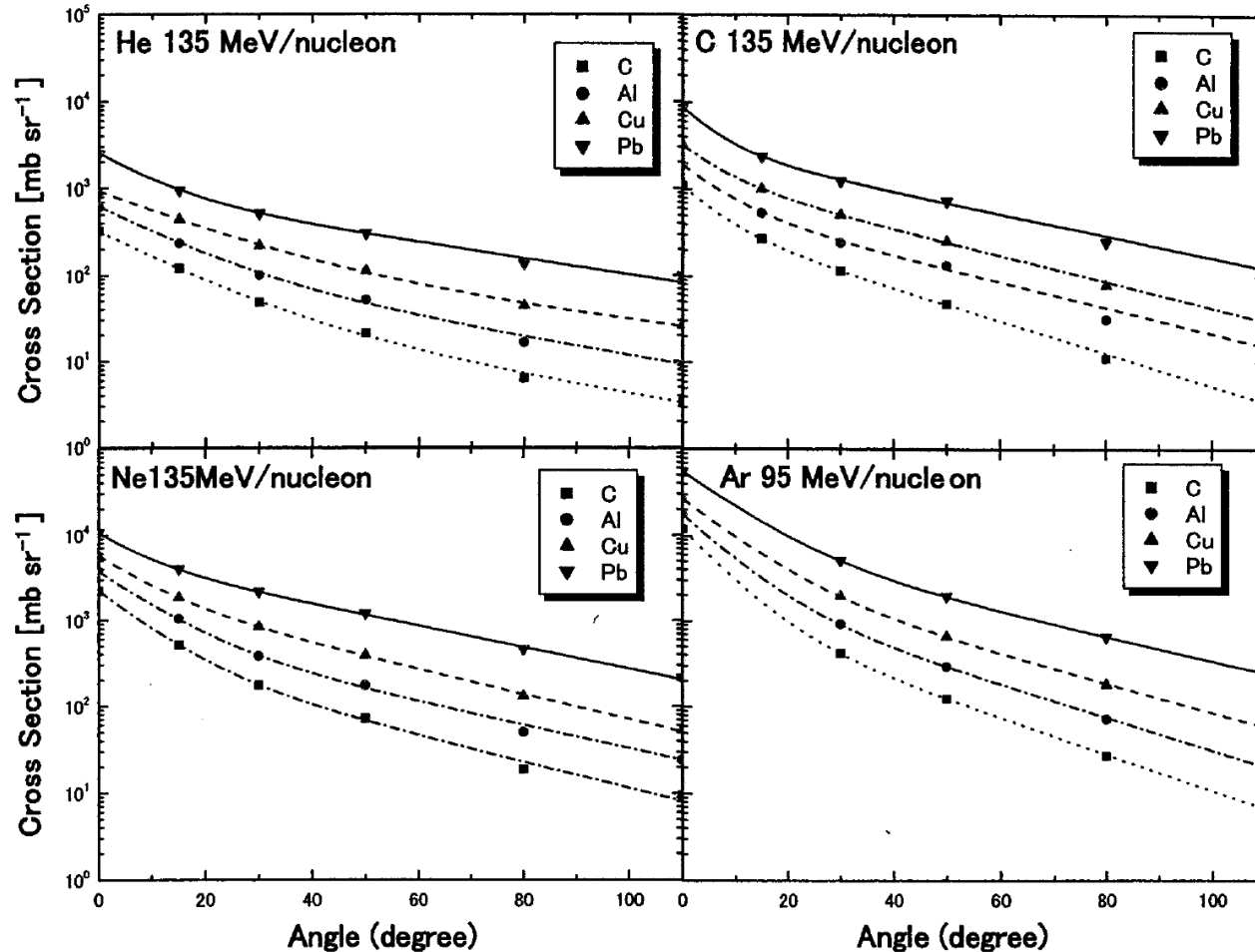


FIG. 8. Angular distributions of neutron production cross sections integrated above 20 MeV.

Thin target, heavy-ion induced reactions

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

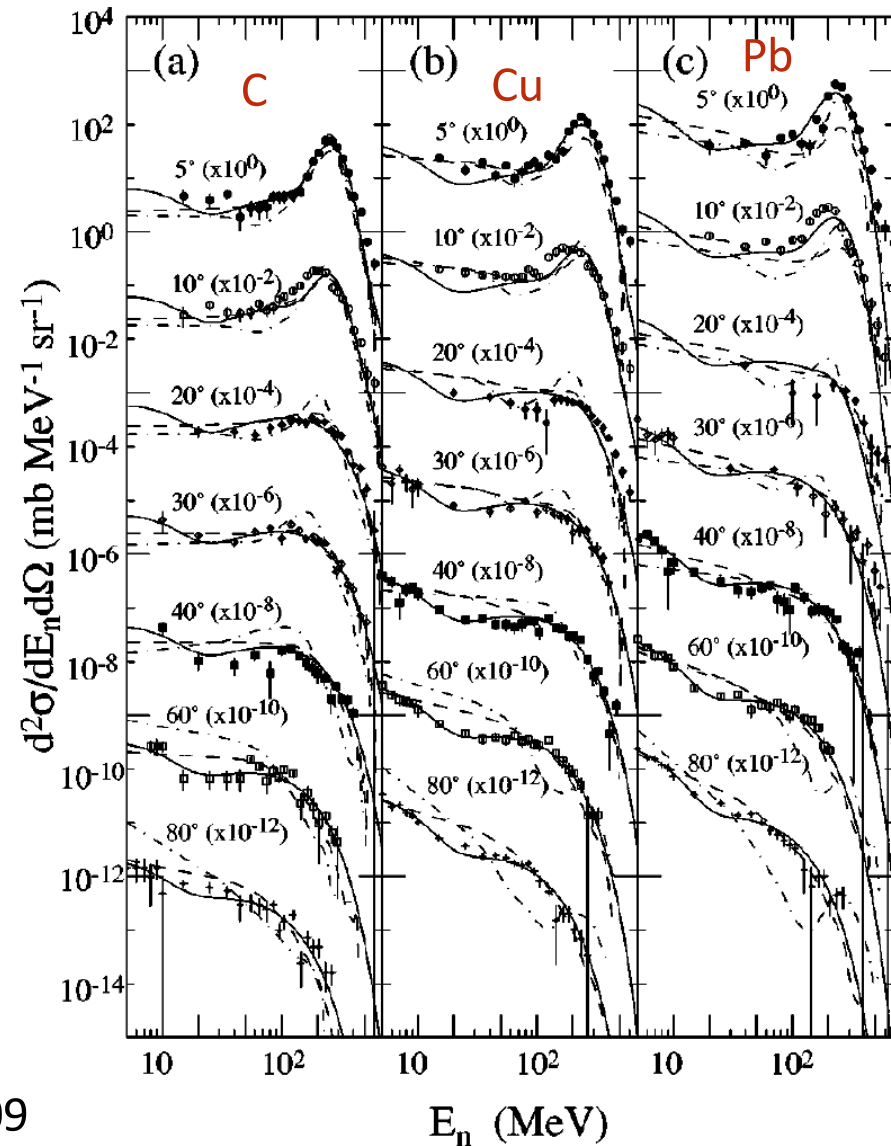
Example: inclusive cross section

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



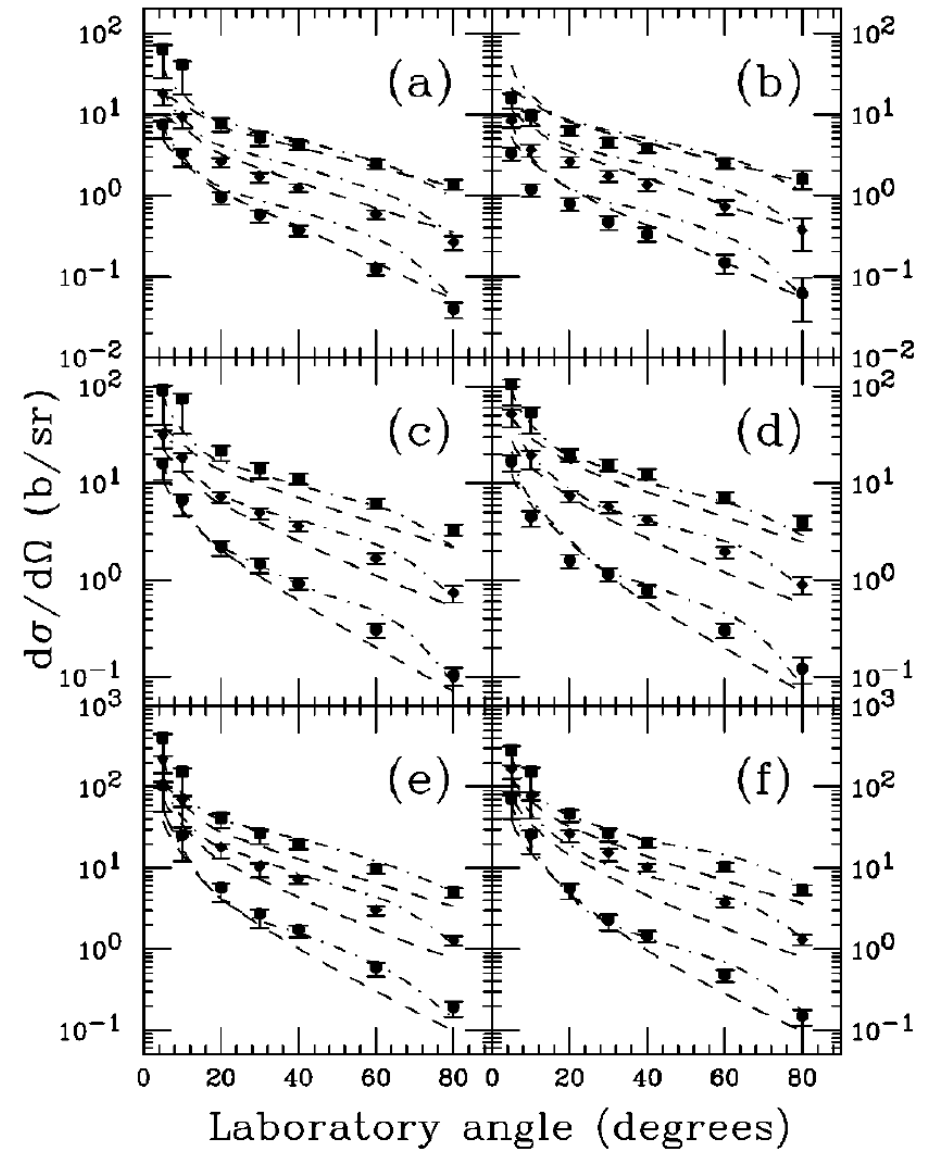
Thin target, heavy-ion induced reactions

@ 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



Angular distribution

Thin target, heavy-ion induced reactions

Example: **inclusive cross section**

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

Differential 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)

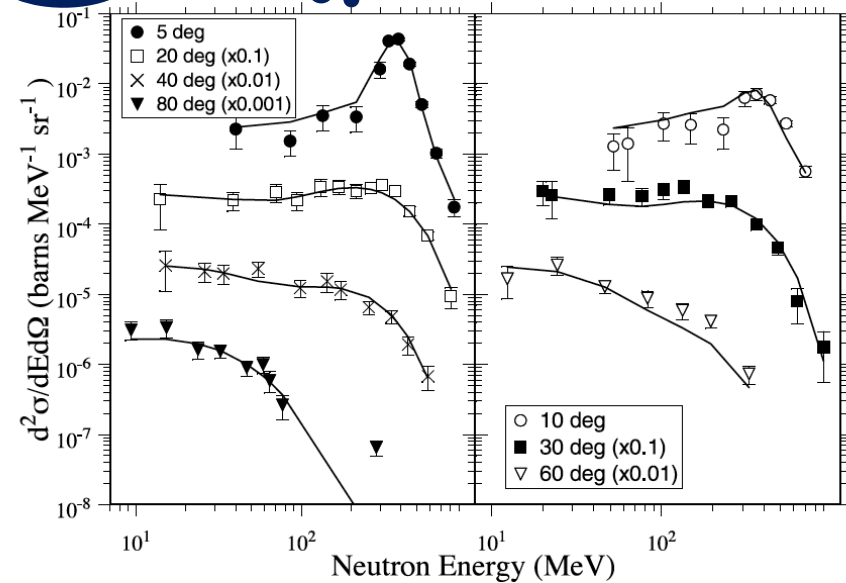


Fig. 5. Double-differential spectra from 400 MeV/nucleon N interacting in a C target. The spectra at each laboratory angle are offset by the indicated factors of 10. The lines come from a moving-source fit described in the text.

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)	E _{min} (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)

Thin target, heavy-ion induced reactions



Inclusive cross sections

Target:

Li, C, Al, Cu, Pb, U and CH₂

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

NUCLEAR SCIENCE AND ENGINEERING **157** (2007) 142

PHYSICAL REVIEW C **64** (2001) 054609

PHYSICAL REVIEW C **64** (2001) 034607

Thin target, heavy-ion induced reactions



Inclusive cross sections

Target:

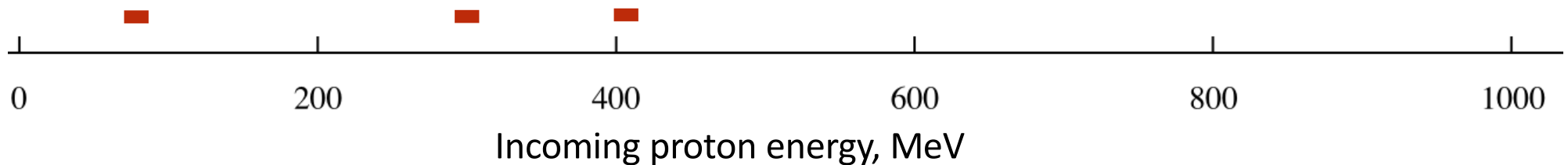
C and CH₂

Beams:

He, C, N

Energy:

135, 290, 400, MeV/u



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

NUCLEAR SCIENCE AND ENGINEERING **157** (2007) 142

PHYSICAL REVIEW C **64** (2001) 054609

PHYSICAL REVIEW C **64** (2001) 034607

Thin target, heavy-ion induced reactions



Inclusive cross sections

Target:

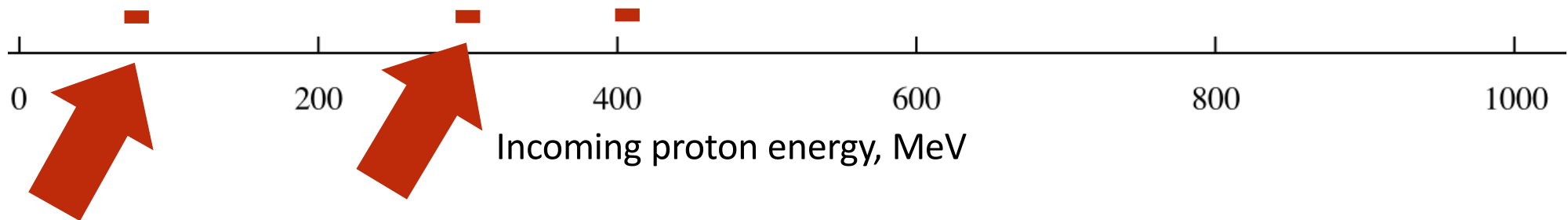
C and CH₂

Beams:

He, C, N

Energy:

135, 290, 400, MeV/u



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

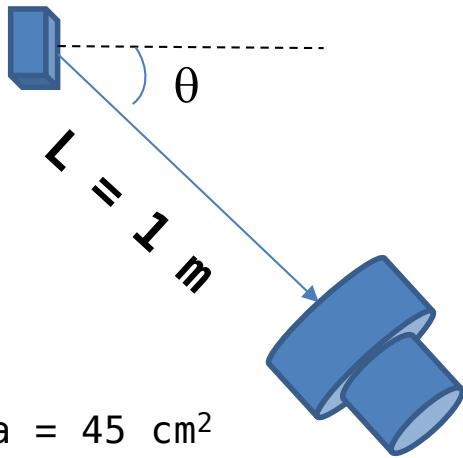
NUCLEAR SCIENCE AND ENGINEERING **157** (2007) 142

PHYSICAL REVIEW C **64** (2001) 054609

PHYSICAL REVIEW C **64** (2001) 034607

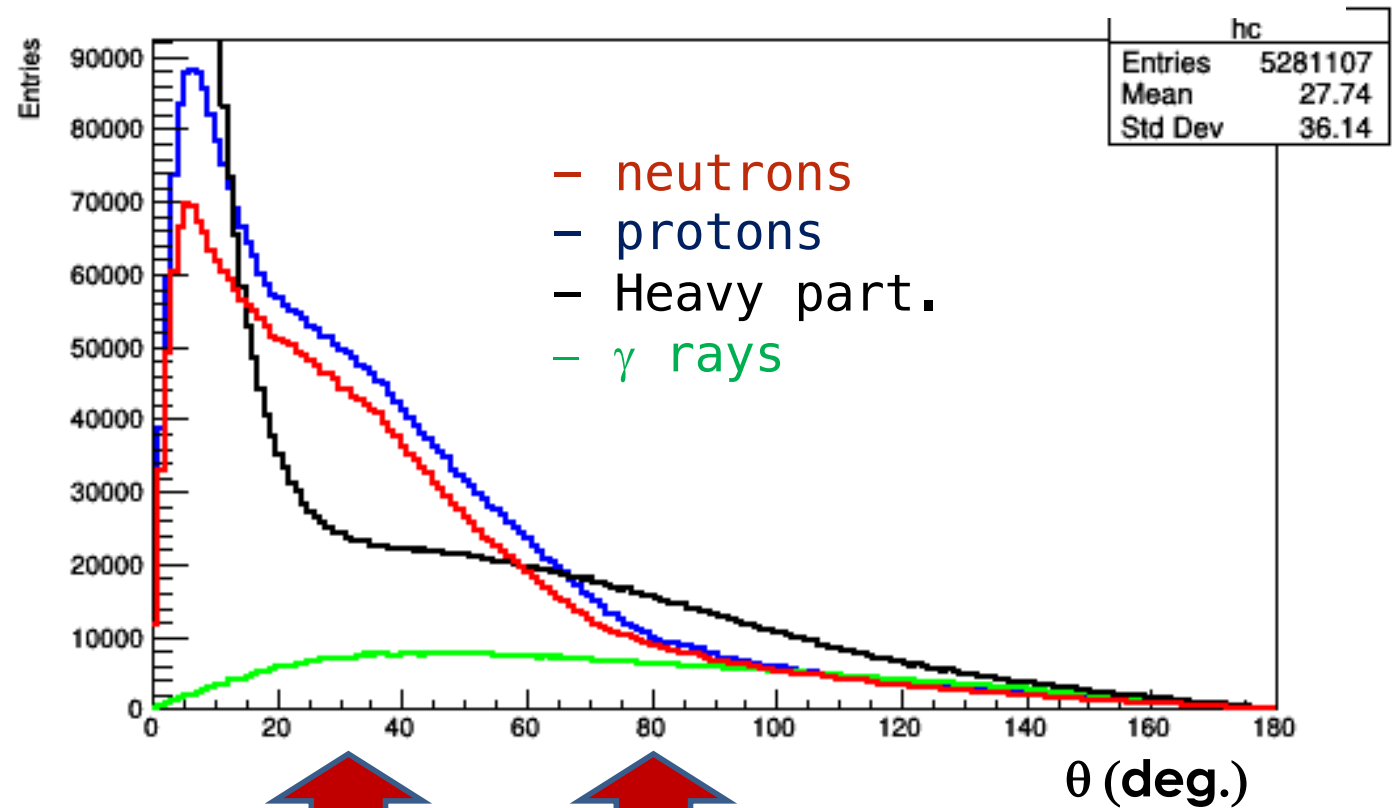
MC simulations – particles from target (5-mm thick)

$^{16}\text{O} + \text{C}_2\text{H}_4$ @200MeV/u (newgeom) statistics: 5×10^7 primaries



Area = 45 cm²
 $\Delta\theta \sim 2$ deg.

E_n	TOF
1 MeV	72 ns
10 MeV	23 ns
50 MeV	10.6 ns
100 MeV	7.8 ns
200 MeV	5.9 ns



Angles:

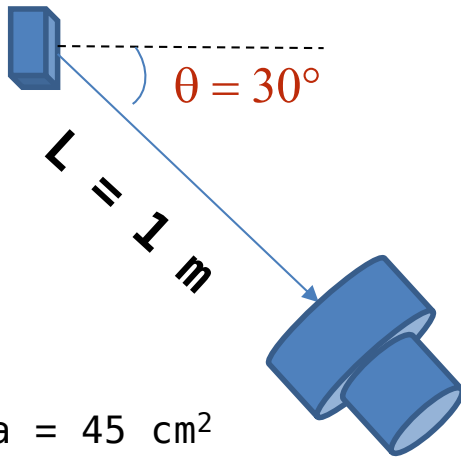
30

80 deg



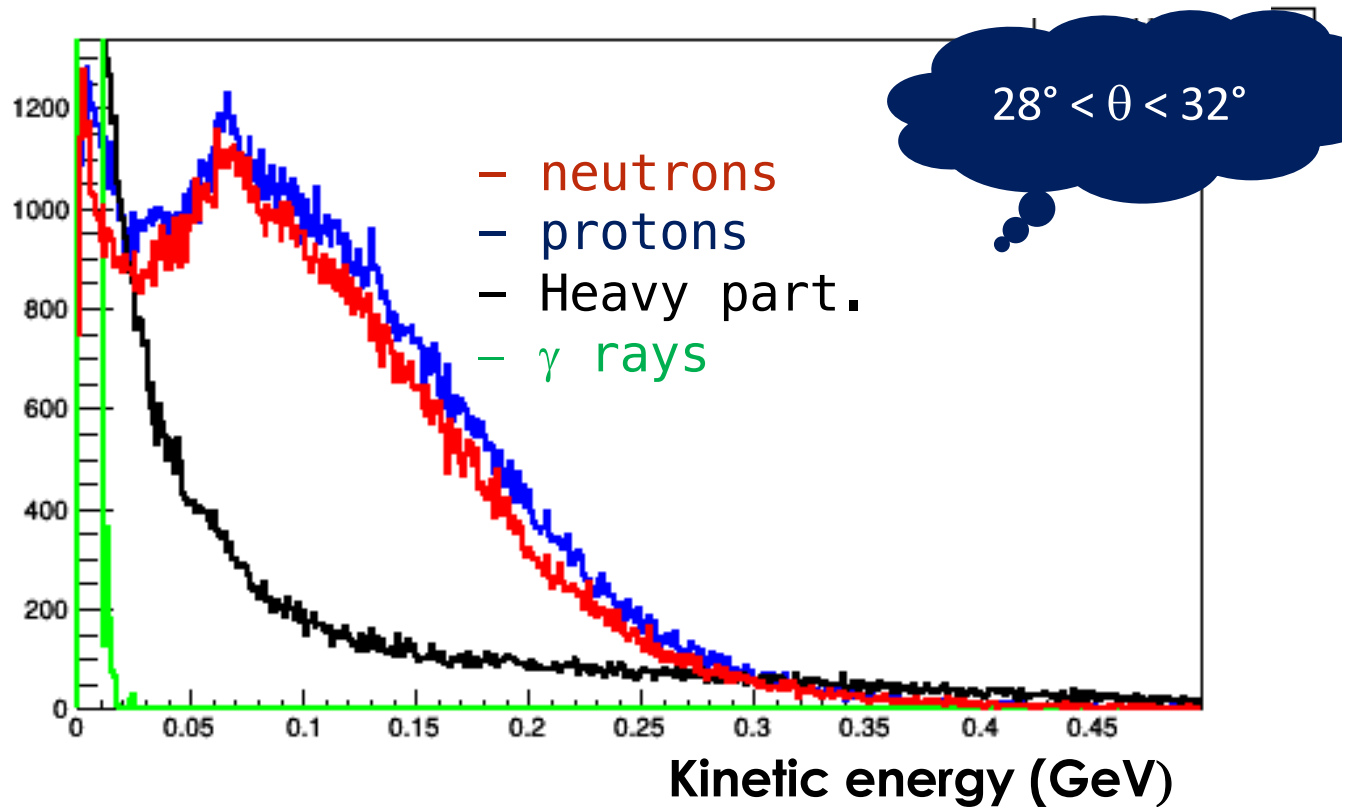
MC simulations – particles from target (5-mm thick)

$^{16}\text{O} + \text{C}_2\text{H}_4$ @200MeV/u (newgeom) statistics: 5×10^7 primaries



Area = 45 cm²
 $\Delta\theta \sim 2$ deg.
 Geometric eff. $\sim 1\%$
 of the ring

E_n	TOF
1 MeV	72 ns
10 MeV	23 ns
50 MeV	10.6 ns
100 MeV	7.8 ns
200 MeV	5.9 ns



~ 181000 neutrons

Geometric efficiency $\sim 1\%$

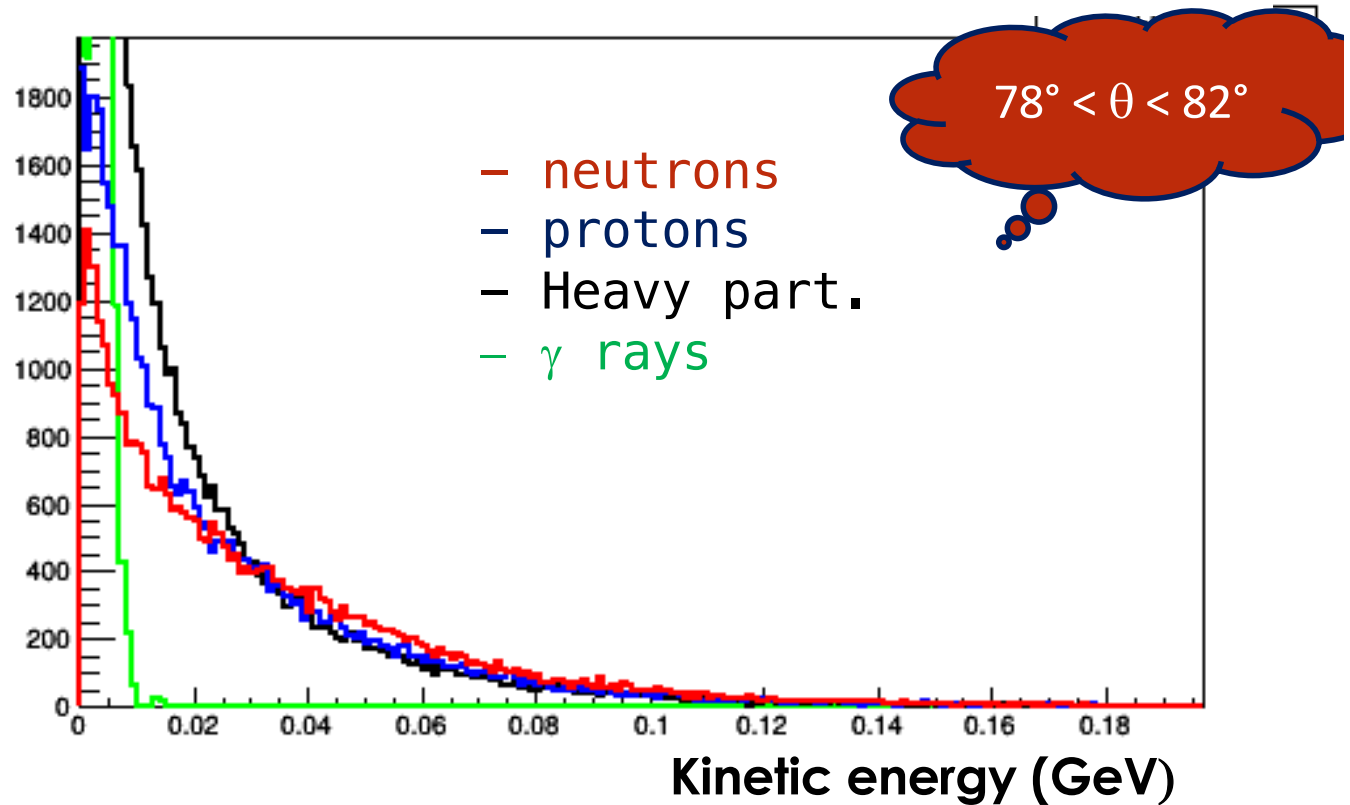
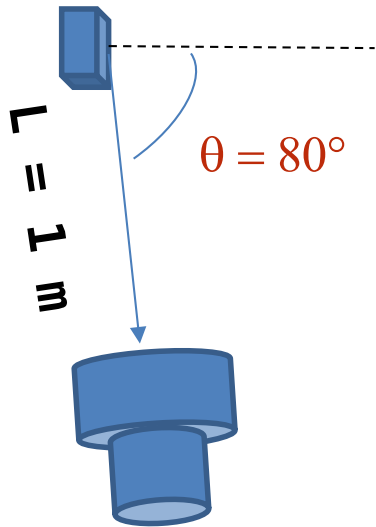
Detection efficiency $\sim 10\%$

$\rightarrow 181$ events in the detector for 5×10^7 primaries



MC simulations – particles from target (5-mm thick)

$^{16}\text{O} + \text{C}_2\text{H}_4$ @200MeV/u (newgeom) statistics: 5×10^7 primaries



E_n	TOF
1 MeV	72 ns
10 MeV	23 ns
50 MeV	10.6 ns
100 MeV	7.8 ns
200 MeV	5.9 ns

~ 36000 neutrons

Geometric efficiency ~ 1%

Detection efficiency ~ 10 %

→ 36 events in the detector for 5×10^7 primaries



Homogeneous THIK target, charged-particle induced reactions

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

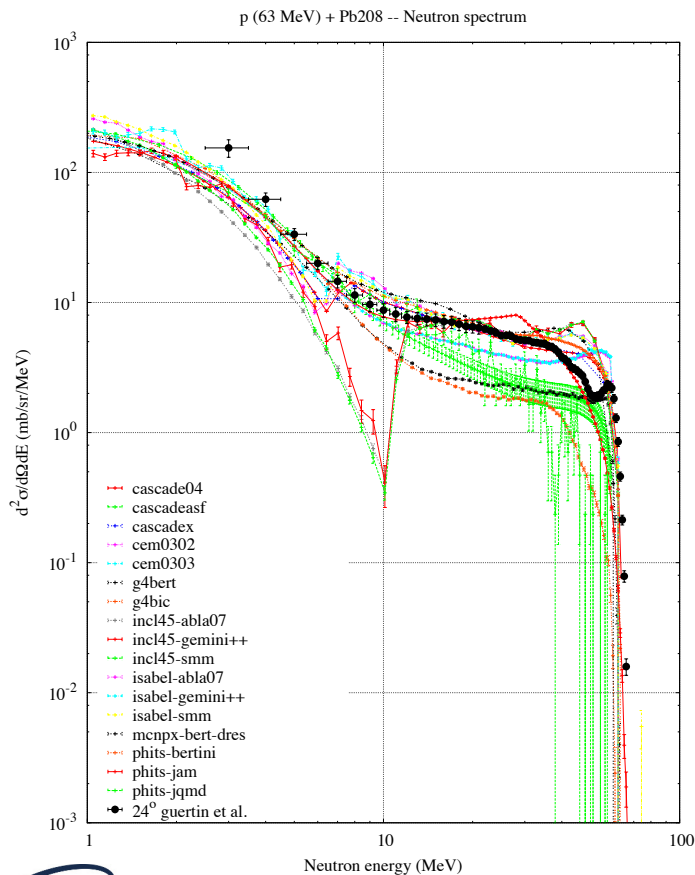
by Nakamura and Heilbronn

Beam ion and energy (MeV/nucleon)	Targets (cm)	Measured spectra	θ (deg)	E_{min} (MeV)	Facility
He (100)	C (5.0) Al (4.0) Cu (1.5) Pb (1.5)	TTY n/d Ω total	0, 7.5, 15, 30, 60, 90	5.5, 5, 4, 3.5, 3.5, 3	HIMAC
He (155)	Al (8.26)	TTY n/d Ω total	10, 30, 45, 60, 90, 125, 160	10, 3, 3, 7, 4, 3, 3	NSCL
He (160)	Pb (3.937)	TTY Total	0, 45, 90, 120, 150	10, 3, 13, 13, 13	SREL
He (177.5)	C (14.73) H ₂ O (22.86) Steel (4.445) Pb (3.937)	TTY 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)	E_{min} (MeV)	Facility
He (180)	C (16.0) Al (12.0) Cu (4.5) Pb (5.0)	TTY n/d Ω total	0, 7.5, 15, 30, 60, 90	17, 11, 5.5, 6.5, 3.5, 3.5	HIMAC
C (100)	C (2.0) Al (1.0) Cu (0.5) Pb (0.5)	TTY n/d Ω total	0, 7.5, 15, 30, 60, 90	4, 4, 3.5, 3.5, 3, 3	HIMAC
C (155)	Al (8.26)	TTY n/d Ω total	10, 30, 45, 60, 90, 125, 160	10, 3, 3, 7, 4, 3, 3	NSCL
C (180)	C (6.0) Al (4.0) Cu (1.5) Pb (1.5)	TTY n/d Ω 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) Al (15.0) Cu (5.0) Pb (5.0)	TTY n/d Ω total	0, 7.5, 15, 30, 60, 90	8.5, 5, 3.5, 3, 3, 3	HIMAC
Ne (100)	C (1.0) Al (1.0) Cu (0.5) Pb (0.5)	TTY n/d Ω total	0, 7.5, 15, 30, 60, 90	6, 6, 5, 5.5, 5.5, 5	HIMAC
Ne (180)	C (4.0) Al (3.0) Cu (1.0) Pb (1.0)	TTY n/d Ω total	0, 7.5, 15, 30, 60, 90	9, 6, 3.5, 3.5, 3, 3	HIMAC
Ne (400)	C (11.0) Al (9.0) Cu (3.0) Pb (3.0)	TTY n/d Ω total	0, 7.5, 15, 30, 60, 90	6, 5.5, 4, 3, 3, 3	HIMAC
Si (800)	C (23.0) Cu (6.5)	TTY n/d Ω total	0, 7.5, 15, 30, 60, 90	11, 8, 8, 4, 3.5, 3.5	HIMAC
Ar (400)	C (7.0) Al (5.5) Cu (2.0) Pb (2.0)	TTY n/d Ω 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/>



IAEA Benchmark of Spallation Models

International Atomic Energy Agency
Nuclear Data Services

Contents: Main, Specifications, Experimental data, Models, Calculation results, Tools, Registration, Memo

Meetings: WS 2010 (Saclay), CM 2009 (Vienna), SM 2009 (Vienna), WS 2008 (Trieste)

Reports: Trieste 2008, ND2010, SNA+MC 2010

Contacts: J.-C. David (CEA), D. Filges (FZJ), S. Leray (CEA), G. Menk (FZJ), N. Otsuka (IAEA), Y. Yariv (Sores)

Links: Geant4, PHITS, Nuclear Data Services, Nuclear Data Section

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 could 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.

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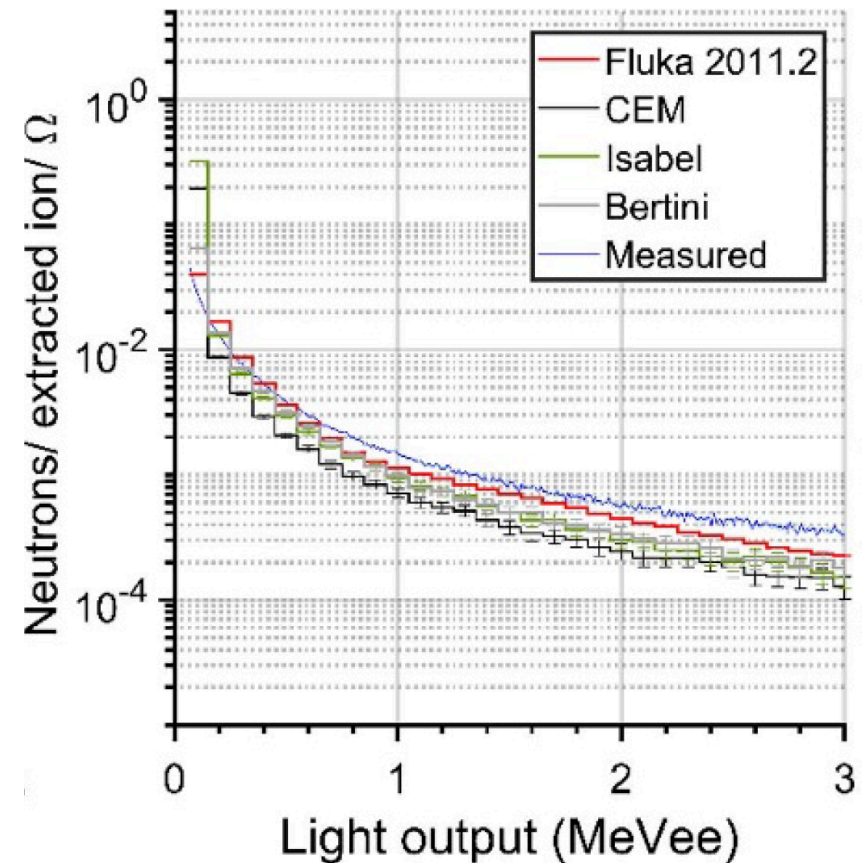
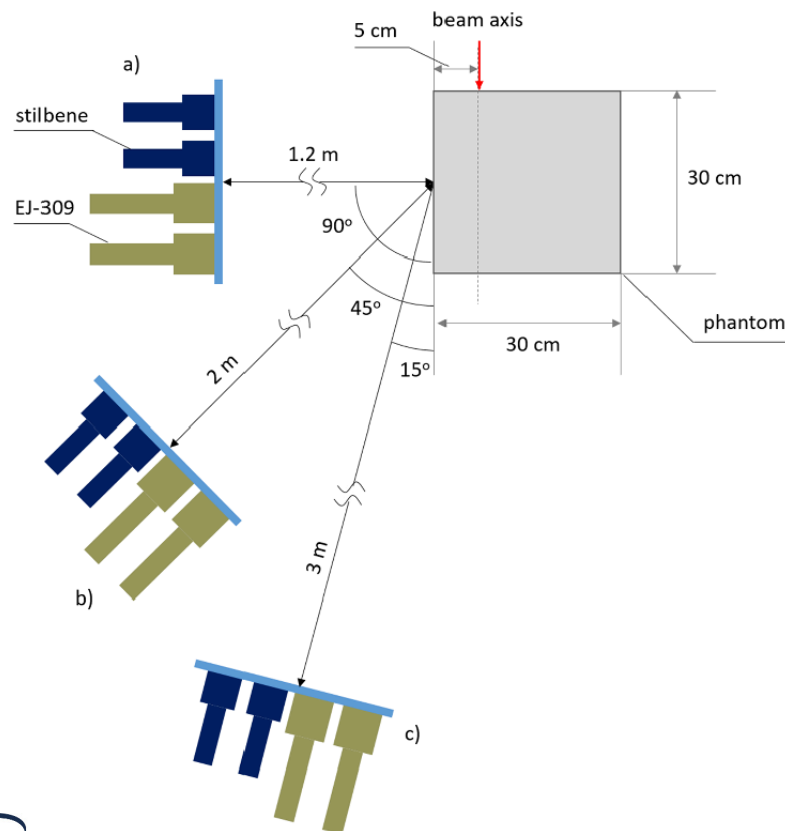
Double differential cross section (neutron)

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

THICK target: non homogenous target (clinical phantom)

	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

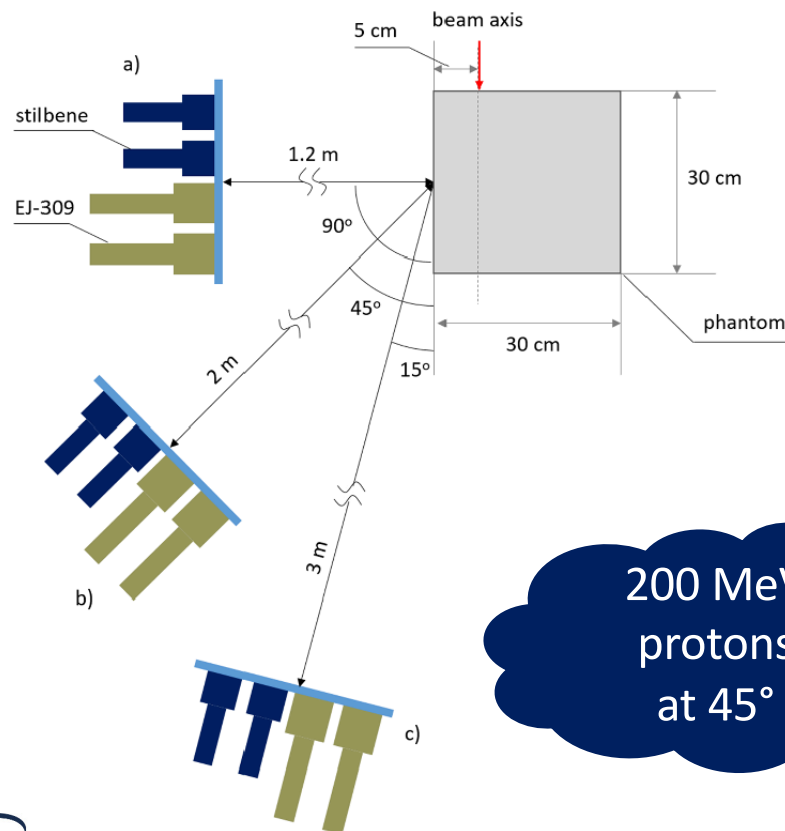
BW3 phantom: 30 cm x 30 cm x 15 cm (thick enough to stop the proton and carbon-ion beams)



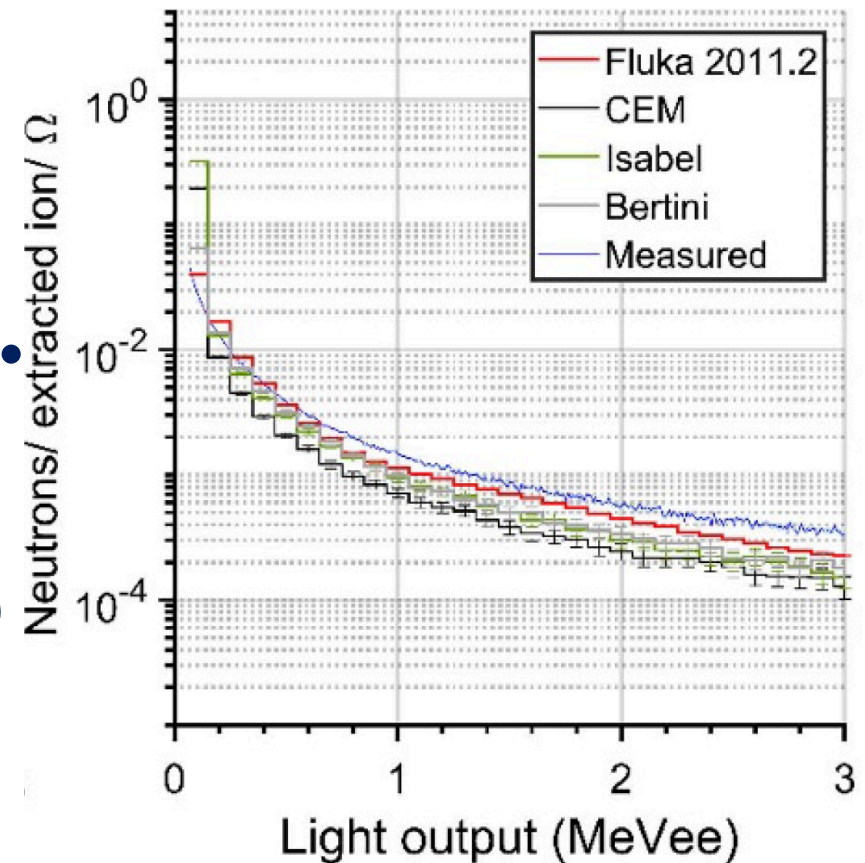
THICK target: non homogenous target (clinical phantom)

	FWHM x (mm)	FWHM y (mm)
Protons, 155 MeV u ⁻¹	9.46	9.69
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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)



200 MeV protons at 45°



THICK target: non homogenous target (clinical phantom)

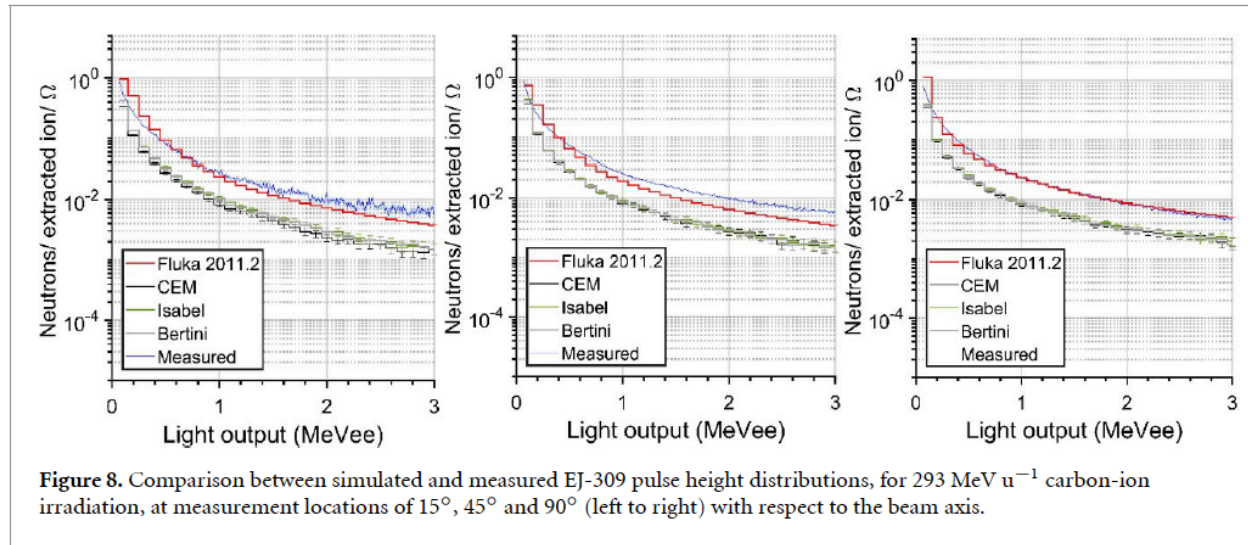


Figure 8. Comparison between simulated and measured EJ-309 pulse height distributions, for 293 MeV u⁻¹ carbon-ion irradiation, at measurement locations of 15°, 45° and 90° (left to right) with respect to the beam axis.

293 MeV/u
&
388 MeV/u
Carbon

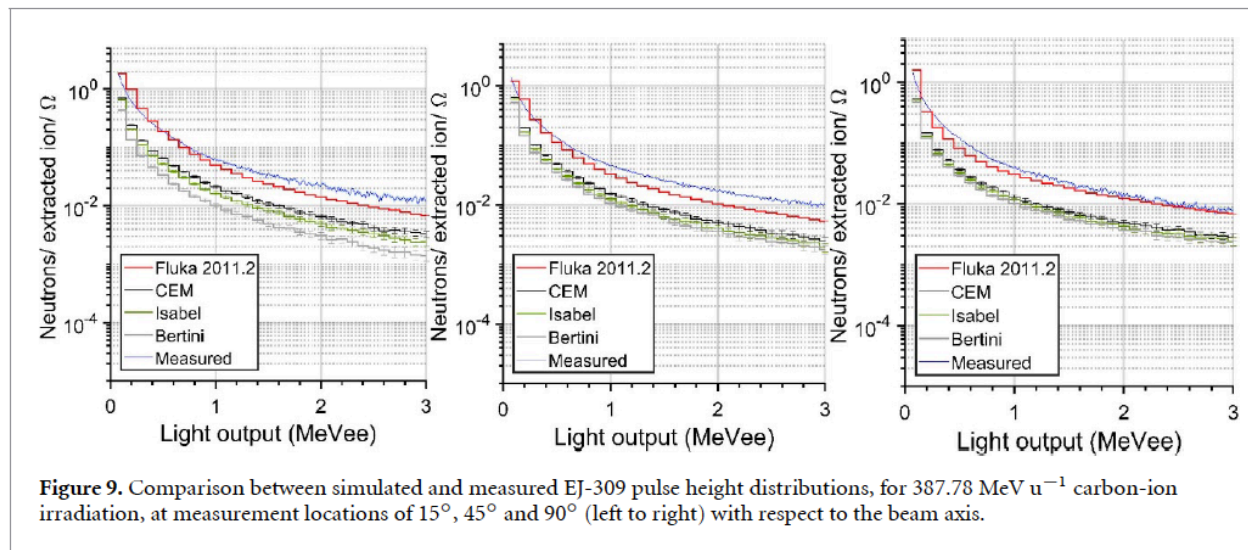


Figure 9. Comparison between simulated and measured EJ-309 pulse height distributions, for 387.78 MeV u⁻¹ carbon-ion irradiation, at measurement locations of 15°, 45° and 90° (left to right) with respect to the beam axis.

Conclusions

- Large number of **experimental data** sets but **often not** made **available** on nuclear reaction databases.
- A few **exclusive cross section** measurements on $p + {}^{12}\text{C}$ and $+ {}^{16}\text{O}$, respectively. **Very challenging experiments** and most valuable data(?)
- Inclusive differential cross sections on **thin targets** for $p + {}^{12}\text{C}$ and ${}^{16}\text{O}$ available at several angles and energies.
- **No neutron data** for the ${}^{12}\text{C} + {}^{16}\text{O}$ reaction. Few neutron data for ${}^{12}\text{C} + {}^{12}\text{C}$.
- Experiments on thick targets, show the **need for more accurate neutron data**.

Worth investigating feasibility @ FOOT ?

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

Similar experiments could be performed @ FOOT?

Conclusions

During the next test beam at CNAO It could be possible to **repeat** some **measurements** present **in the literature** about neutron production in $p+^{12}\text{C}$ and $^{12}\text{C}+^{12}\text{C}$ reactions:

- $p + ^{12}\text{C}$ @ 30 and 60 (150?) deg. with **energy** of **113** and **256 MeV**
- $^{12}\text{C} + ^{12}\text{C}$ @ 30 and 80 deg. with **energy** of **135** and **290 MeV/u**

These tests will provide the information about the feasibility of detecting neutrons with the present setup and with other detectors.

Dedicated simulations are required to be able to better prepare the test and estimate the required beam time.

Dedicated beam time (approximately ... h) is necessary to perform the test. Count rate might be an issue!



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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/>

