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

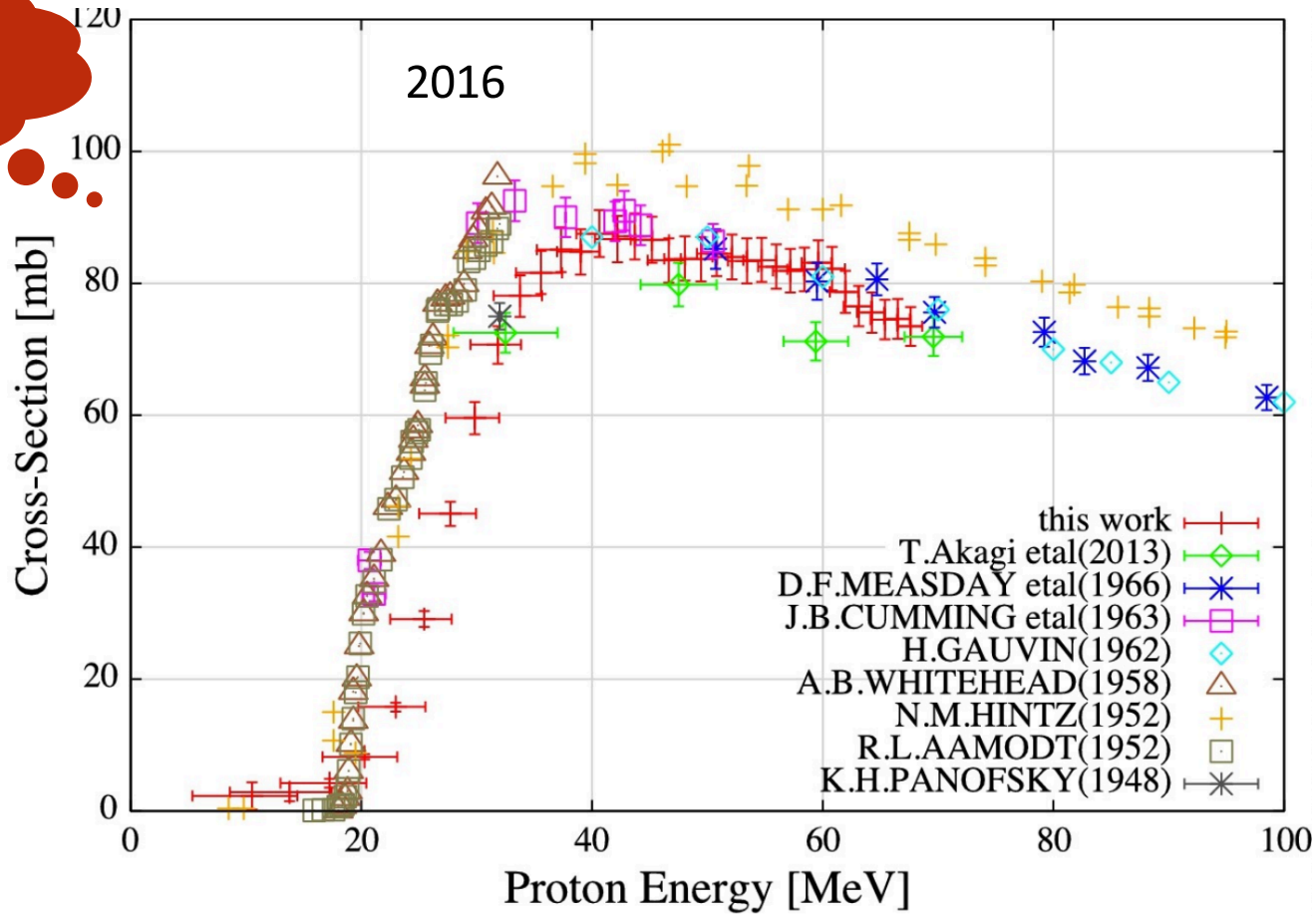
- **Neutron** production in **THIN** targets: cross sections, angular distribution, … as **input to MC**
  - Proton-induced reactions: inclusive Vs exclusive cross section
  - Light-ion induced reactions

- **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

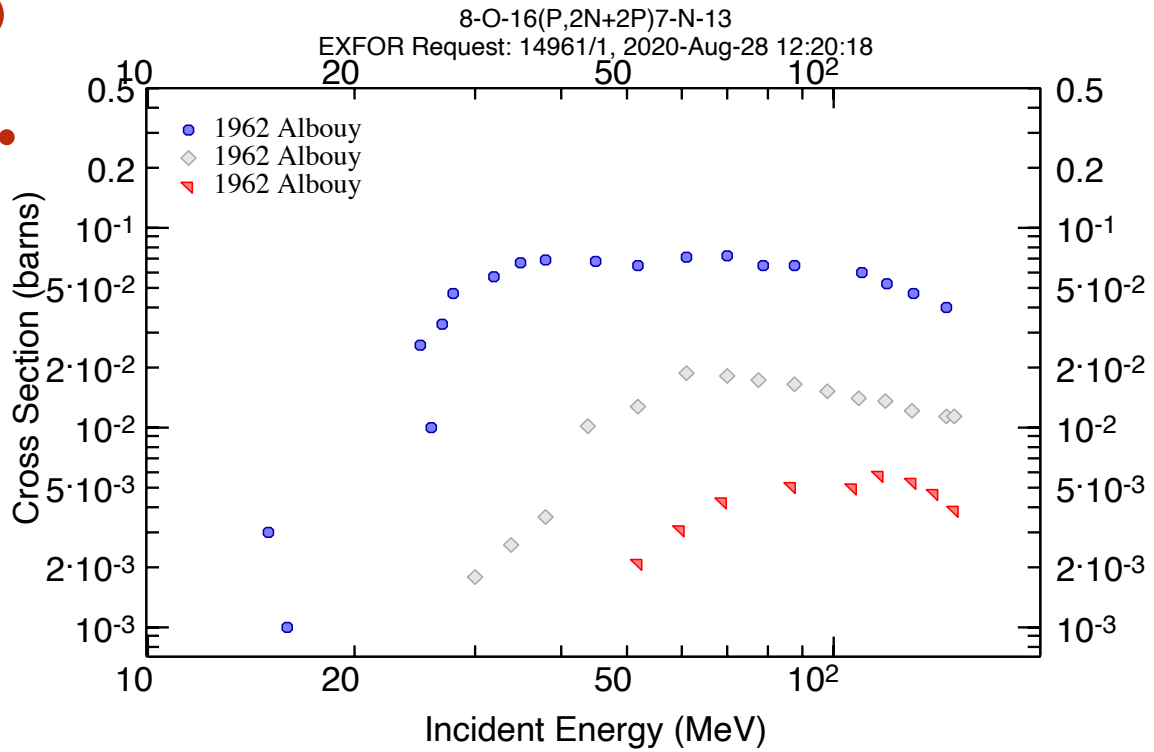
INFN Istituto Nazionale di Fisica Nucleare

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

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



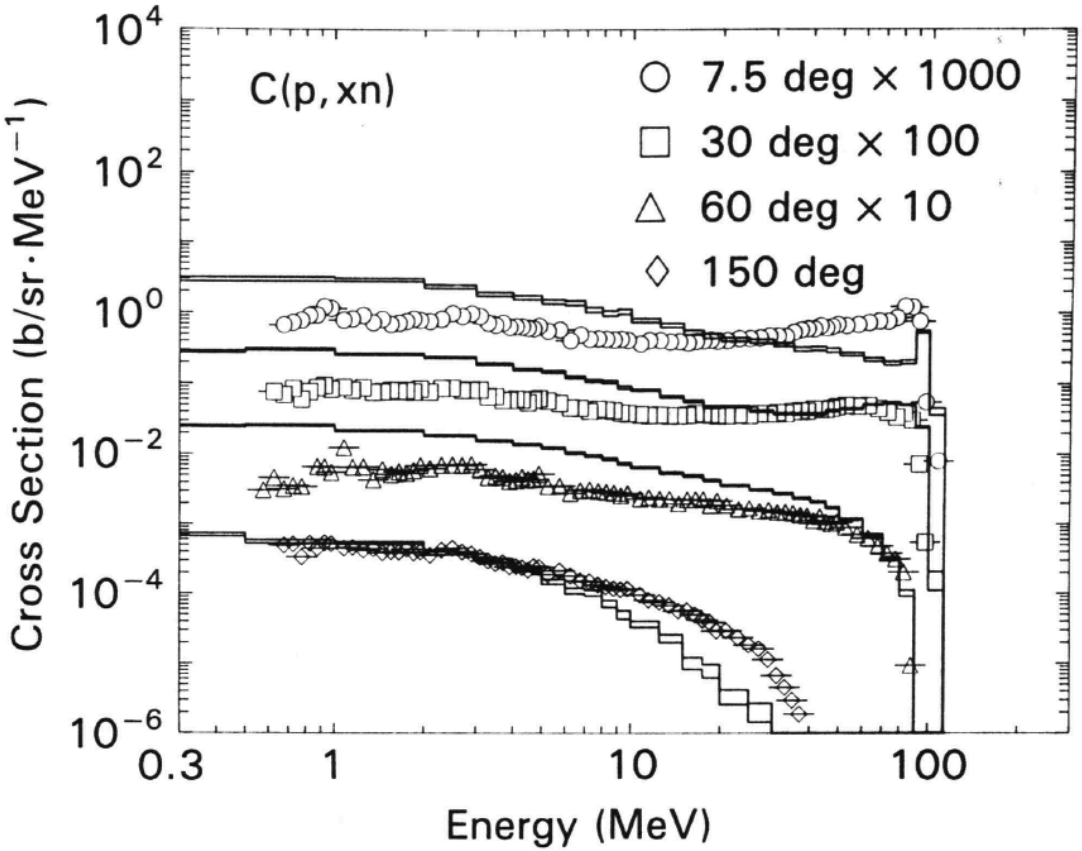
Data retrieved from the EXFOR database

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



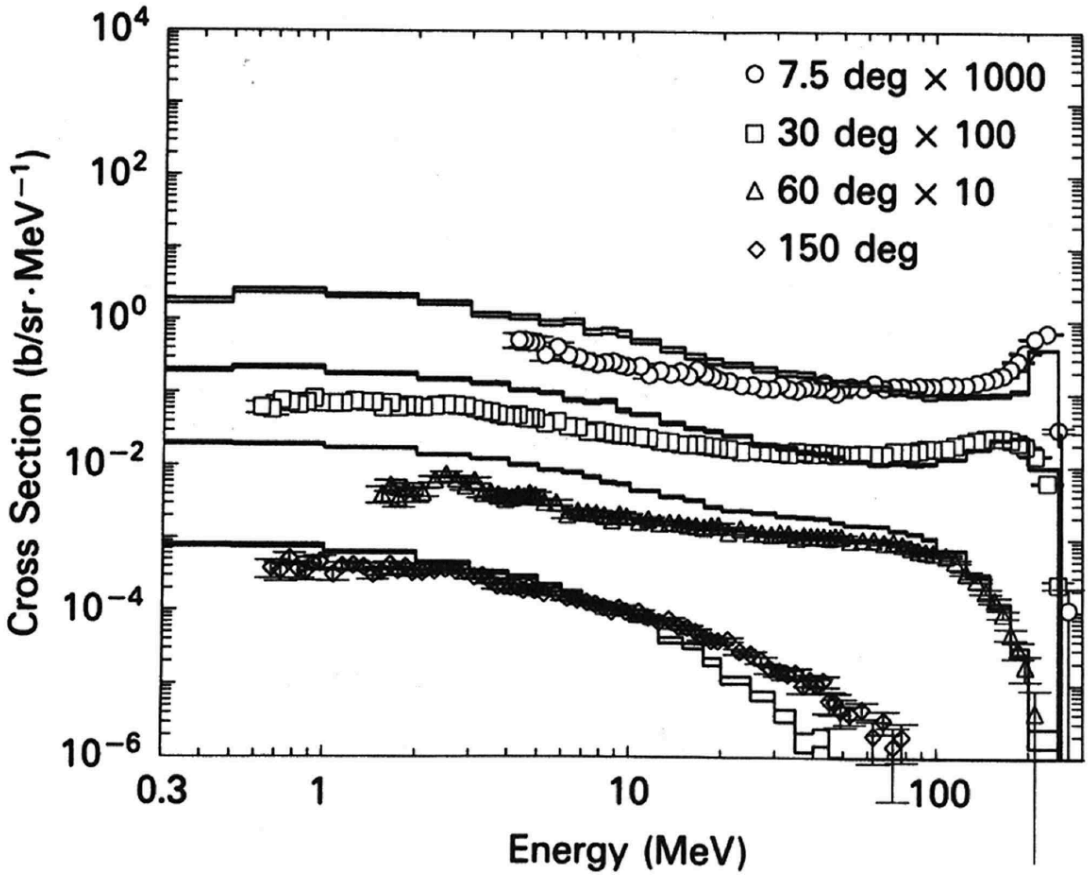
NUCLEAR SCIENCE AND ENGINEERING: 102, 310-321 (1989)

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



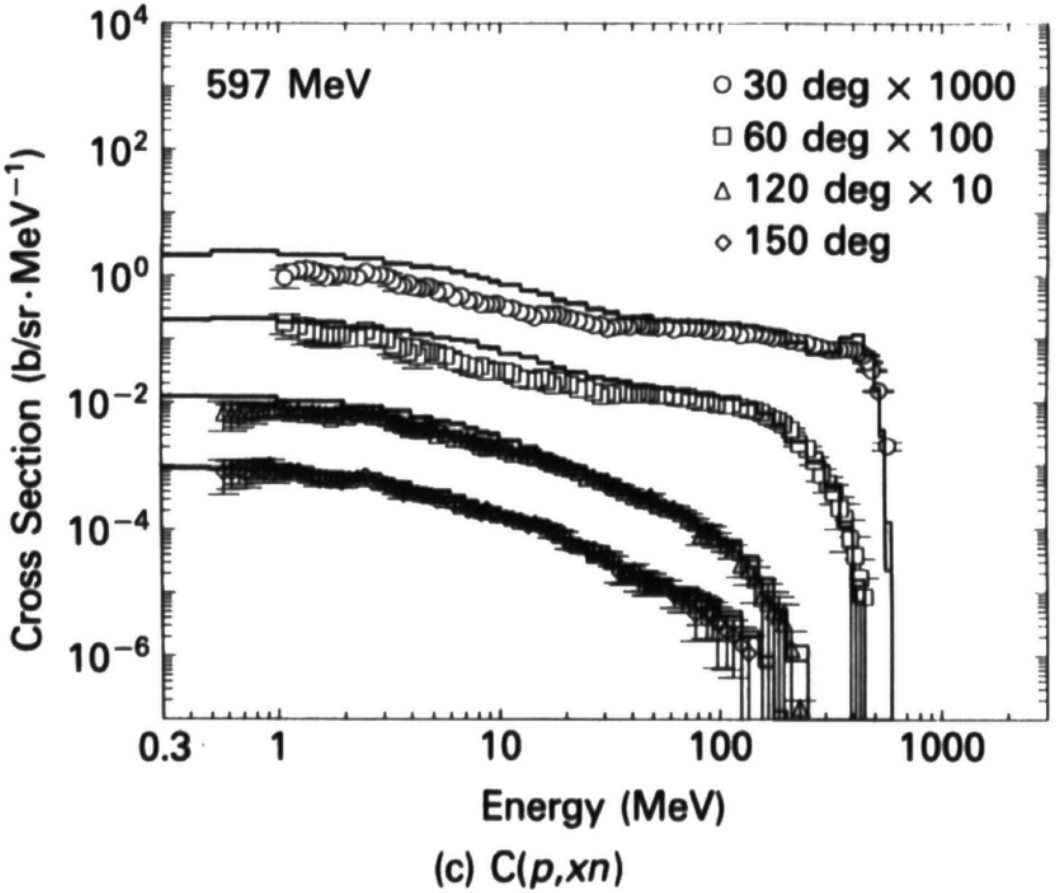
NUCLEAR SCIENCE AND ENGINEERING: 110, 289-298 (1992)

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



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

INFN Istituto Nazionale di Fisica Nucleare

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

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

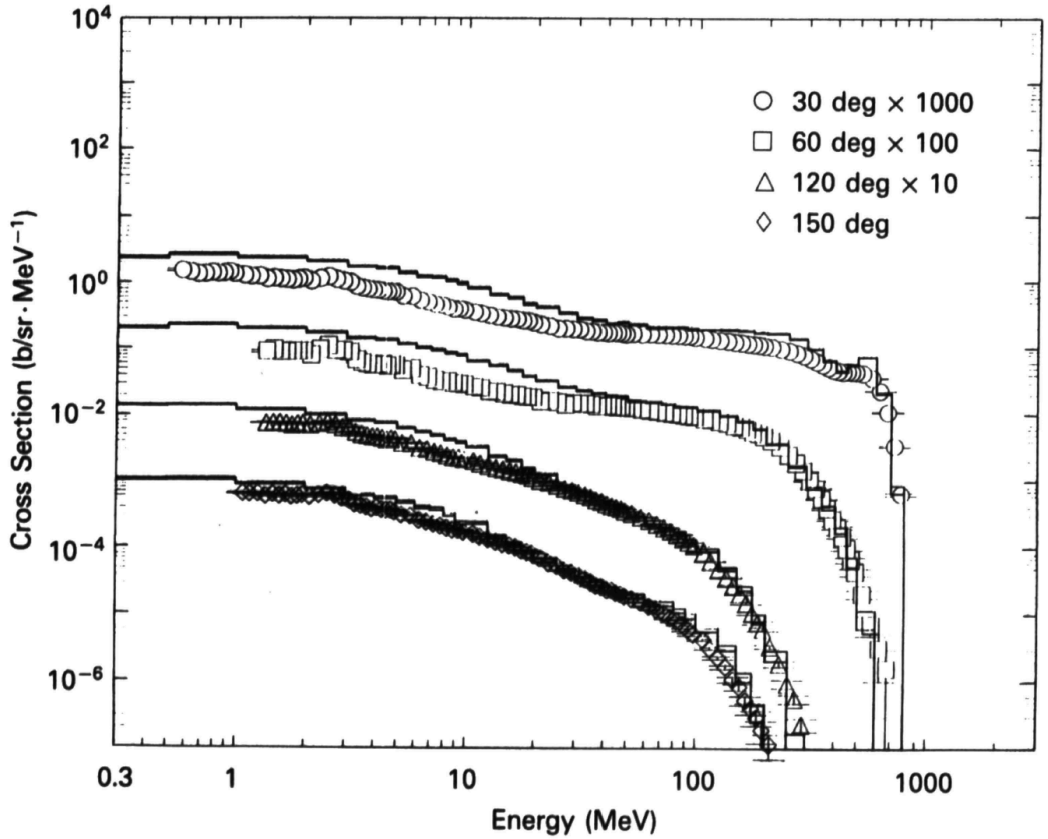


Fig. 3. Experimental differential cross sections for carbon compared with HETC calculations.

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

INFN Istituto Nazionale di Fisica Nucleare

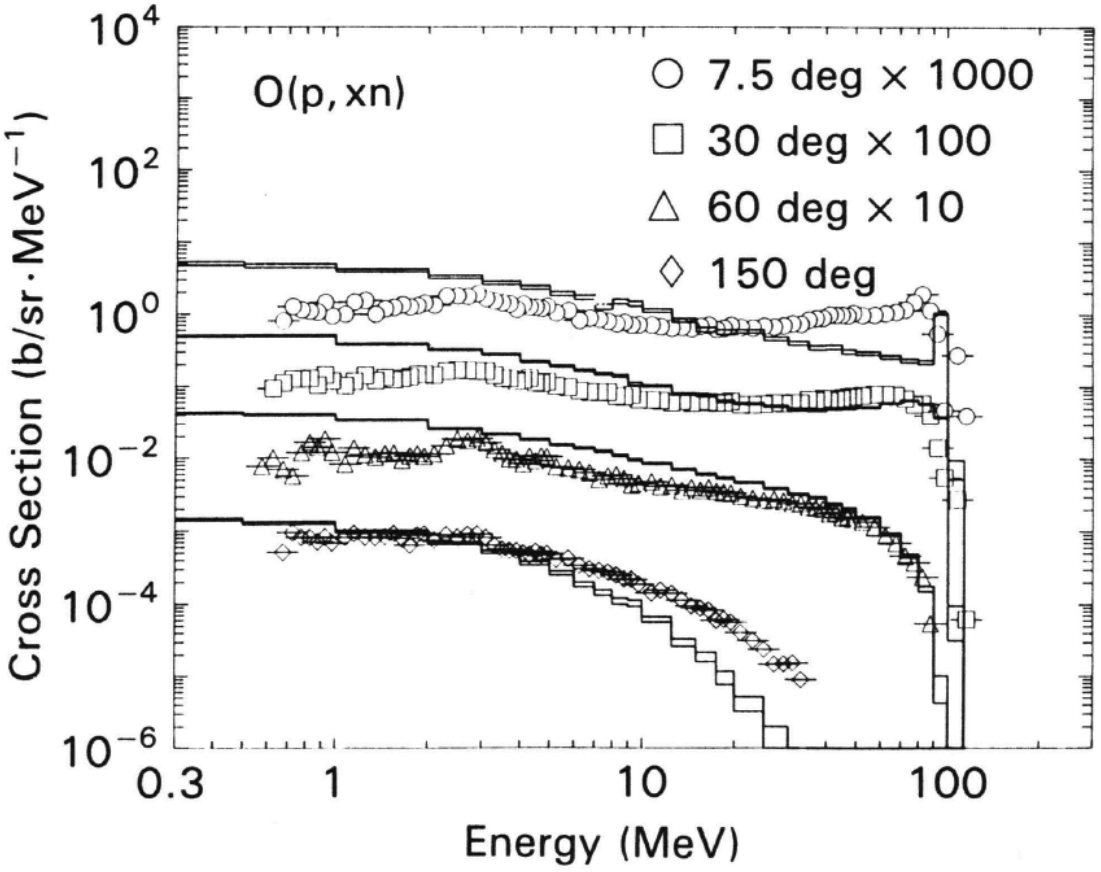
ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

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



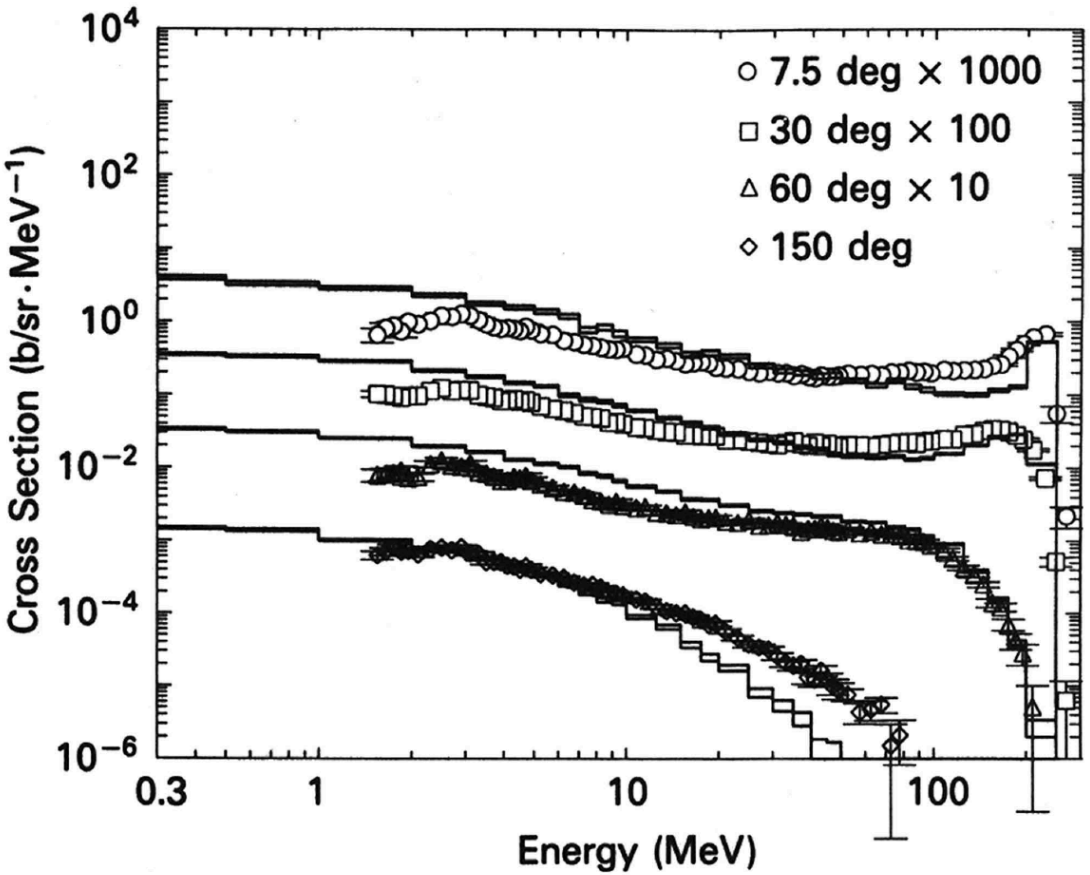
NUCLEAR SCIENCE AND ENGINEERING: 102, 310-321 (1989)

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



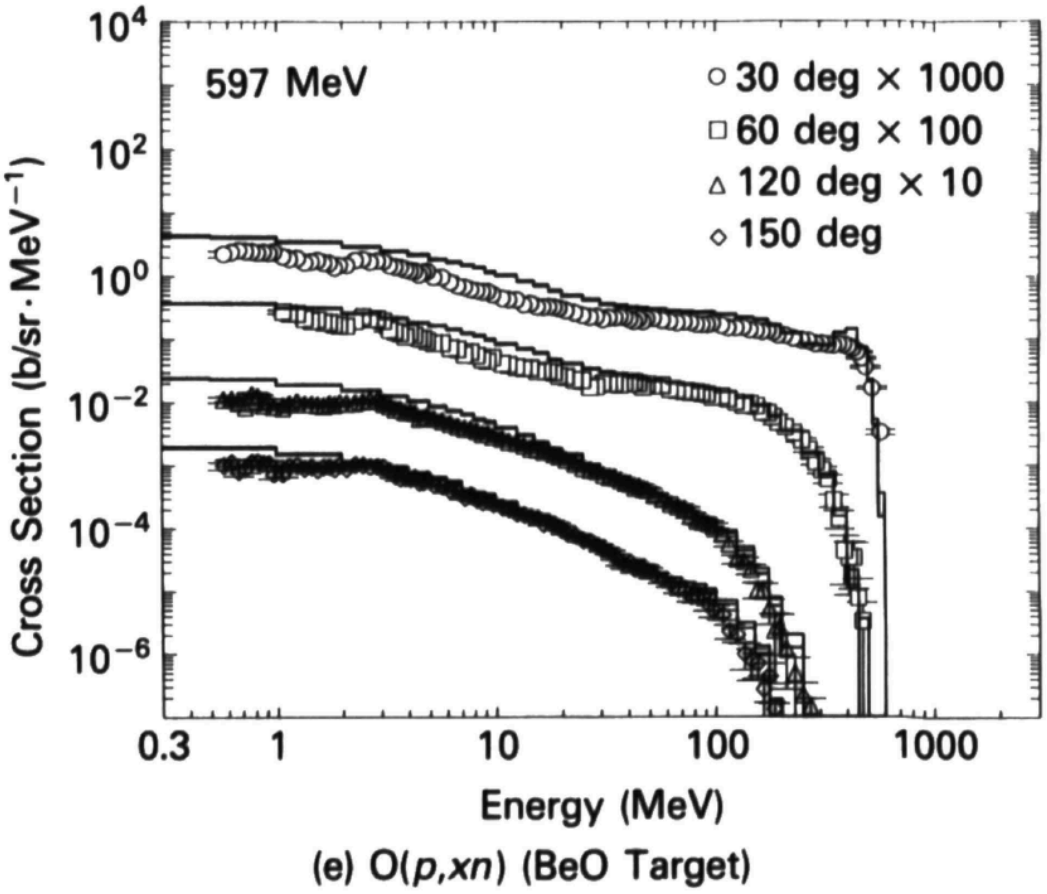
NUCLEAR SCIENCE AND ENGINEERING: 110, 289-298 (1992)

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



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

INFN Istituto Nazionale di Fisica Nucleare

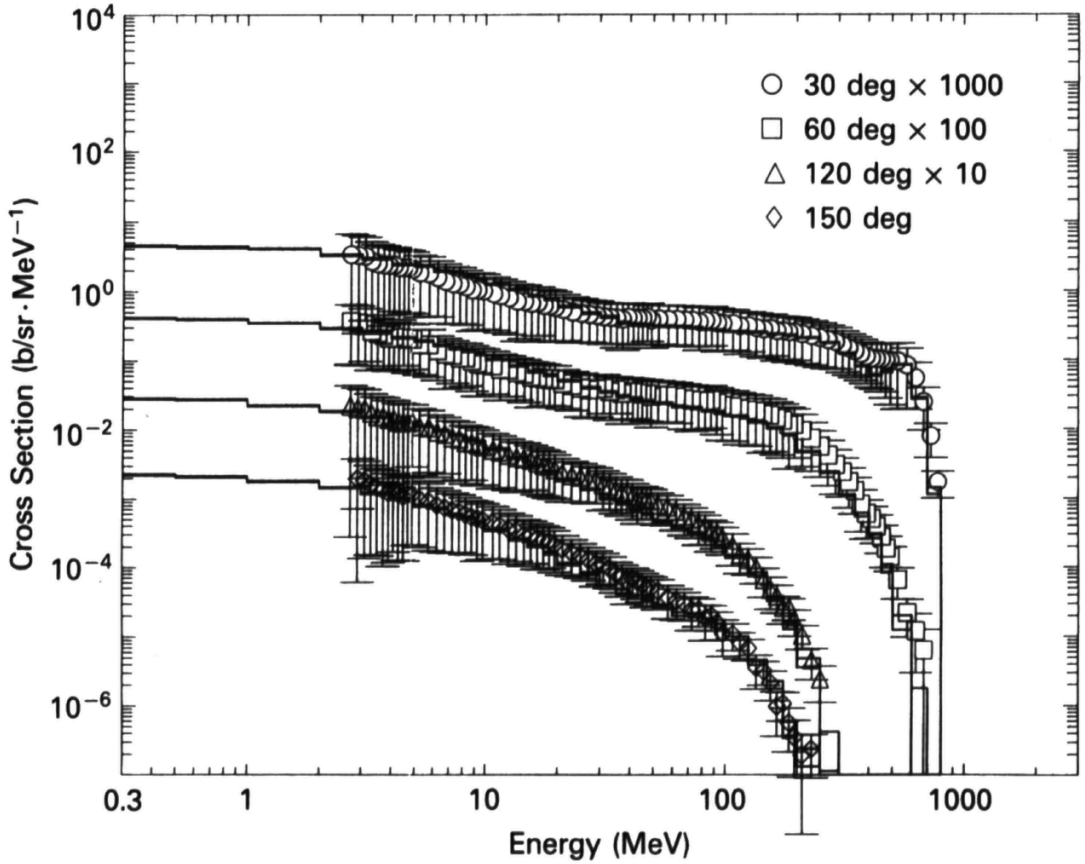
ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

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)

INFN Istituto Nazionale di Fisica Nucleare

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

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)
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

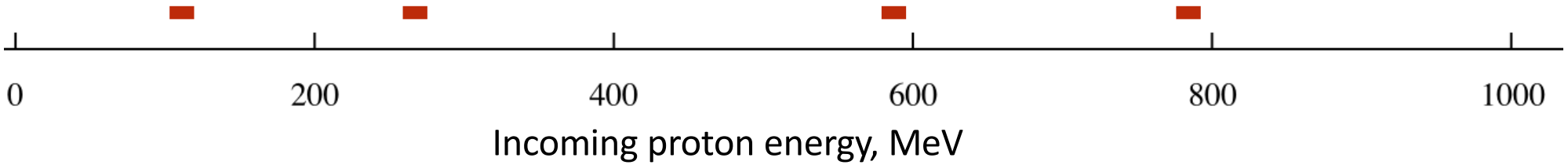
Inclusive cross sections

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 - 1 2 (1993)

INFN Istituto Nazionale di Fisica Nucleare

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

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

TOF technique

Target:

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

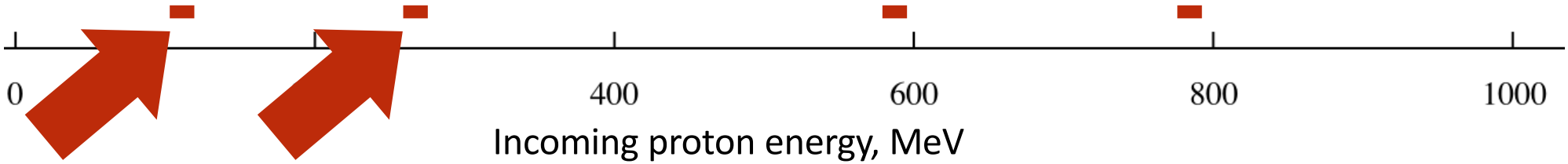
Inclusive cross sections

Energy:

113, 256, 597, 800 MeV

Angle:

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



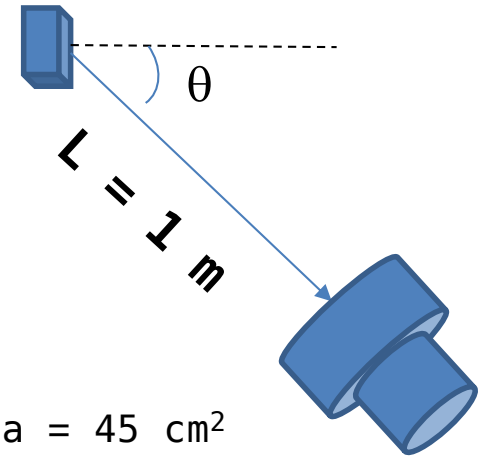
NUCLEAR SCIENCE AND ENGINEERING: 102, 310-321 (1989)
NUCLEAR SCIENCE AND ENGINEERING: 110, 289-298 (1992)
NUCLEAR SCIENCE AND ENGINEERING: 112, 78-86 (1992)
NUCLEAR SCIENCE AND ENGINEERING: 115, 1 - 1 2 (1993)

INFN Istituto Nazionale di Fisica Nucleare

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

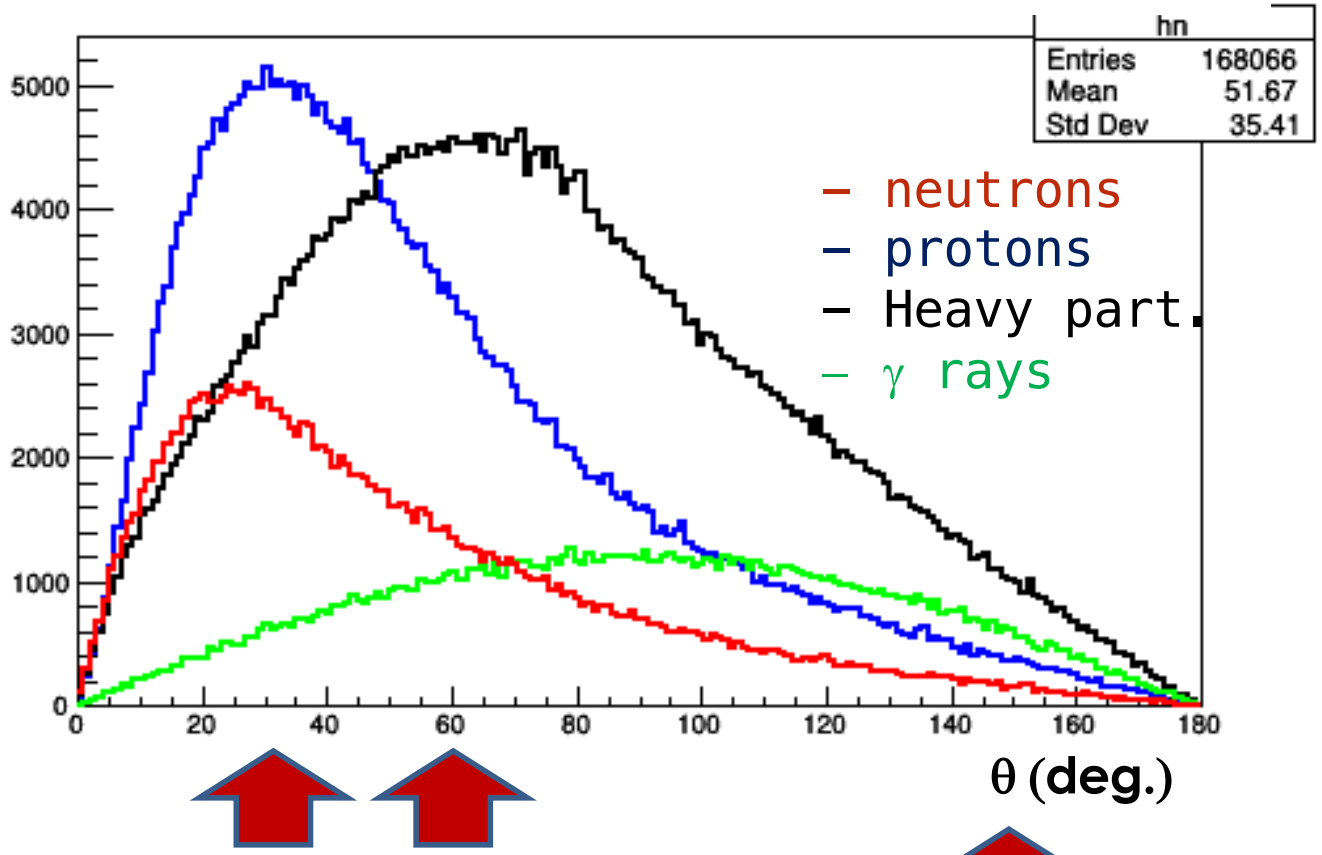
MC simulations – particles from target (5-mm thick)

$^1H+C_2H_4$ @200MeV/u (newgeom) statistics: $5x10^7$ primaries



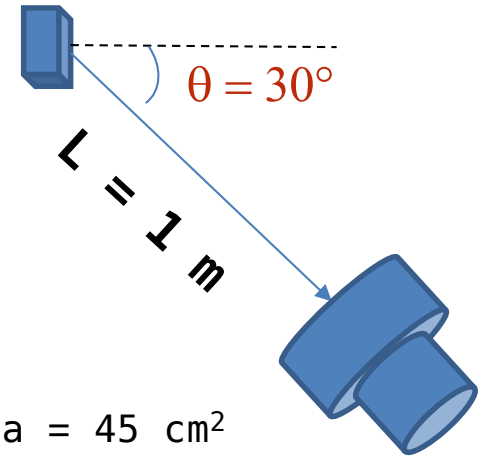
Area = 45 cm^2
$\Delta\theta$ ~ 2 deg.

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



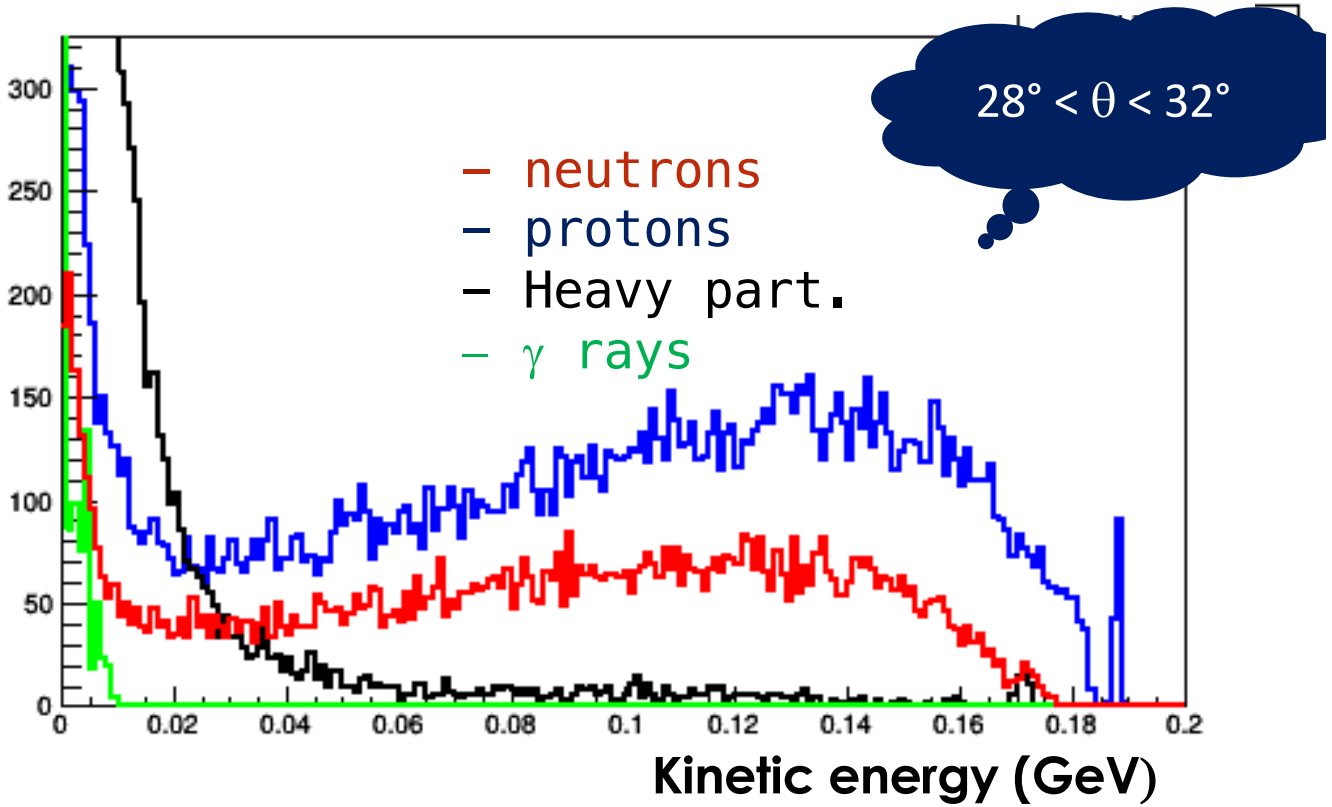
MC simulations – particles from target (5-mm thick)

$^{1}H+C_2H_4$ @200MeV/u (newgeom) statistics: $5x10^7$ primaries



Area = 45 cm^2
$\Delta\theta$ ~ 2 deg.
Geometric eff. ~ 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

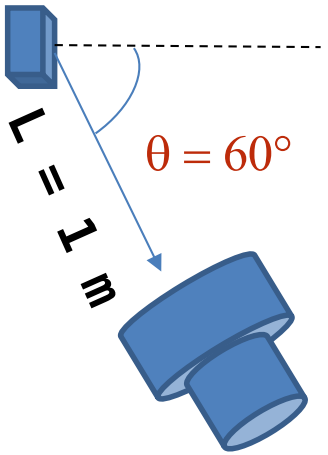


~ 10000 neutrons
Geometric efficiency ~ 1%
Detection efficiency ~ 10 %
→ **10 events in the detector for $5x10^7$ primaries**

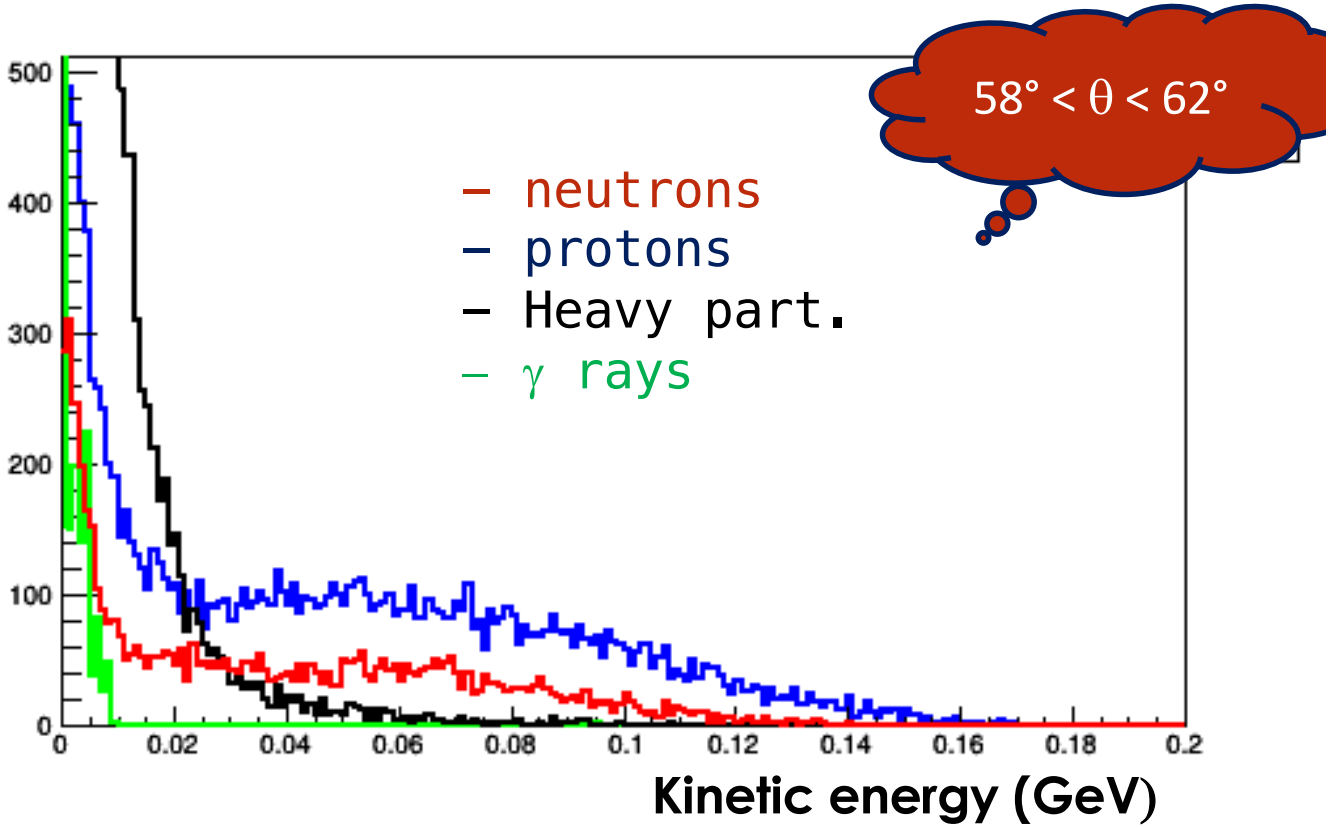
ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

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

$^{1}H+C_2H_4$ @200MeV/u (newgeom) statistics: $5x10^7$ 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 $5x10^7$ primaries

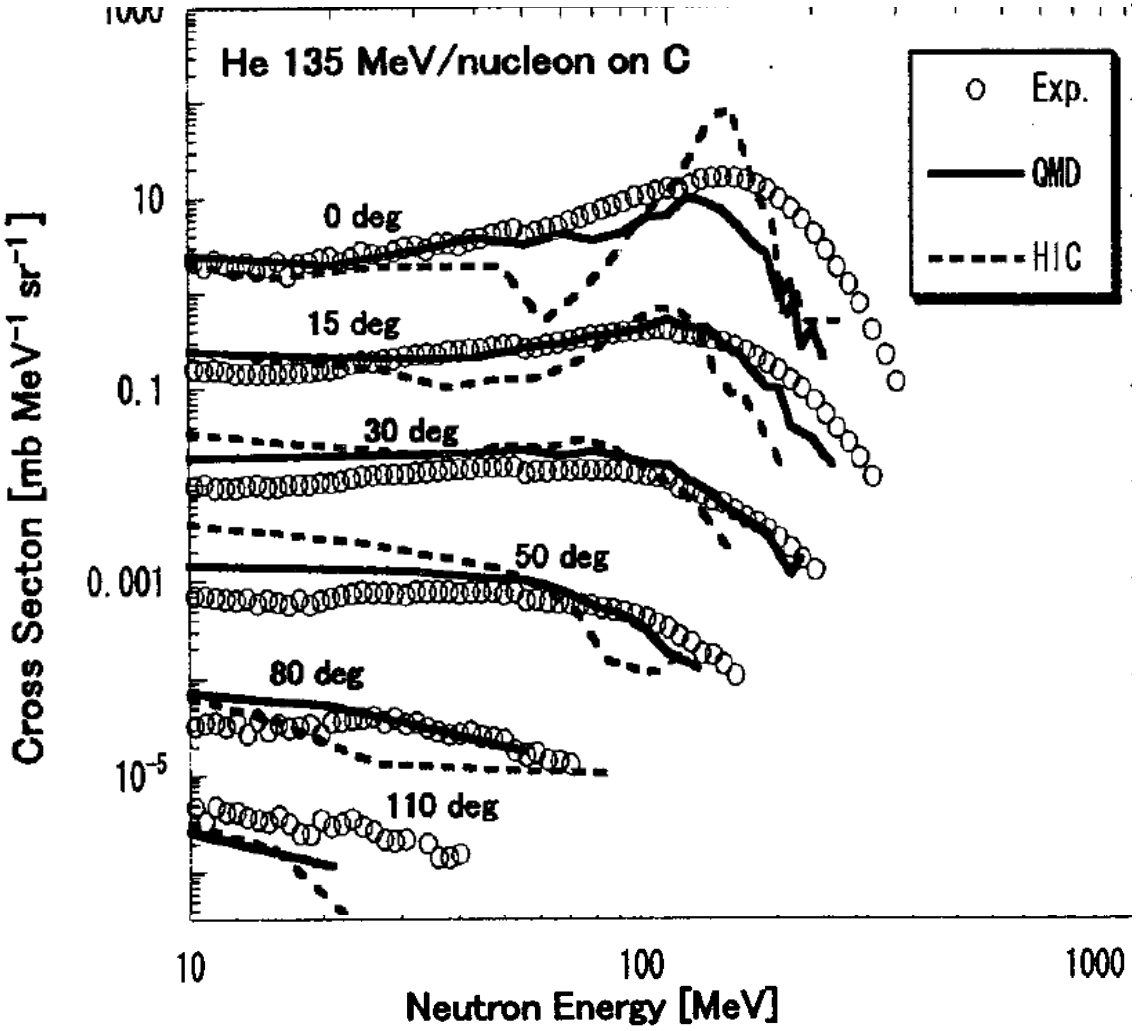
ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

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)



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

INFN Istituto Nazionale di Fisica Nucleare

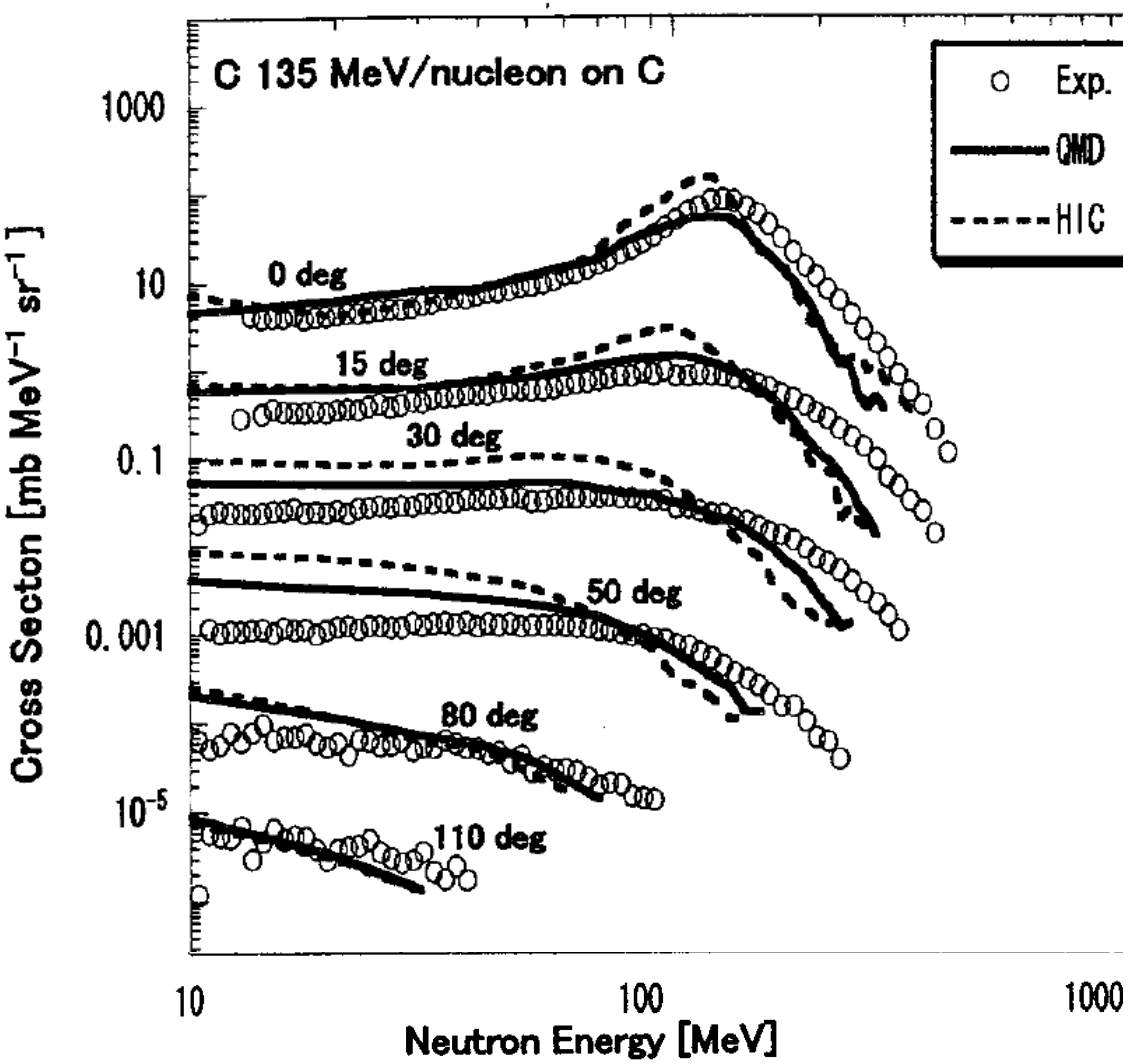
ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

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)



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

INFN Istituto Nazionale di Fisica Nucleare

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

Thin target, heavy-Ion induced reactions

@ 135 MeV/u

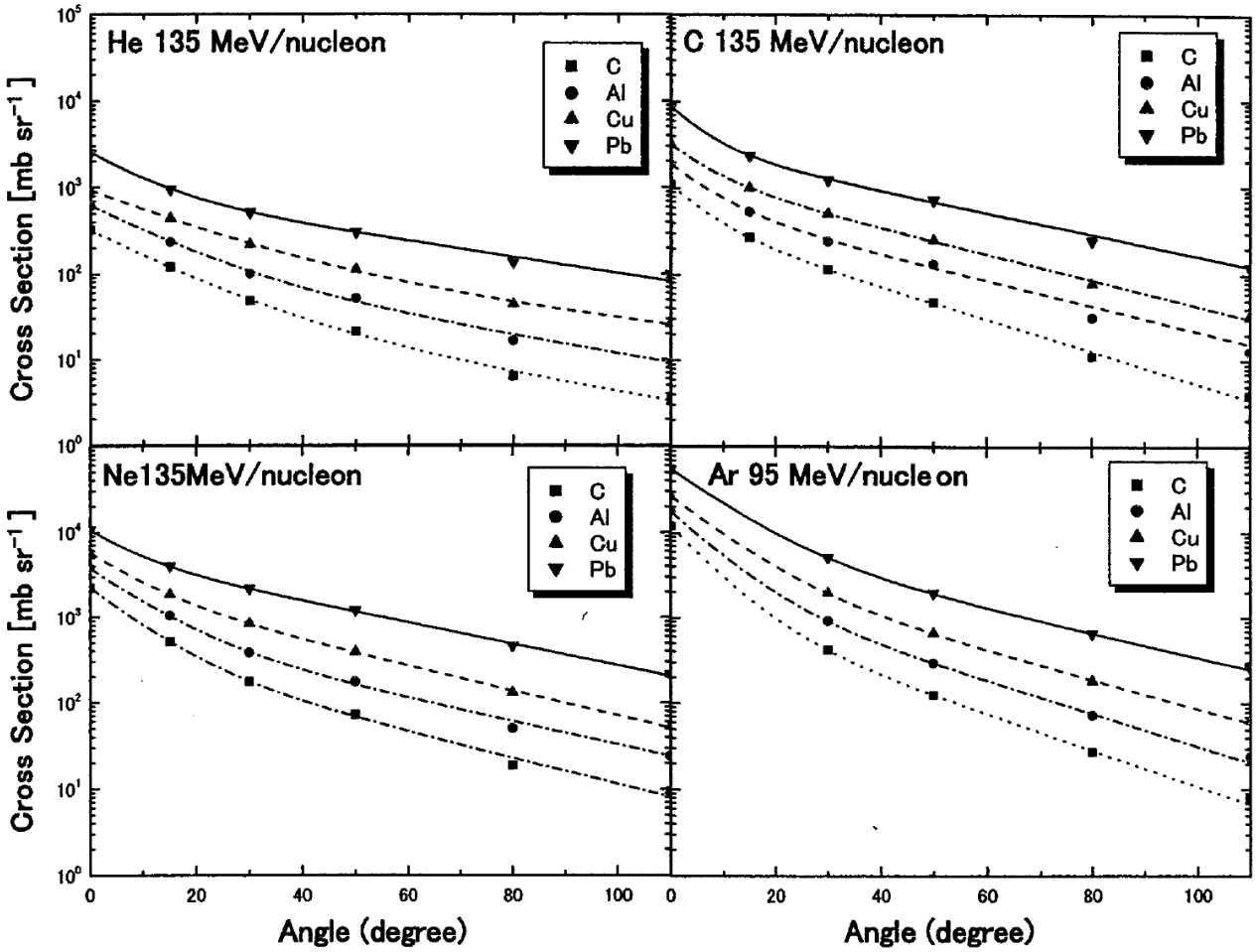


FIG. 8. Angular distributions of neutron production cross sections integrated above 20 MeV.

Angular distribution

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

Thin target, heavy-Ion induced reactions

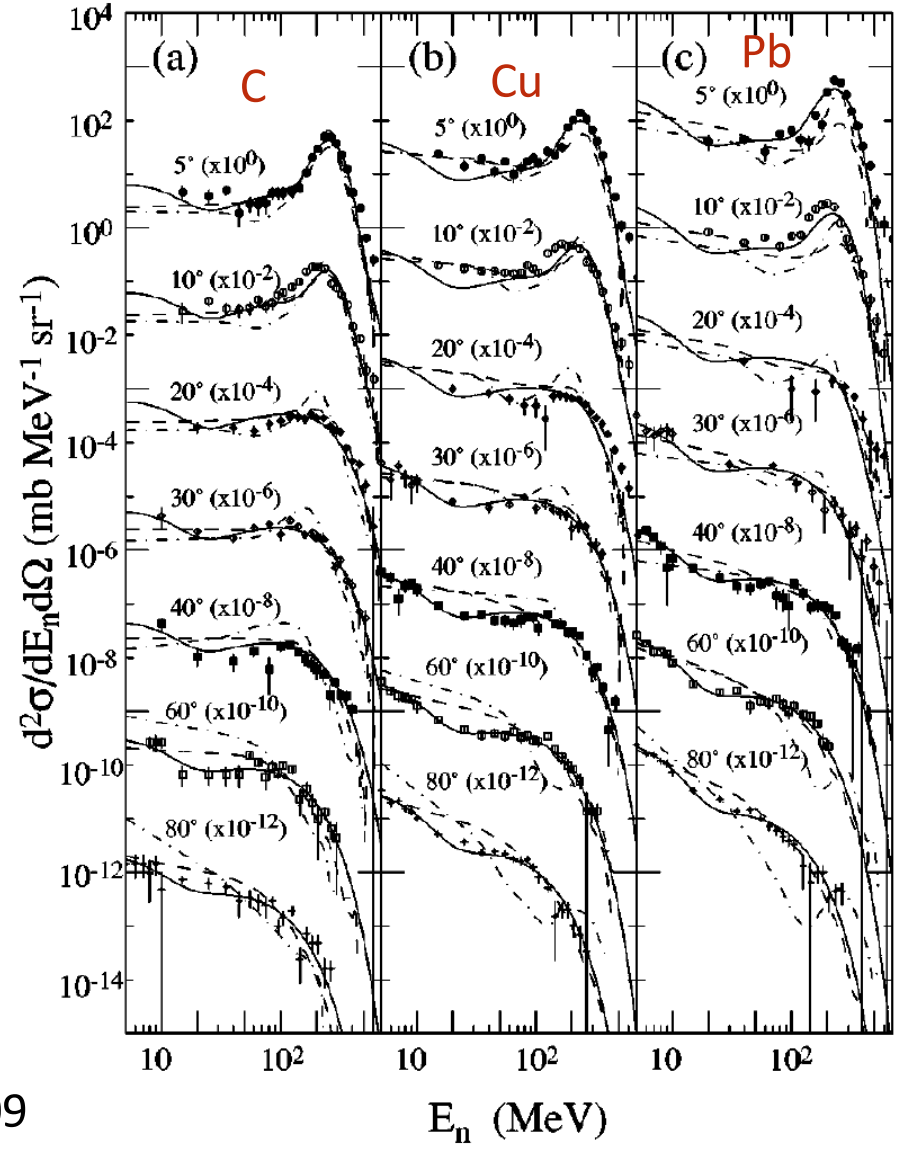
@ 290 MeV/u
@ 400 MeV/u
@ 600 MeV/u

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



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

Thin target, heavy-Ion induced reactions

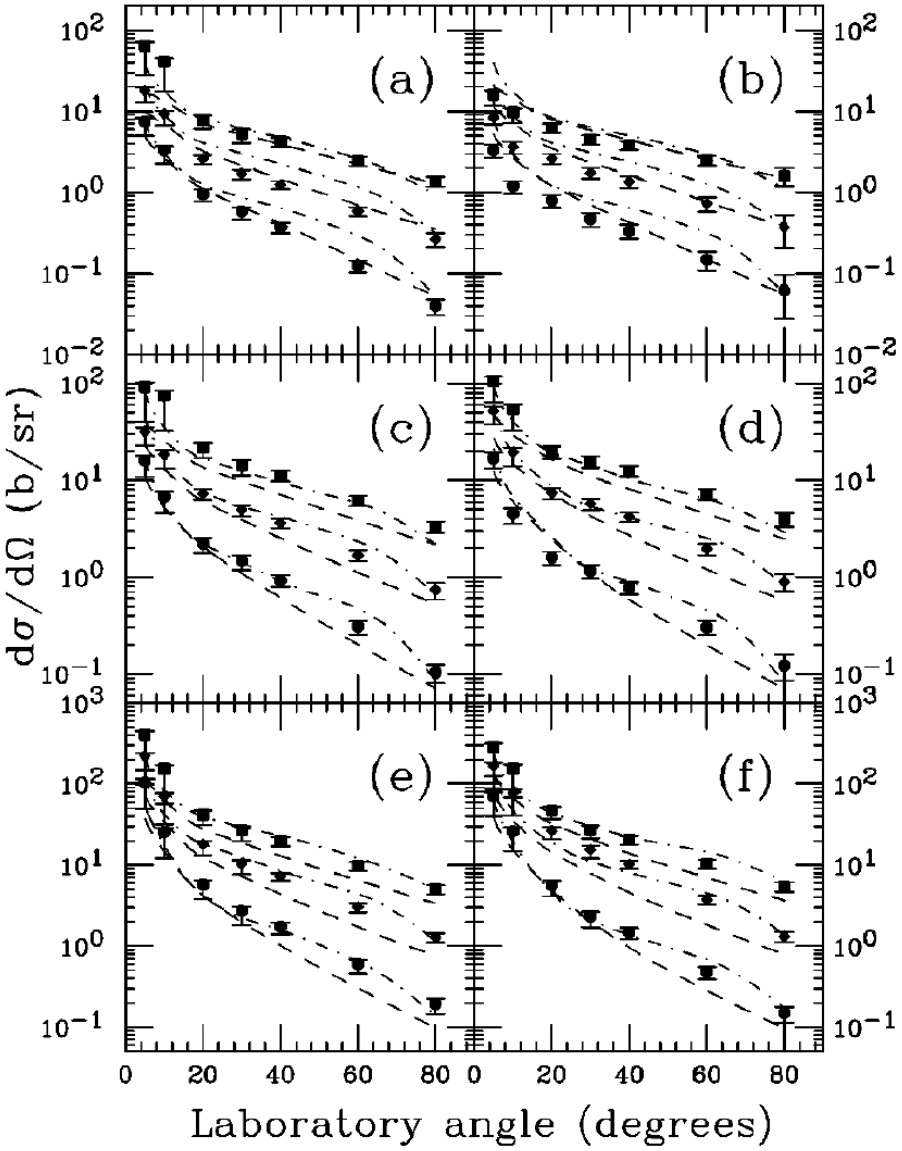
@ 290 MeV/u
@ 400 MeV/u
@ 600 MeV/u

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



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

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

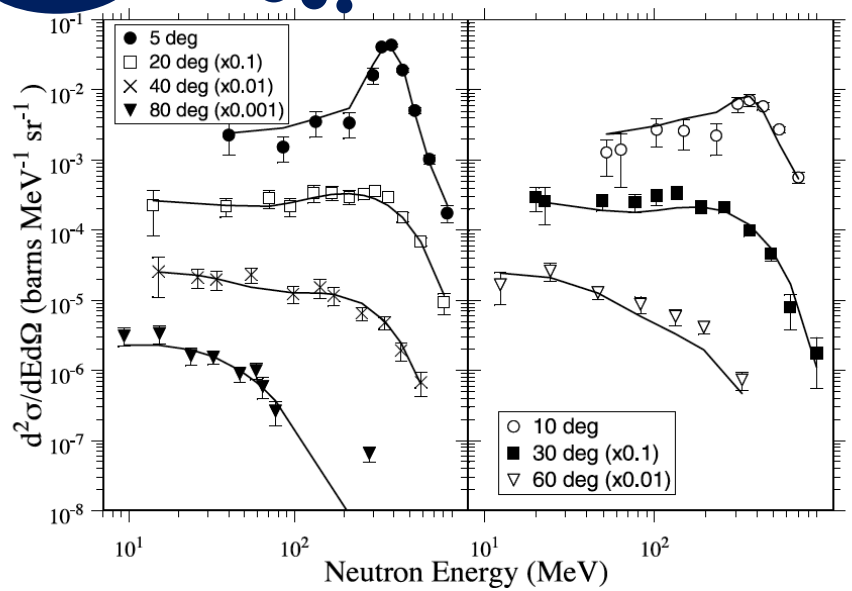


Fig. 5. Double-differential spectra from 400 MeV/nucleon N interacting in a C target. The spectra at each laboratory angle are offset by the indicated factors of 10. The lines come from a moving-source fit described in the text.

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

INFN Istituto Nazionale di Fisica Nucleare

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

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)

INFN
Istituto Nazionale di Fisica Nucleare

Thin target, heavy-Ion induced reactions

TOF technique

Target:

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

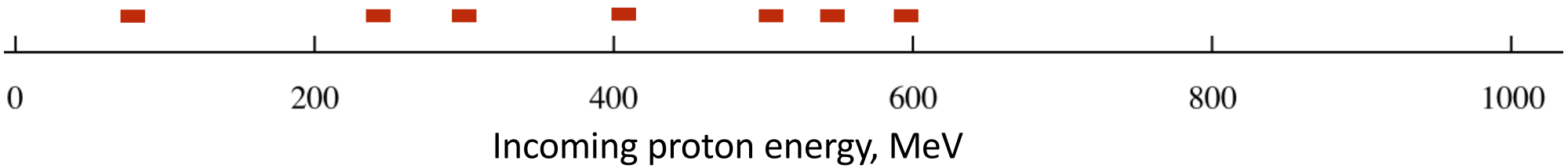
Inclusive cross sections

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

INFN Istituto Nazionale di Fisica Nucleare

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

Thin target, heavy-Ion induced reactions

TOF technique

Target:

C **and CH_2**

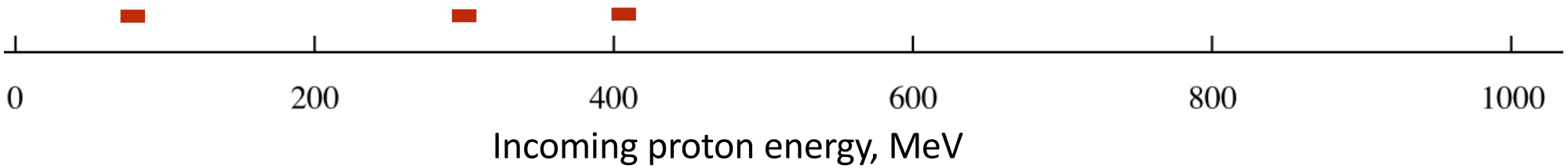
Inclusive cross sections

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

INFN Istituto Nazionale di Fisica Nucleare

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

Thin target, heavy-Ion induced reactions

TOF technique

Target:

C **and CH_2**

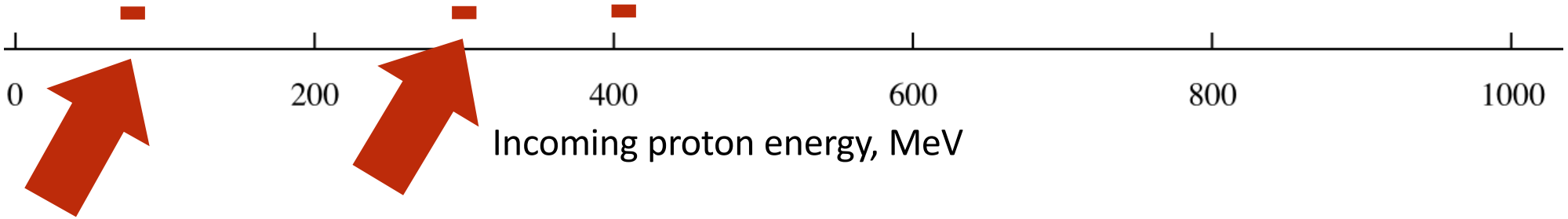
Inclusive cross sections

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

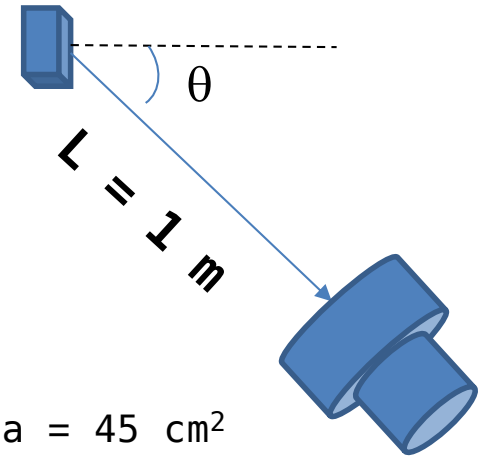
PHYSICAL REVIEW C **64** (2001) 034607

INFN Istituto Nazionale di Fisica Nucleare

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

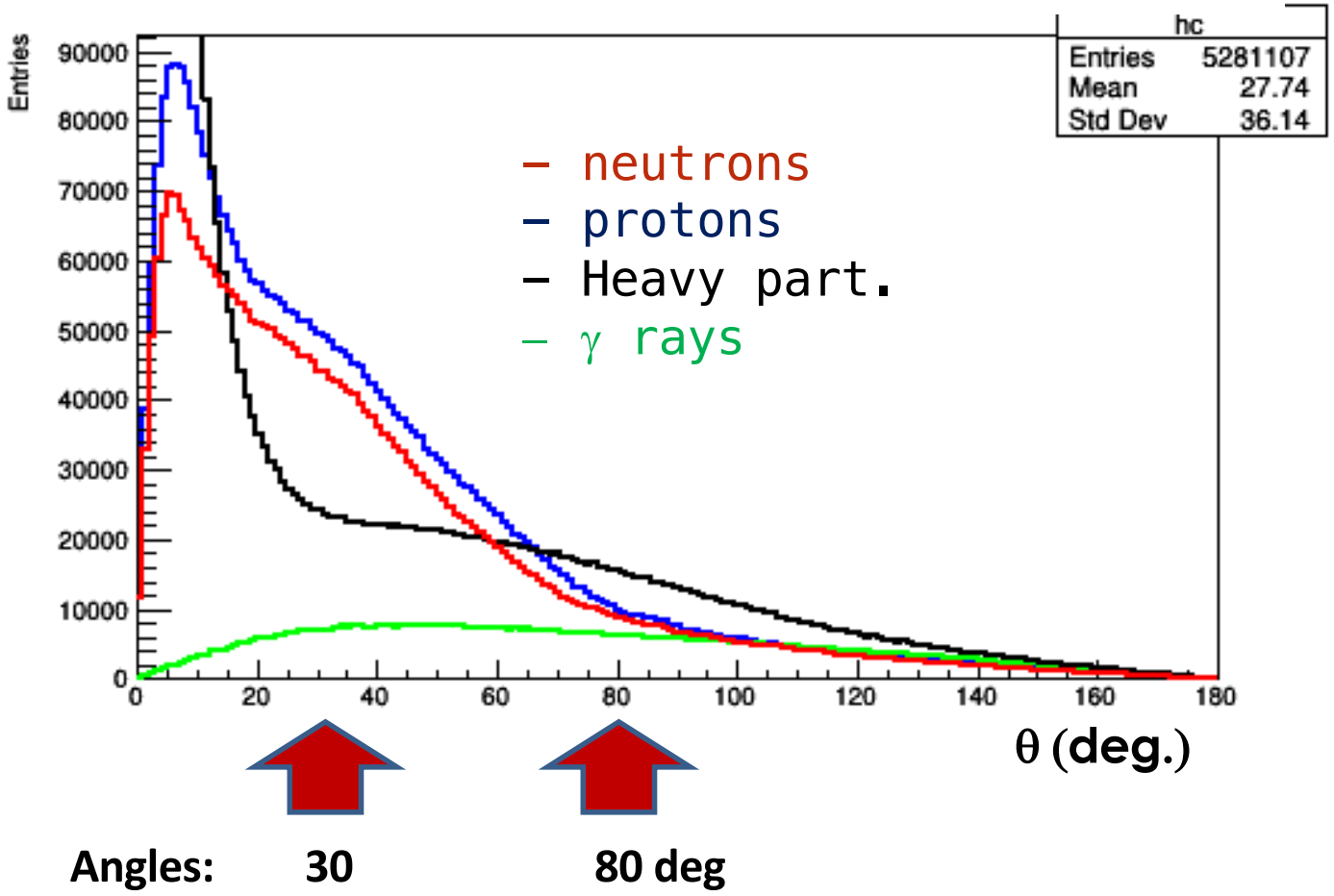
MC simulations – particles from target (5-mm thick)

$^{16}O+C_2H_4$ @200MeV/u (newgeom) statistics: $5x10^7$ primaries



Area = 45 cm^2
$\Delta\theta$ ~ 2 deg.

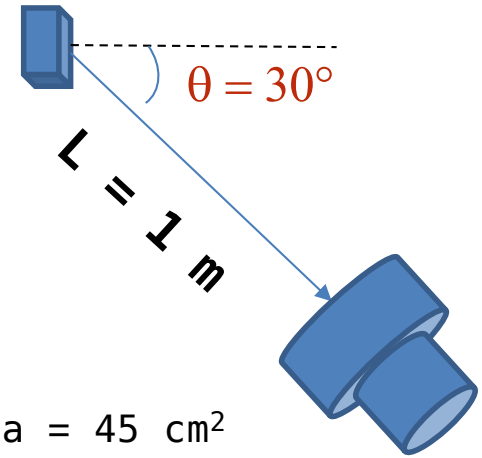
E_n	TOF
1 MeV	72 ns
10 MeV	23 ns
50 MeV	10.6 ns
100 MeV	7.8 ns
200 MeV	5.9 ns



Angles: 30 80 deg

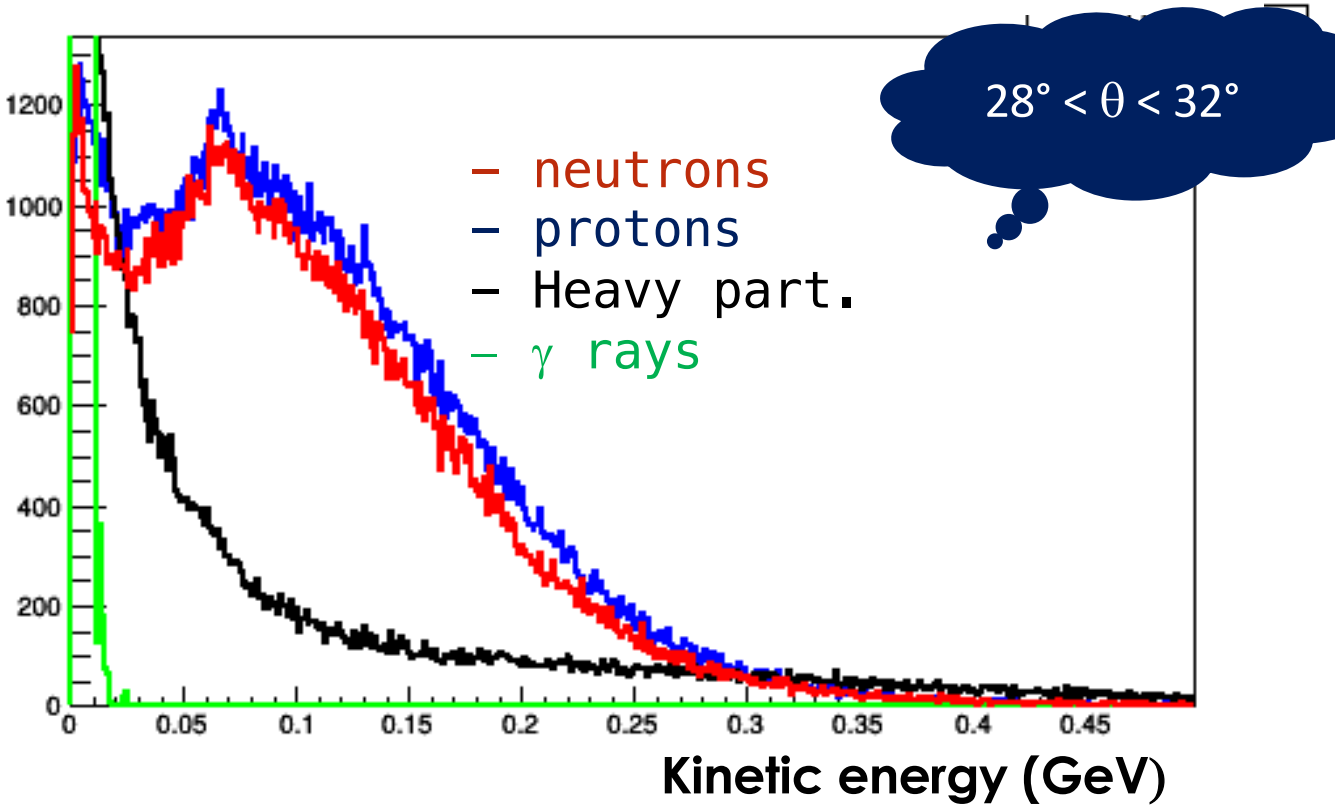
MC simulations – particles from target (5-mm thick)

$^{16}O+C_2H_4$ @200MeV/u (newgeom) statistics: $5x10^7$ primaries



Area = 45 cm^2
$\Delta\theta$ ~ 2 deg.
Geometric eff. ~ 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

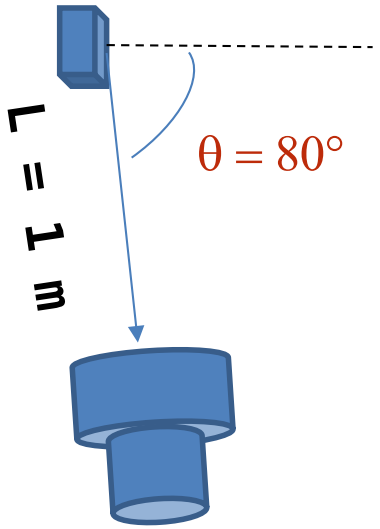


~ 181000 neutrons
Geometric efficiency ~ 1%
Detection efficiency ~ 10 %
→ **181 events in the detector for $5x10^7$ primaries**

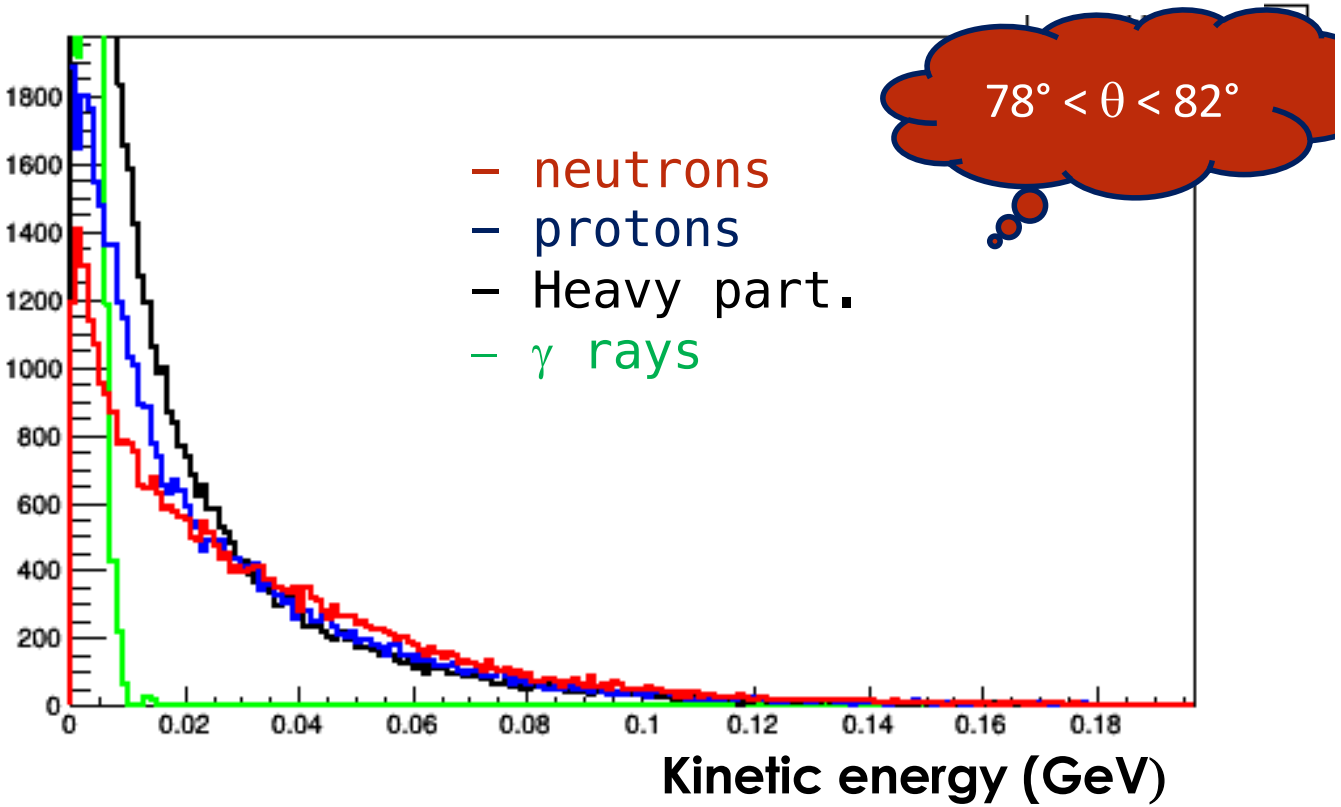
ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

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

$^{16}O+C_2H_4$ @200MeV/u (newgeom) statistics: $5x10^7$ 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 $5x10^7$ primaries**

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Homogeneous THIK target, charged-particle induced reactions

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

by Nakamura and Heilbronn

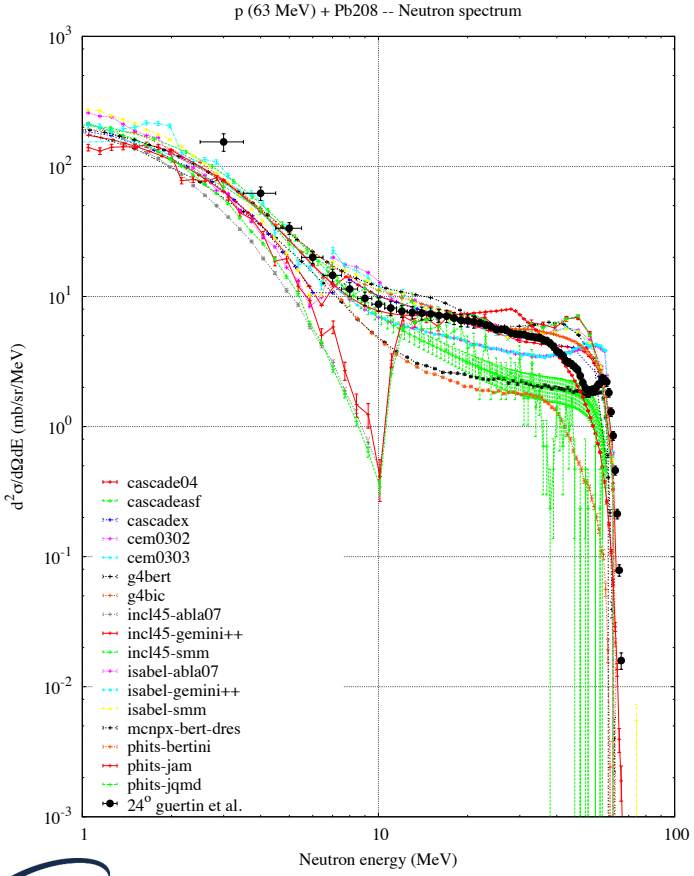
Beam ion and energy (MeV/nucleon)	Targets (cm)	Measured spectra	θ (deg)	Emin (MeV)	Facility
He (100)	C (5.0) Al (4.0) Cu (1.5) Pb (1.5)	TTY n/dΩ total	0, 7.5, 15, 30, 60, 90	5.5, 5, 4, 3.5, 3.5, 3	HIMAC
He (155)	Al (8.26)	TTY n/dΩ total	10, 30, 45, 60, 90, 125, 160	10, 3, 3, 7, 4, 3, 3	NSCL
He (160)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

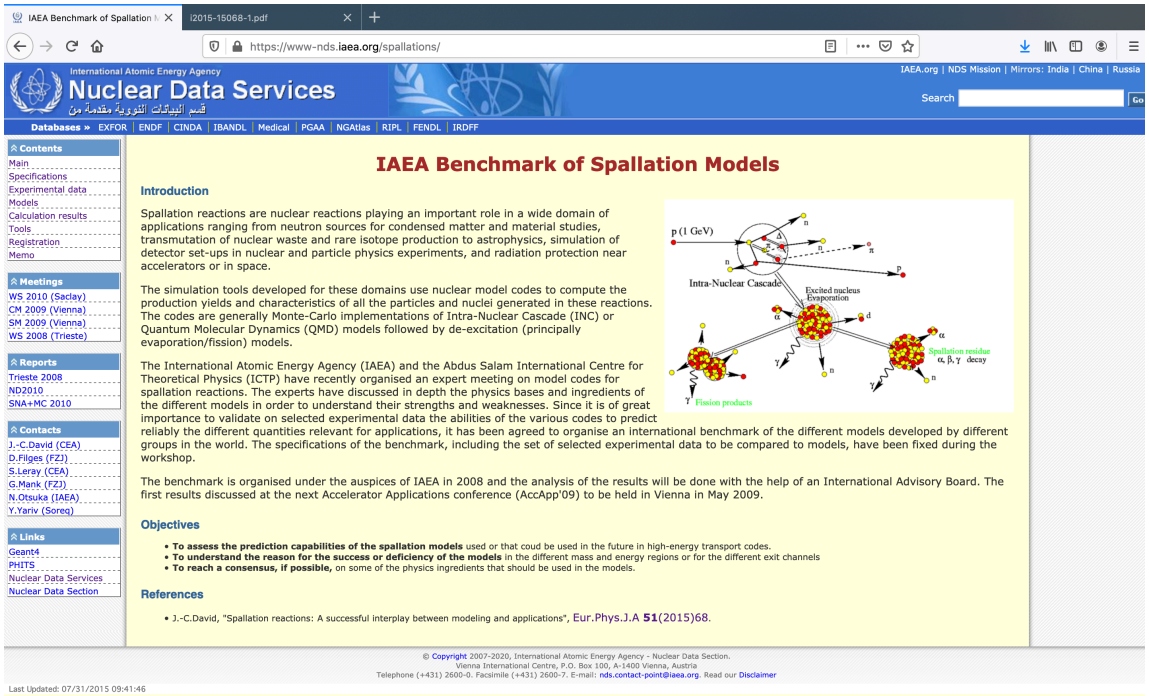
Beam ion and energy (MeV/nucleon)	Targets (cm)	Measured spectra	θ (deg)	Emin (MeV)	Facility
He (180)	C (16.0) Al (12.0) Cu (4.5) Pb (5.0)	TTY n/dΩ total	0, 7.5, 15, 30, 60, 90	17, 11, 5.5, 6.5, 3.5, 3.5	HIMAC
C (100)	C (2.0) Al (1.0) Cu (0.5) Pb (0.5)	TTY n/dΩ total	0, 7.5, 15, 30, 60, 90	4, 4, 3.5, 3.5, 3, 3	HIMAC
C (155)	Al (8.26)	TTY n/dΩ 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/dΩ 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/dΩ 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/dΩ 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/dΩ 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/dΩ 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/dΩ 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/dΩ total	0, 7.5, 15, 30, 60, 90	10, 7, 3.5, 3.5, 3, 3	HIMAC

INFN
Istituto Nazionale di Fisica Nucleare

Homogeneous THIK target, charged-particle induced reactions

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





Double differential cross section (neutron)

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

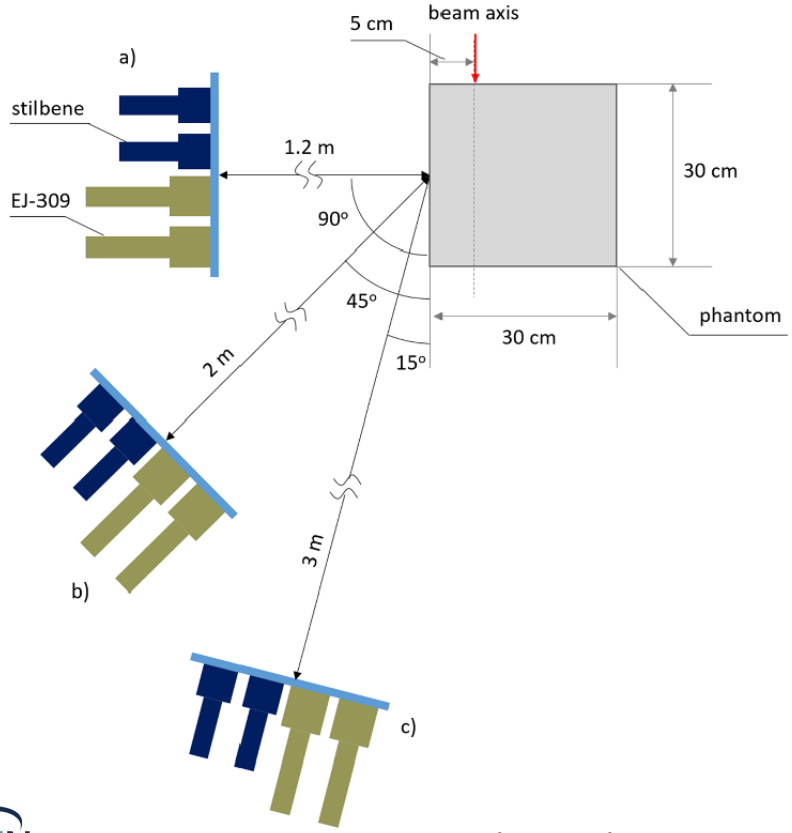
INFN
Istituto Nazionale di Fisica Nucleare

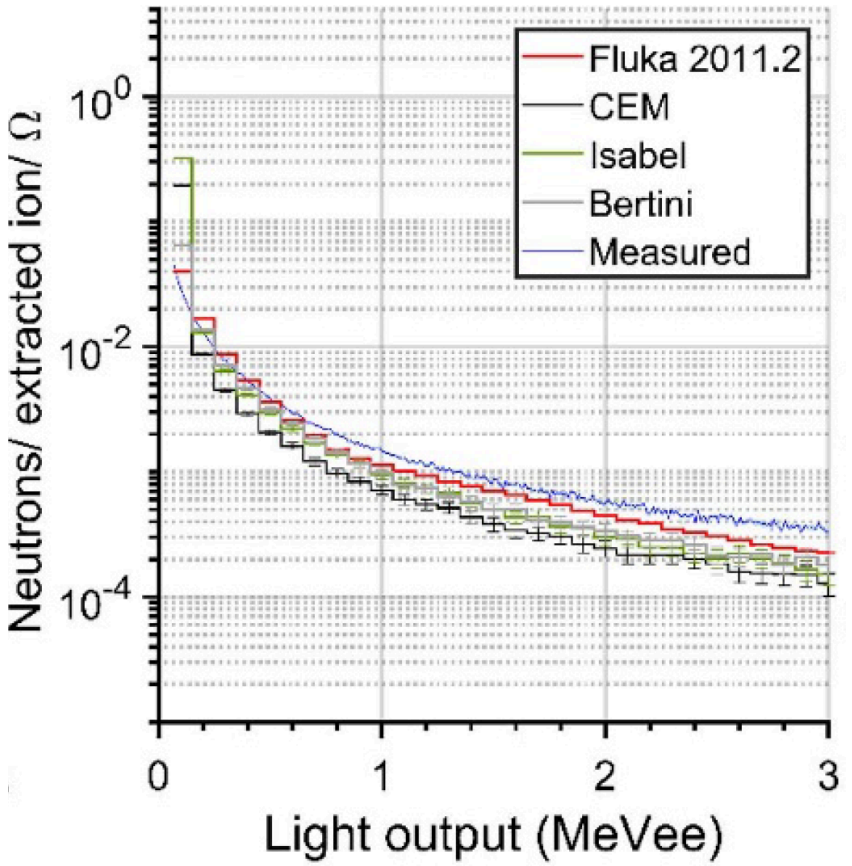
THICK target: non homogenous target (clinical phantom)

@ 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)





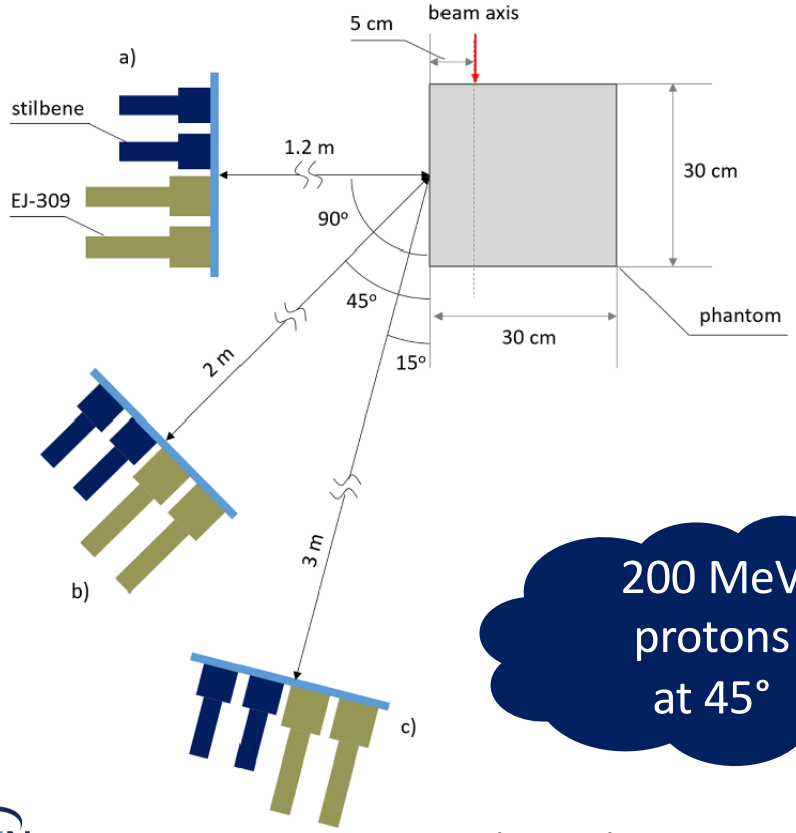
Phys. Med. Biol. **65** (2020) 155002

THICK target: non homogenous target (clinical phantom)

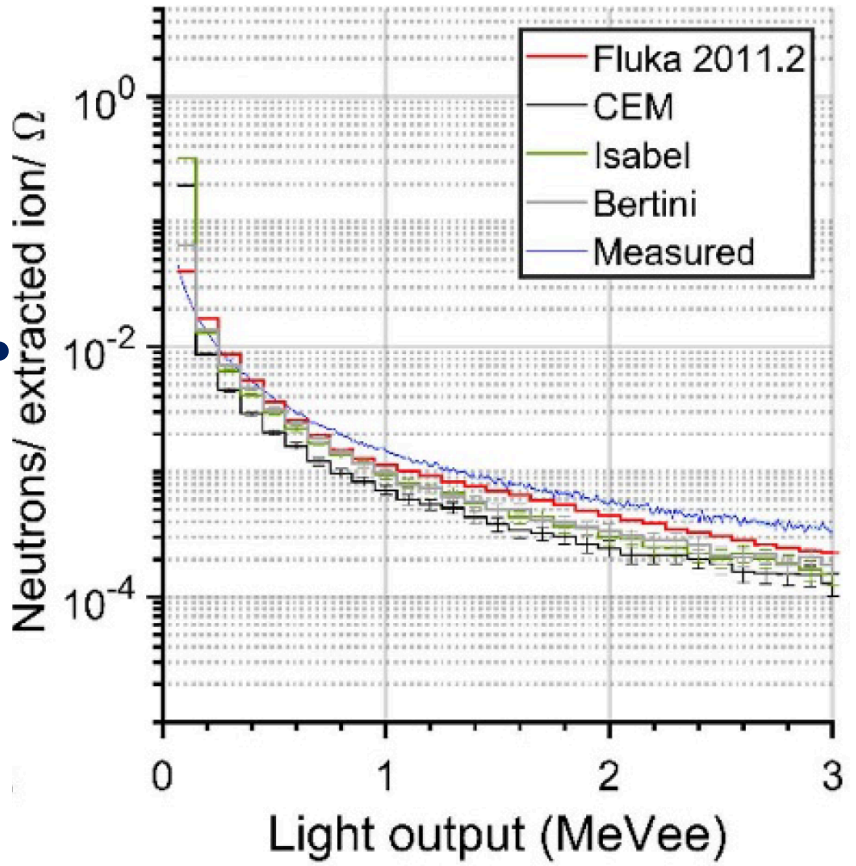
@ CNAO

	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)



200 MeV protons at 45°



Phys. Med. Biol. **65** (2020) 155002

INFN Istituto Nazionale di Fisica Nucleare

THICK target: non homogenous target (clinical phantom)

@ CNAO

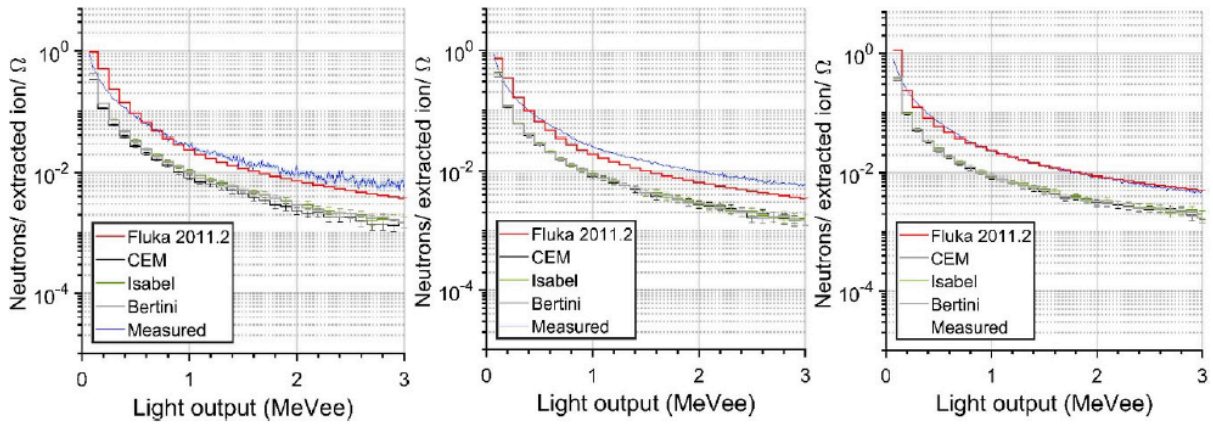


Figure 8. Comparison between simulated and measured EJ-309 pulse height distributions, for 293 MeV u^{-1} carbon-ion irradiation, at measurement locations of 15°, 45° and 90° (left to right) with respect to the beam axis.

293 MeV/u
&
388 MeV/u
Carbon

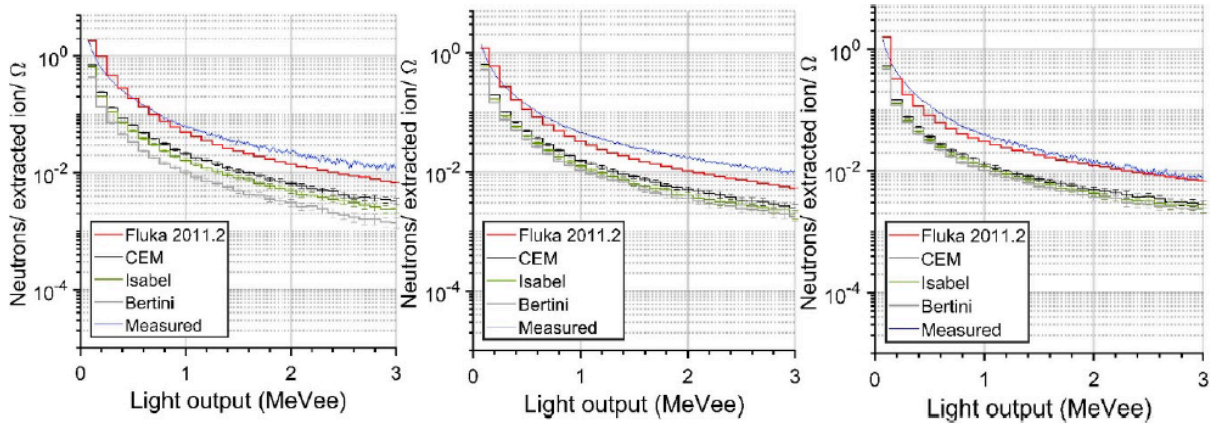


Figure 9. Comparison between simulated and measured EJ-309 pulse height distributions, for 387.78 MeV u^{-1} carbon-ion irradiation, at measurement locations of 15°, 45° and 90° (left to right) with respect to the beam axis.

INFN
Istituto Nazionale di Fisica Nucleare

Phys. Med. Biol. **65** (2020) 155002

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

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?

INFN
Istituto Nazionale di Fisica Nucleare

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

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}C and ^{12}C+^{12}C reactions:

- p + ^{12}C @ 30 and 60 (150?) deg. with **energy** of **113** and **256 MeV**
- ^{12}C + ^{12}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 neessary to perform the test. Count rate might be an issue!

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Cristian Massimi

Department of Physics and Astronomy

cristian.massimi@unibo.it

www.unibo.it

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/