Double differential cross sections for the productions of secondary neutrons from heavy ion reactions at energy *E/A* = 290-600 MeV

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- Introduction
- Experiment
- Results
- Summary

Introduction

- Recent development of accelerator facilities
  - High energy heavy ion beam
    - Radiology …
  - Radioactive Nuclear Beam
    - Nuclear Structure (Neutron Halo)
    - Reactions
      (Big Bang nucleosynthesis)
- Radiation shielding design
  - Simulation codes
    (transport code …)
  - Cross sections for secondary neutron production

- Several works

  - Ne on C, Al, Cu and U at *E/A*=337 MeV (R.A. Cecil *et al.*, 1981)
  - Nb on Nb and Au on Au at *E/A*=800 MeV (R. Madey *et al.*, 1988,1990)
  - Ne on Pb at *E/A*=790 MeV (A.R. Baldwin *et al.*, 1992)

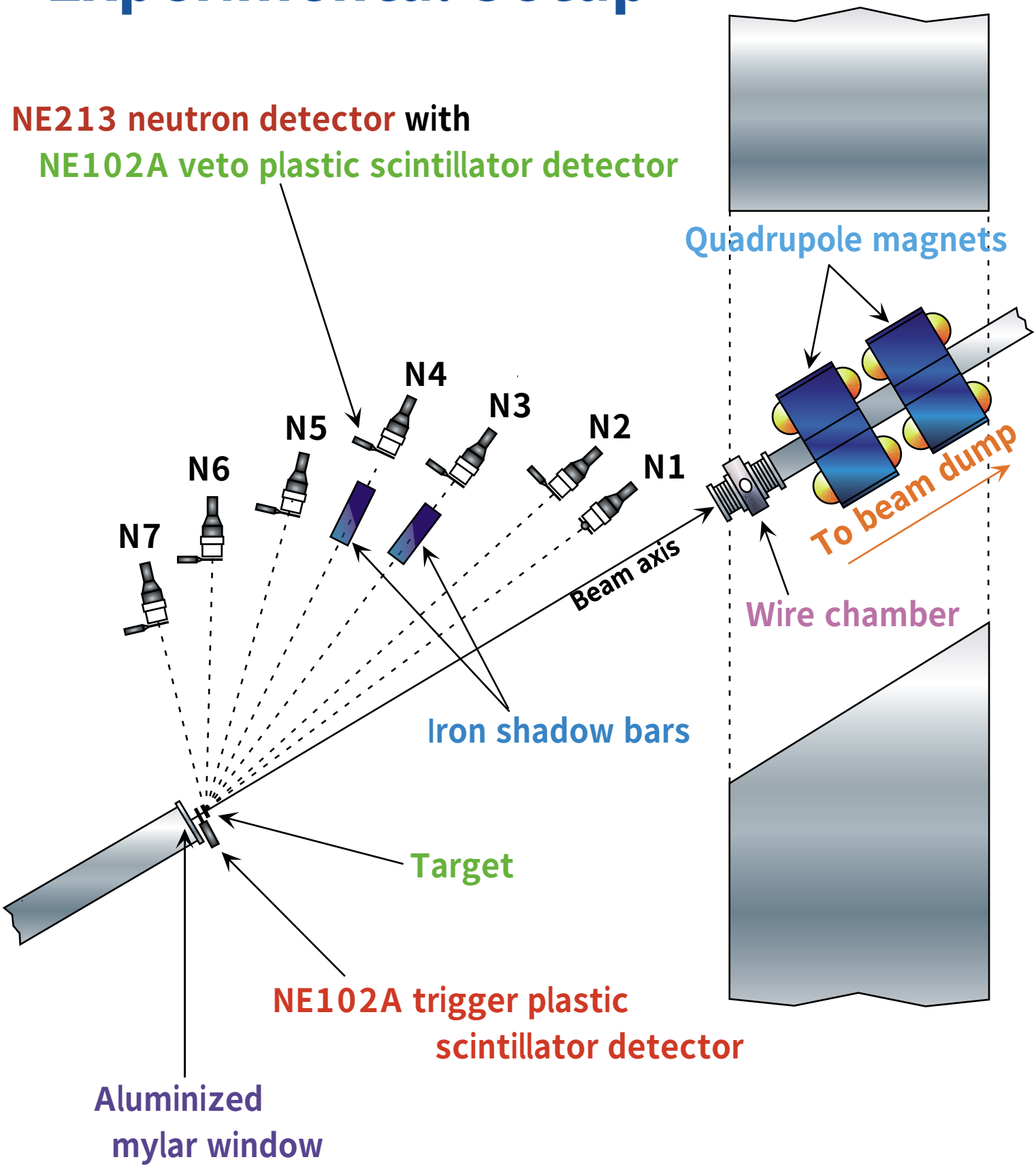
- No systematic measurement

Experiment

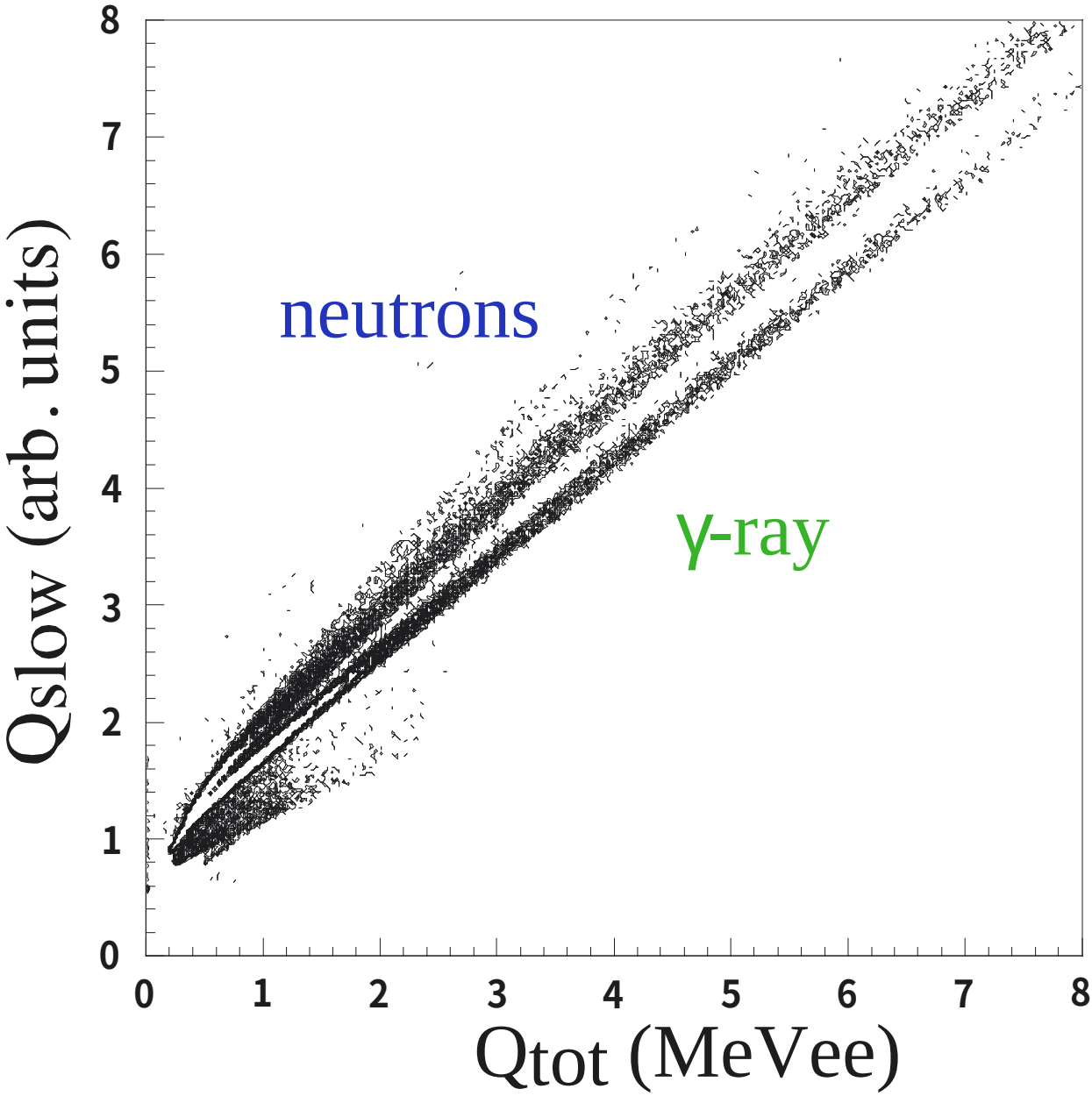
- National Institute of Radiological Sciences (NIRS)
  - Heavy ion synchrotron (HIMAC)
- Heavy ion beams
  - ✓ Carbon at E/A = 290 and 400 MeV
  - ✓ Neon at E/A = 400 and 600 MeV
  - ✓ Argon at E/A = 400 and 560 MeV
- Targets
  - Carbon, Copper and Lead
  - Thickness

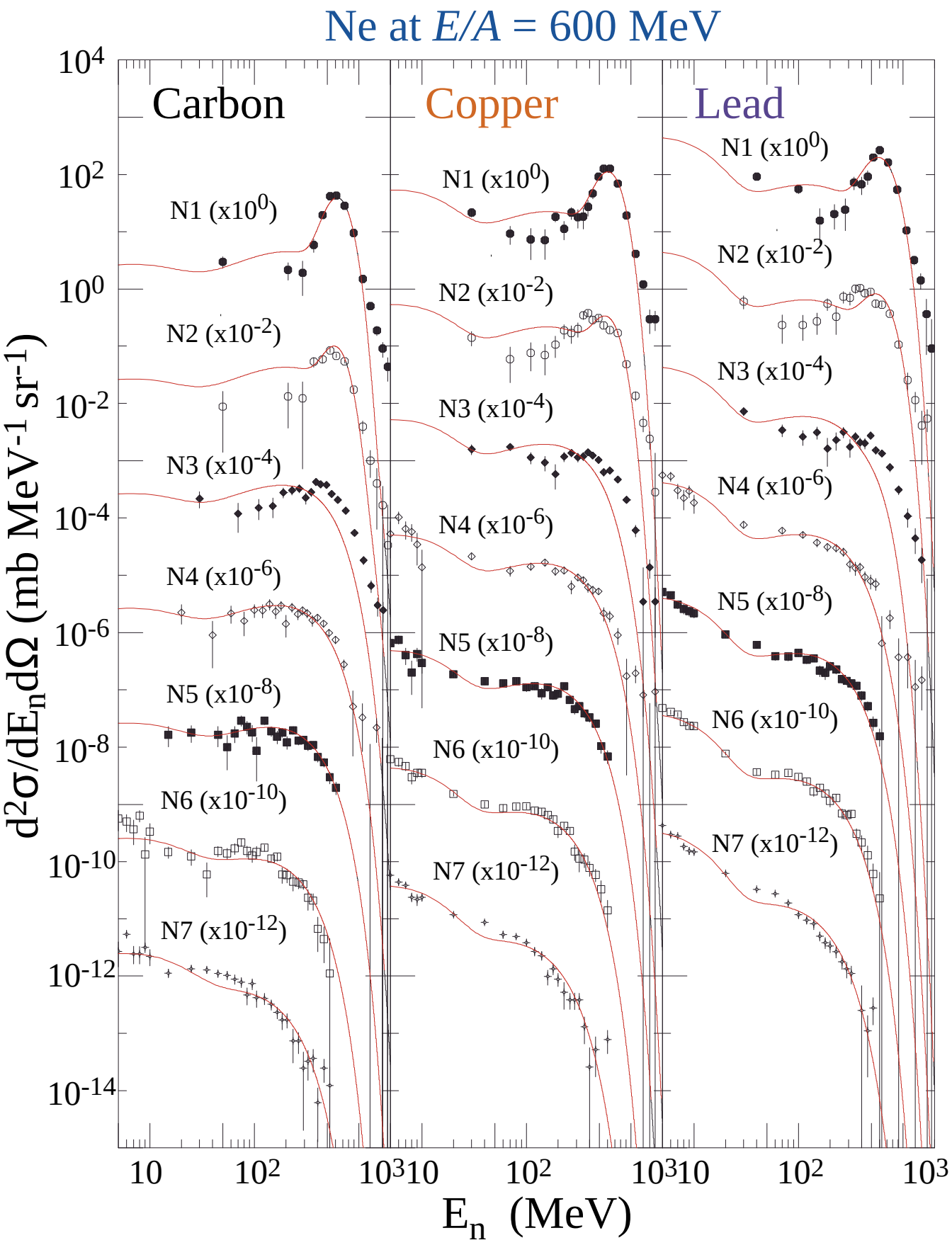
    $\Delta E \sim 5\text{-}10\ \%$

Experimental Setup



n/γ discrimination




Ne at E/A = 600 MeV
Carbon
Copper
Lead
N1 (x10^0)
N2 (x10^-2)
N3 (x10^-4)
N4 (x10^-6)
N5 (x10^-8)
N6 (x10^-10)
N7 (x10^-12)
d²σ/dE_n dΩ (mb MeV^-1 sr^-1)
E_n (MeV)

Results

- Moving source model
  - Direct component

$$\frac{d^2N}{p_n^2 dp_n d\Omega} = Ne^{-(p_x^2/2\sigma_{direct}^2)}$$

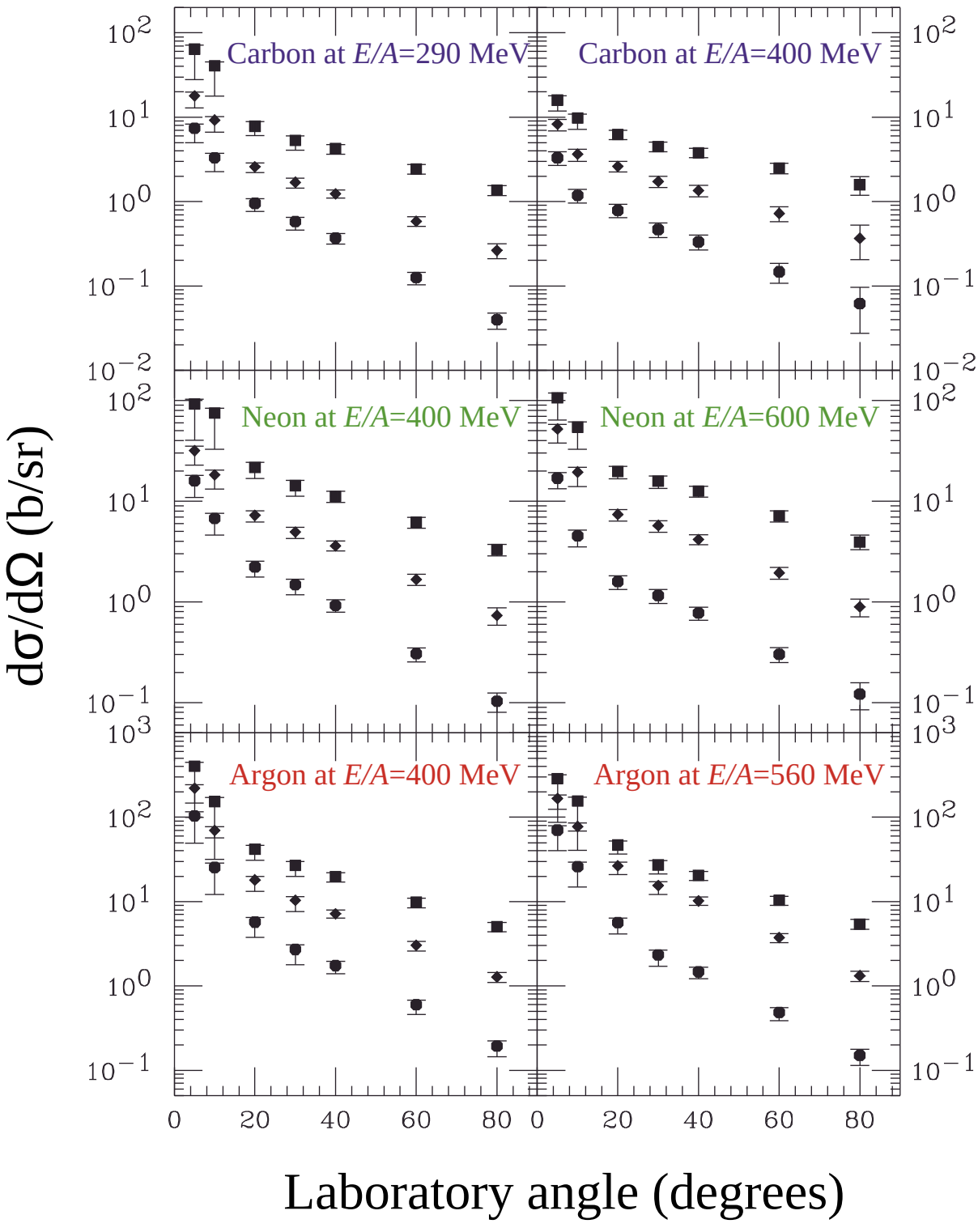
  - Pre-equilibrium and equilibrium component

$$\frac{d^2N}{p_n^2 dp_n d\Omega} = N(2\pi mT)^{-3/2} e^{-(p_x^2/2mT)}$$

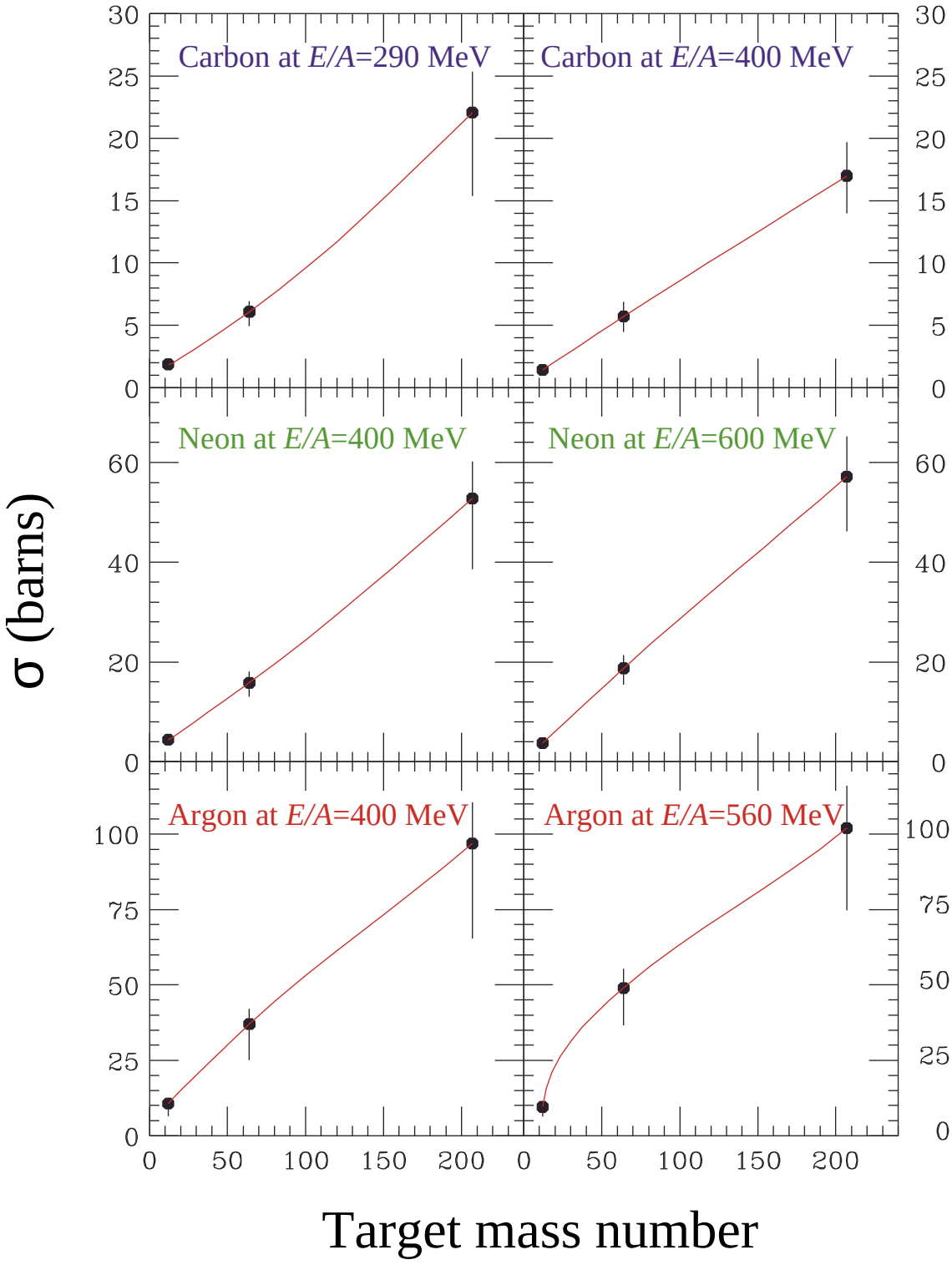
  - The energy distribution in the lab

$$\frac{d^2N}{dE_n d\Omega} = \sum^{3} p_n^{lab} E_n \frac{d^2N}{p_n^2 dp_n d\Omega}$$

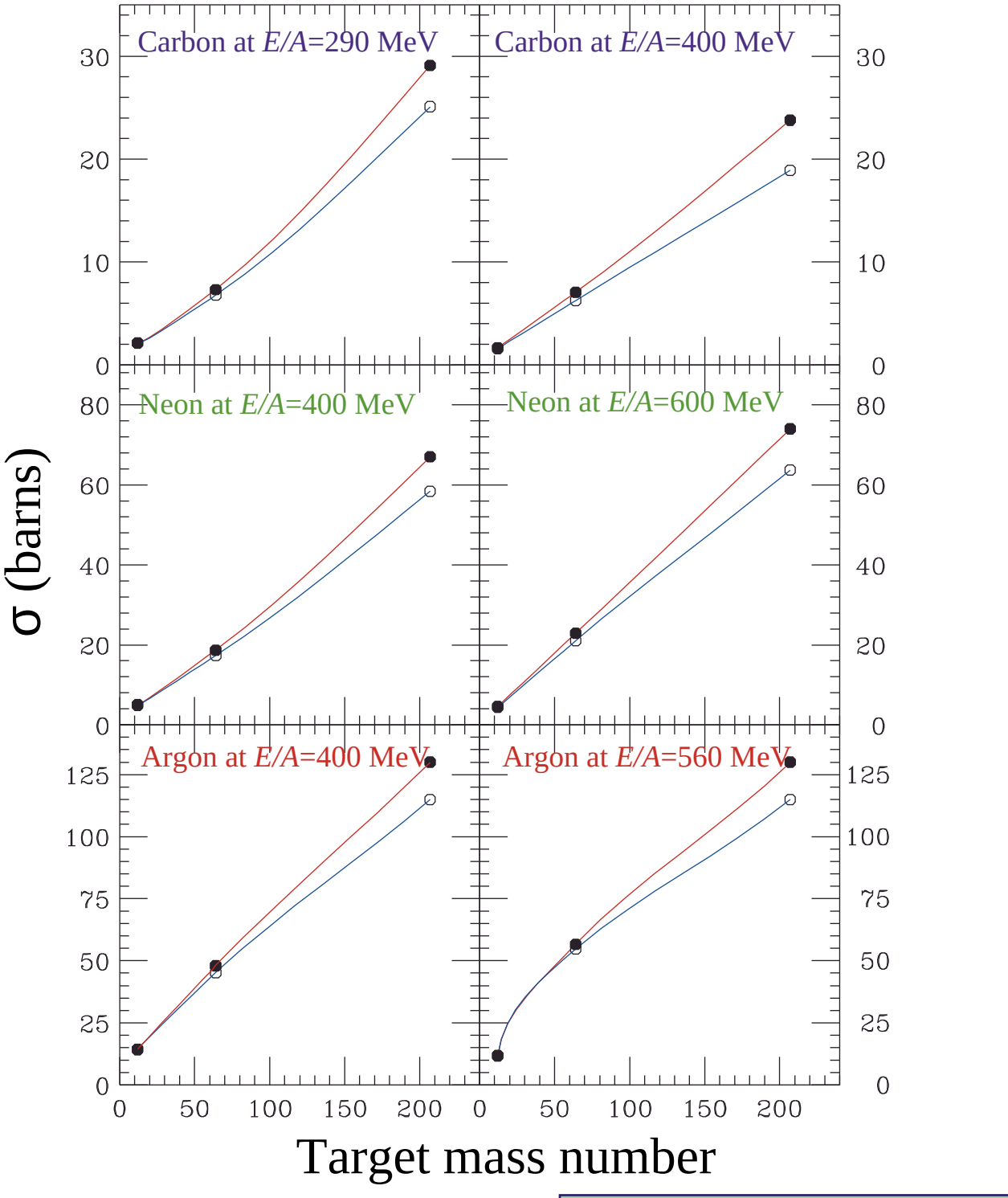
$$E_n = \gamma_{c.m.}(E_n^{lab} - \beta_{c.m.} p_n^{lab} \cos\theta^{lab})$$


Carbon at E/A=290 MeV
Carbon at E/A=400 MeV
Neon at E/A=400 MeV
Neon at E/A=600 MeV
Argon at E/A=400 MeV
Argon at E/A=560 MeV
dσ/dΩ (b/sr)
Laboratory angle (degrees)
0
20
40
60
80
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}

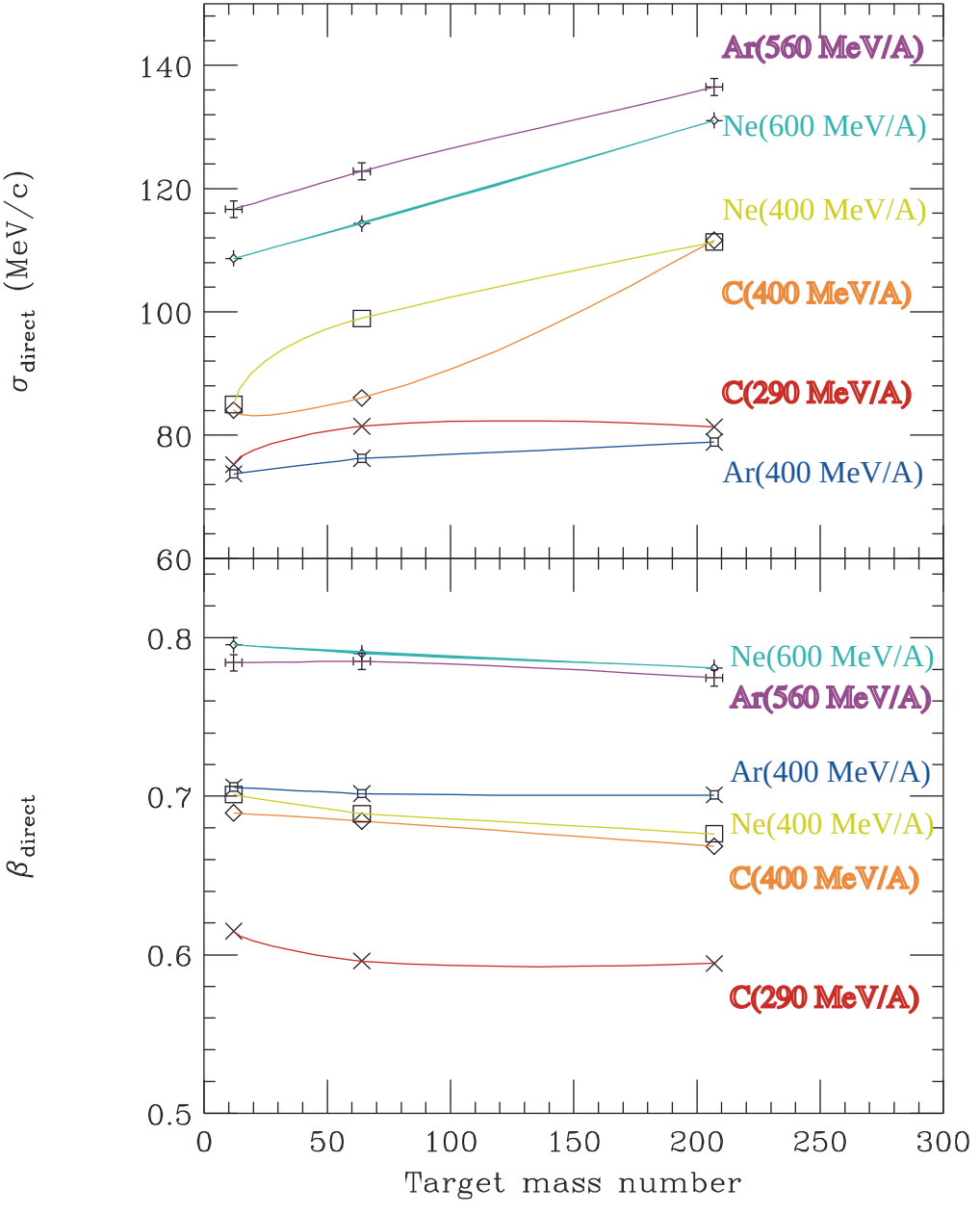
Total cross sections (θ=5 80 degrees)



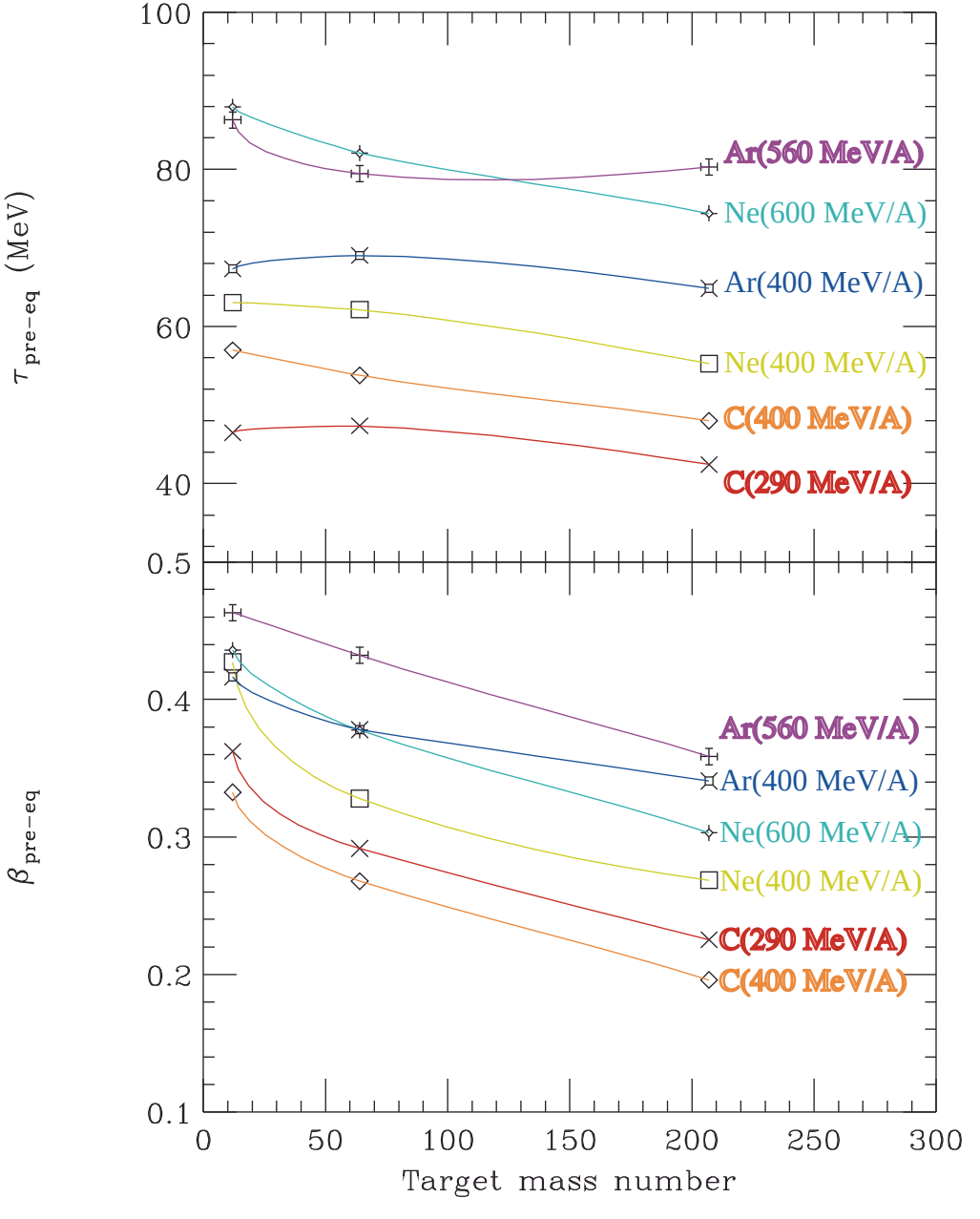
Total cross sections



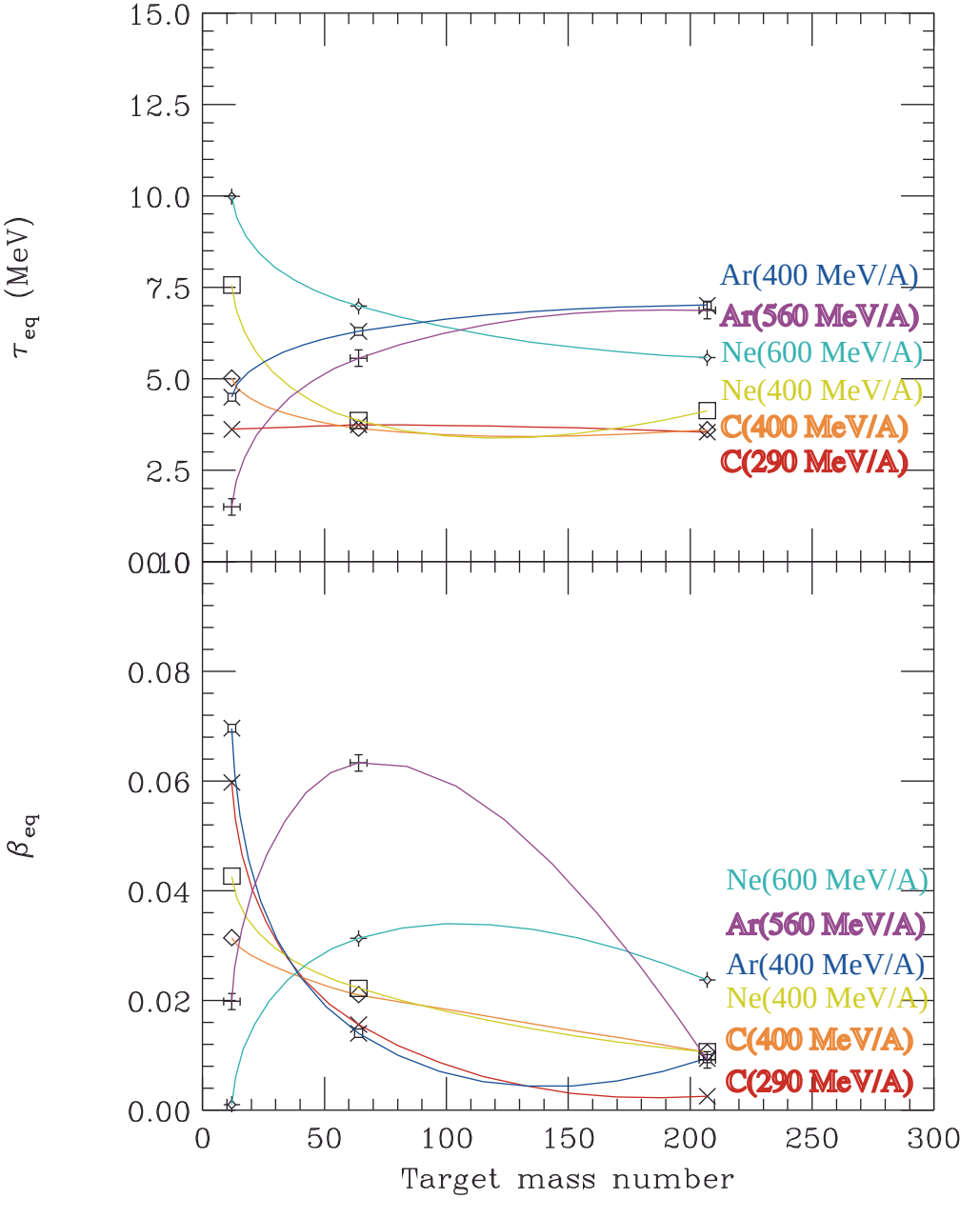
Direct component



Pre-equilibrium component

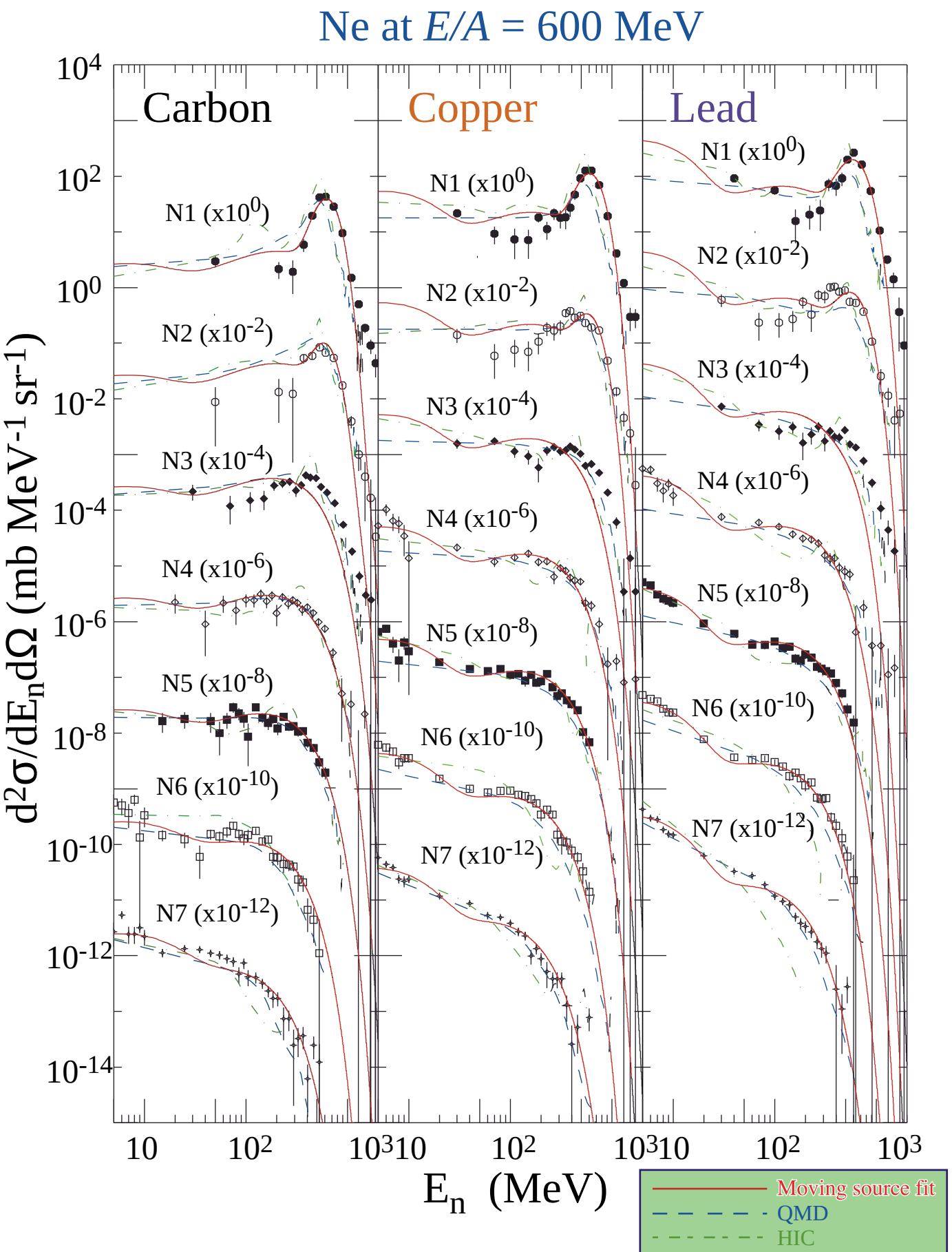


Equilibrium component



Comparison with the models

- Quantum Molecular Dynamics (QMD)
  - J. Aichelin (1991)
- Heavy Ion Code (HIC)
  - H.W. Bertini *et al.* (1974)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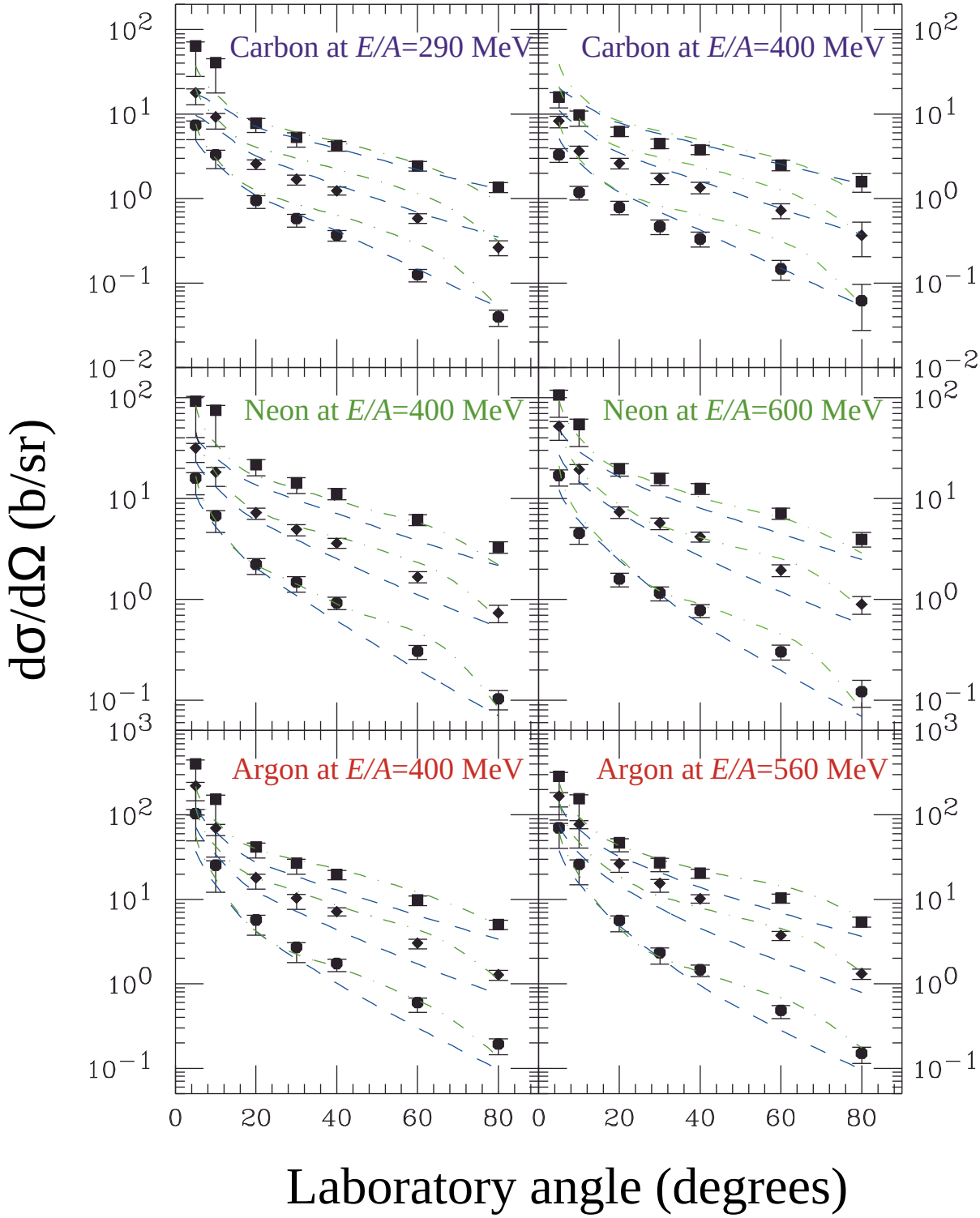
N6 (x10^-10)
N7 (x10^-12)
d²σ/dE_n dΩ (mb MeV^-1 sr^-1)
E_n (MeV)
Moving source fit
QMD
HIC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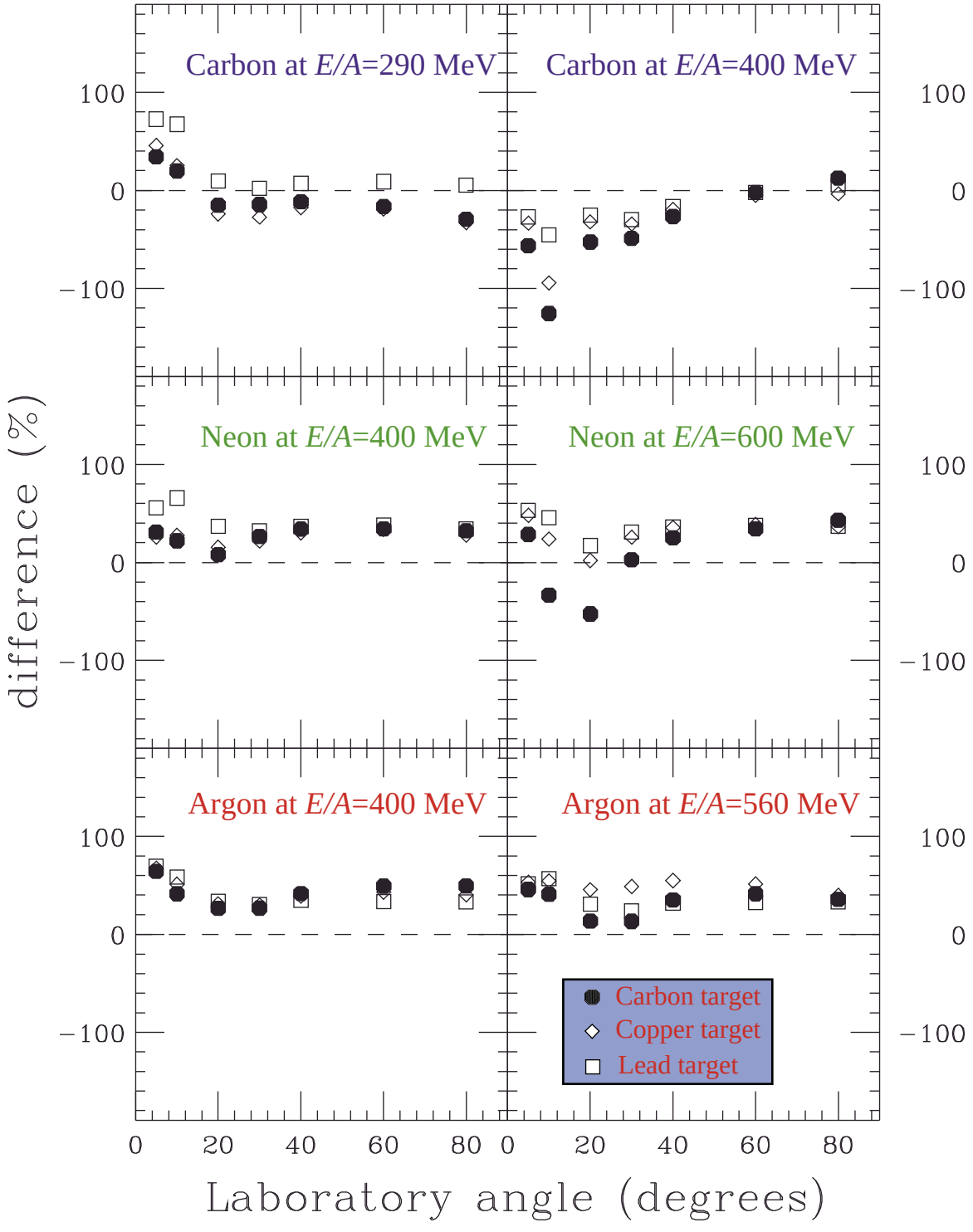
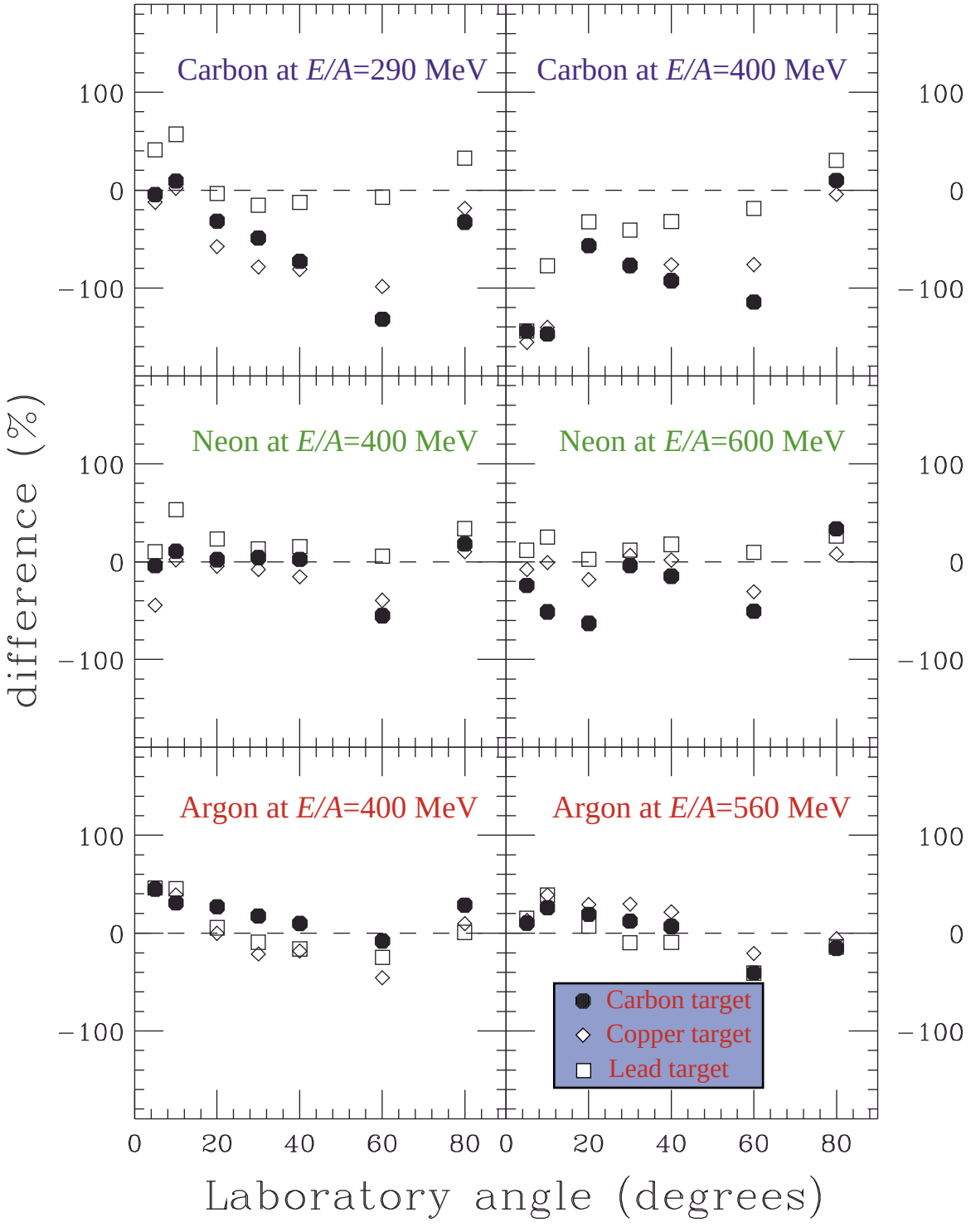
Neon at E/A=600 MeV
Argon at E/A=400 MeV
Argon at E/A=560 MeV
dσ/dΩ (b/sr)
Laboratory angle (degrees)
QMD
HIC

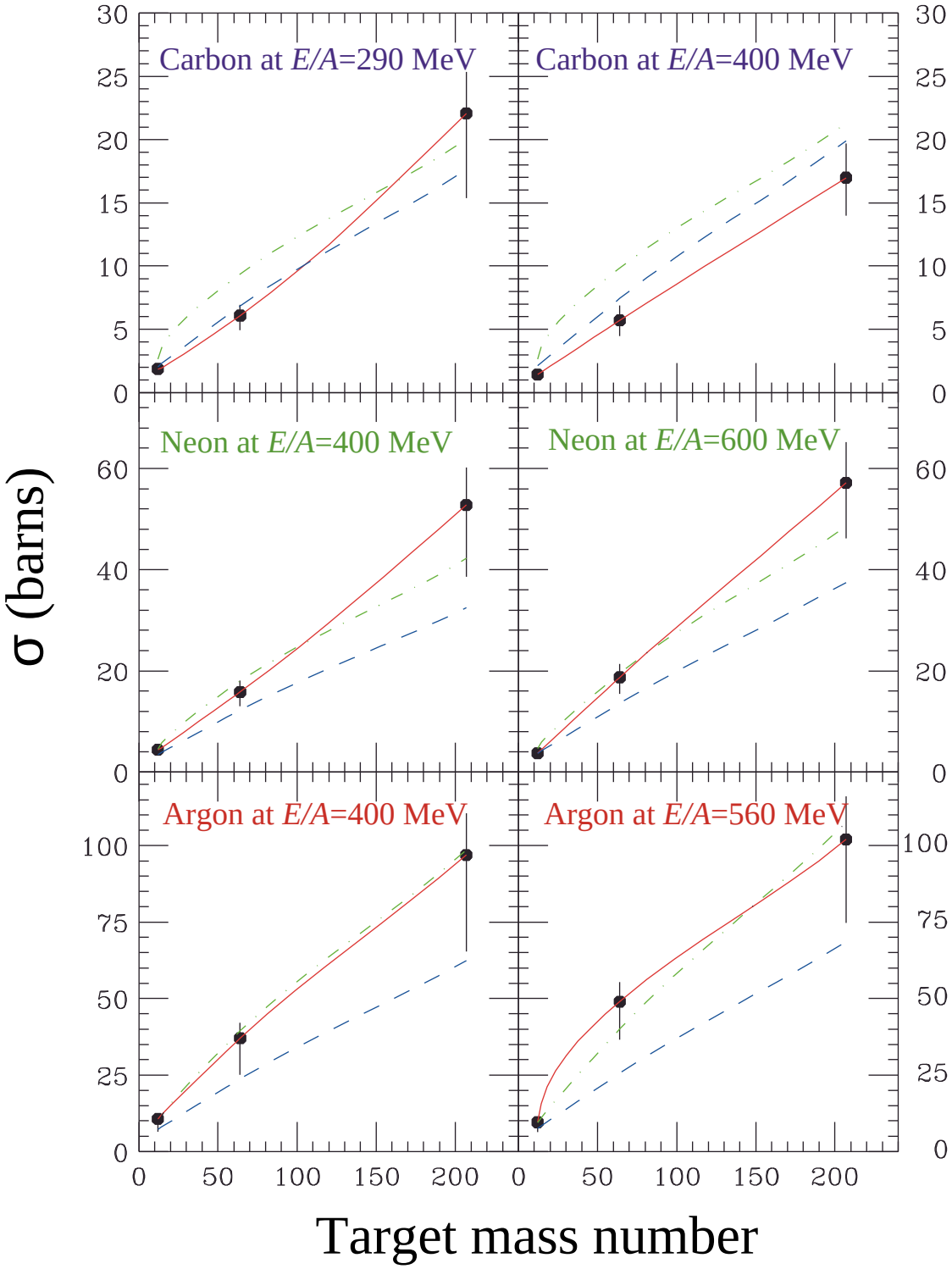
Comparison with QMD simulation



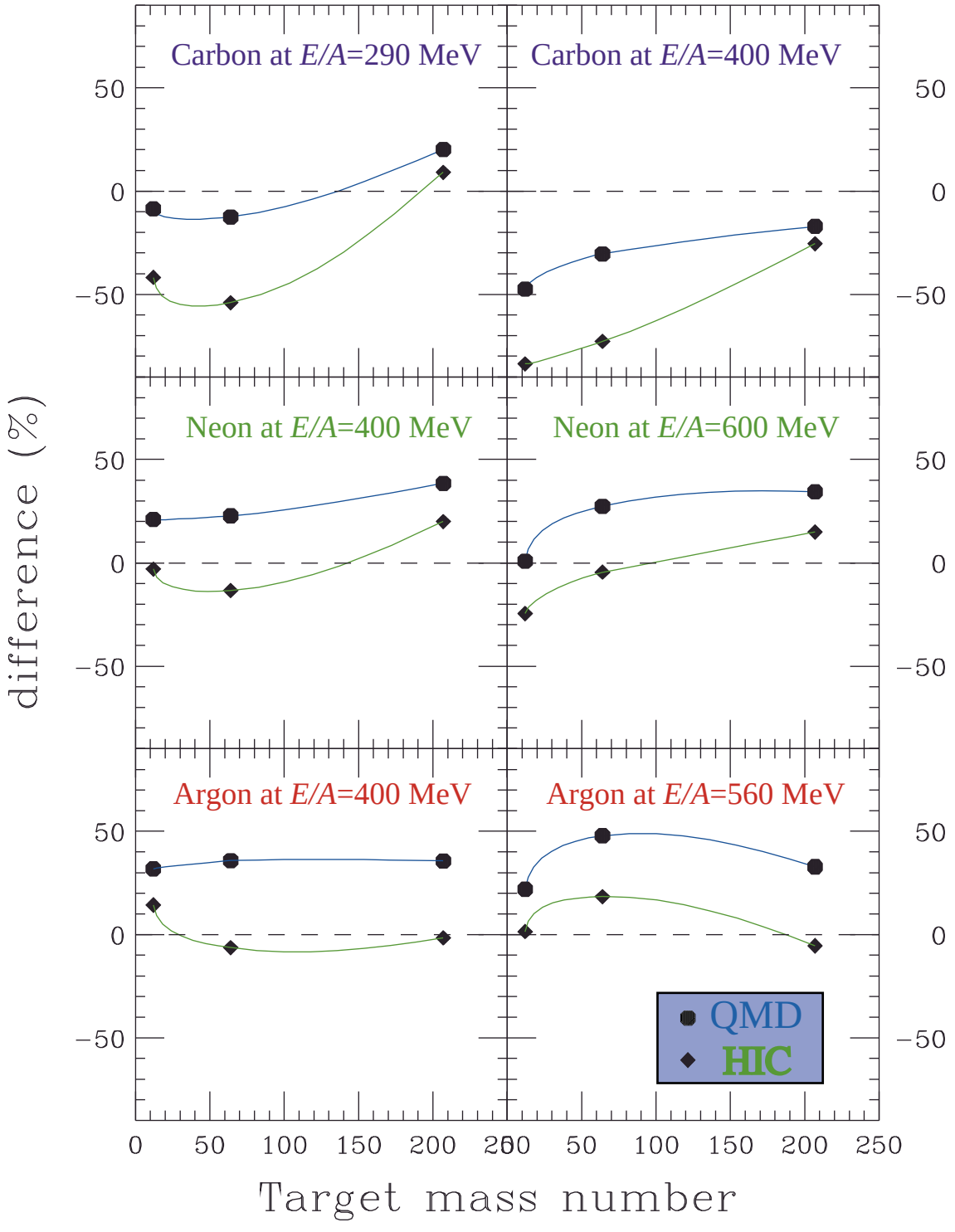
Comparison with HIC simulation



Total cross sections (θ=5 80 degrees)



Comparison with the simulations



Summary

- Systematic measurements
- Moving source fit
  - Reproduce well
- Comparison with the models
  - QMD
    - Systematic underestimation
  - HIC
    - Heavy projectile and target
- Further study
  - Xe at E/A = 400 MeV (in progress)
  - He at E/A = 230 MeV
  - Si at E/A = 290 - 800 MeV