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QMD Approach to Spallation Reactions

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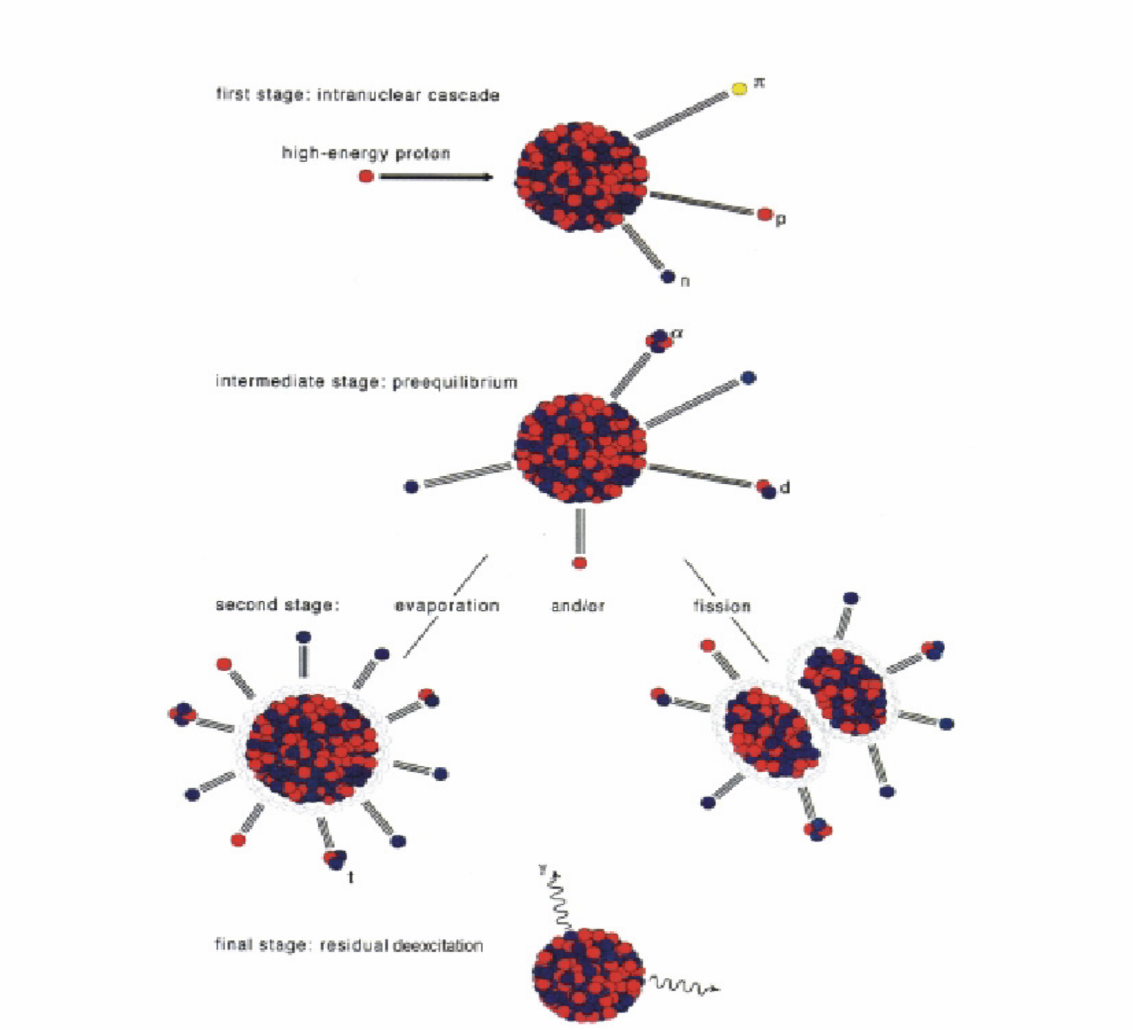
QMD APPROACH TO SPALLATION REACTIONS



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Spallation Reactions

- Projectile splits the target nucleus into multiple fragments
- Emission of large number of neutrons

Applications

- Accelerator driven transmutation.
- Production of U-233 from thorium
- Accelerator driven sub-critical system for power production.
- Material science studies.

We need to estimate:

- **Neutron yield distribution** (energy and angular)
- Neutron cost =

(Neutron yield per projectile)/(Projectile energy in GeV)

- **Production cross section of fragments**

Generally,

Intra-nuclear cascade (INC) models used.

In INC incorporation of pre-equilibrium stage is not done in a self-consistent way.

We have used, instead,

the Quantum Molecular Dynamics (QMD) approach

followed by a

Statistical Decay Model (SDM)

OBSERVATIONS:

- Non-equilibrium processes do not contribute much (~ 25%) to neutron emission

However, high-energy neutrons are produced through these processes.

- Major contribution to neutron emission is from statistical decay (evaporation+fission) of primary fragments

- SDM is responsible for low energy emission restricted up to about 50 MeV
- The non-equilibrium process (QMD), on the other hand, gives rise to high-energy neutrons with energies extending beyond 400 MeV
- Angular distribution of neutrons is not highly anisotropic

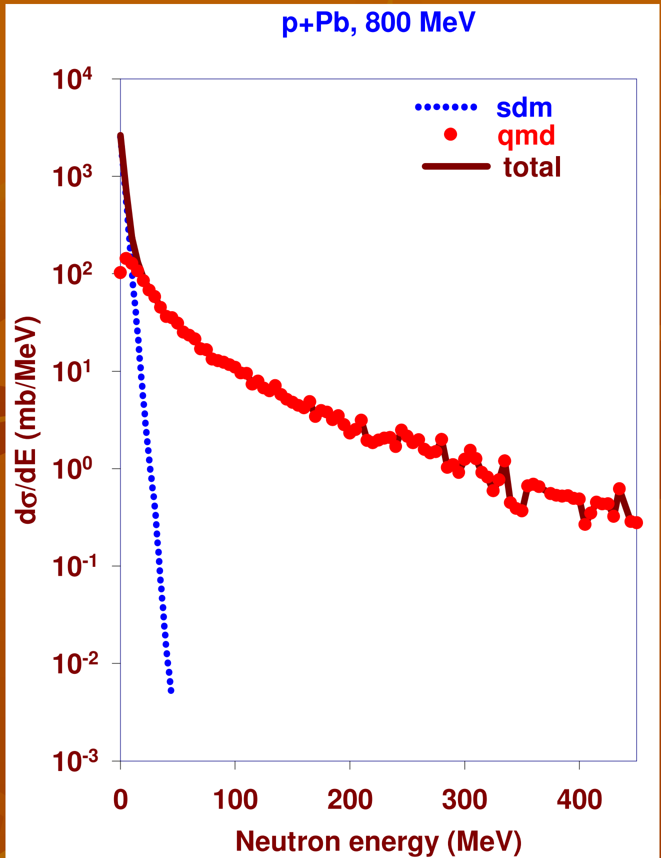
- Production of ***projectile-like*** and ***target-like*** fragments is high
- Calculated neutron multiplicity distribution shows under prediction at low multiplicity at high incident energies
- Radioactive gases like tritium, xenon and krypton are produced in significant quantities.
- Several other long-lived radio-nuclides are also produced

Saturation activities of the following radio-nuclides produced will be about 10^{11} dps for 1 mA proton on 1 mm thick Pb:

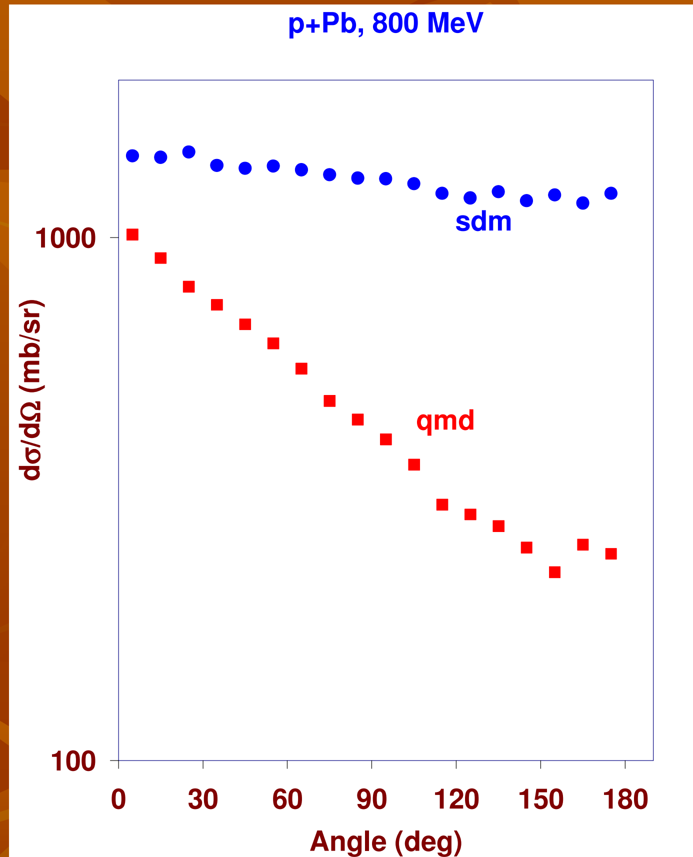
^{32}Si (*172 y*), ^{35}S (*87.5 d*), ^{49}V (*330 d*), ^{54}Mn (*312.2 d*), ^{55}Fe (*2.7 y*), ^{60}Co (*5.6 y*), ^{65}Zn (*244 d*), ^{88}Zr (*83.4* d), ^{90}Zr (*1.53x10^{6} y*), ^{91}Nb (*6.8x10^{2} y, 60.86 d*), ^{99}Mo (*65.94 h*), ^{106}Ru (*368 d*), ^{109}Cd (*462.6 d*), ^{139}Ce (*137.5 d*), ^{159}Dy (*144.4d*)

***Table 1*. Average neutron multiplicity and kinetic energy carried out (800 MeV p on Pb).**

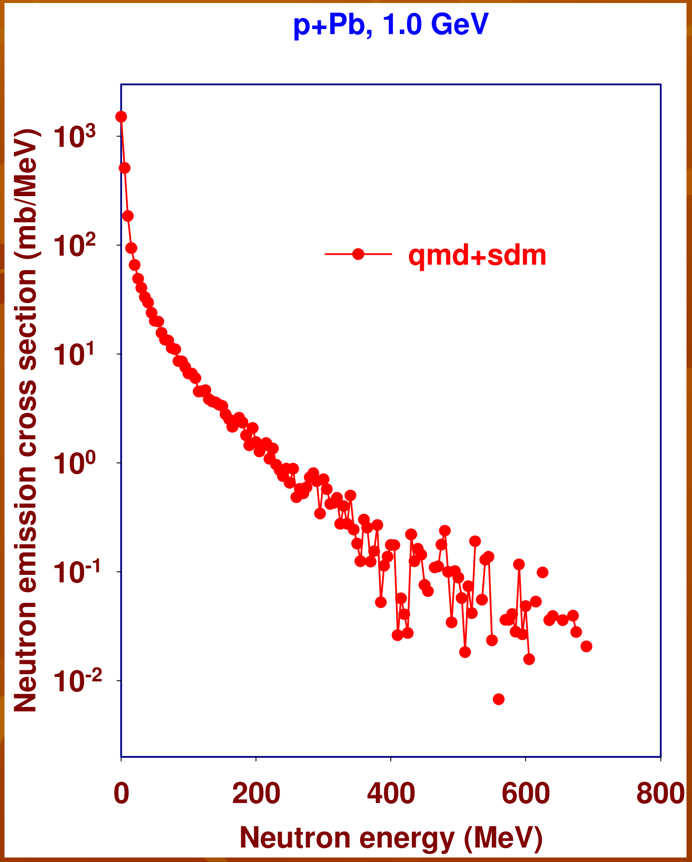
	Emission energy (MeV)		
	0-2	2-20	20-E_{inc}
M^{QMD}	4.48	7.59	2.26
M^{exp}		6.5 ± 0.7	1.9 ± 0.2
M^{INCL}	4.9	6.9	2.2
M^{BPQ}	5.2	7.1	2.1
$E \times M^{QMD}$	4.65	46.17	187.57
$E \times M^{exp}$		38 ± 4	200 ± 20
$E \times M^{INCL}$	5	42	211
$E \times M^{BPQ}$	5	42	224

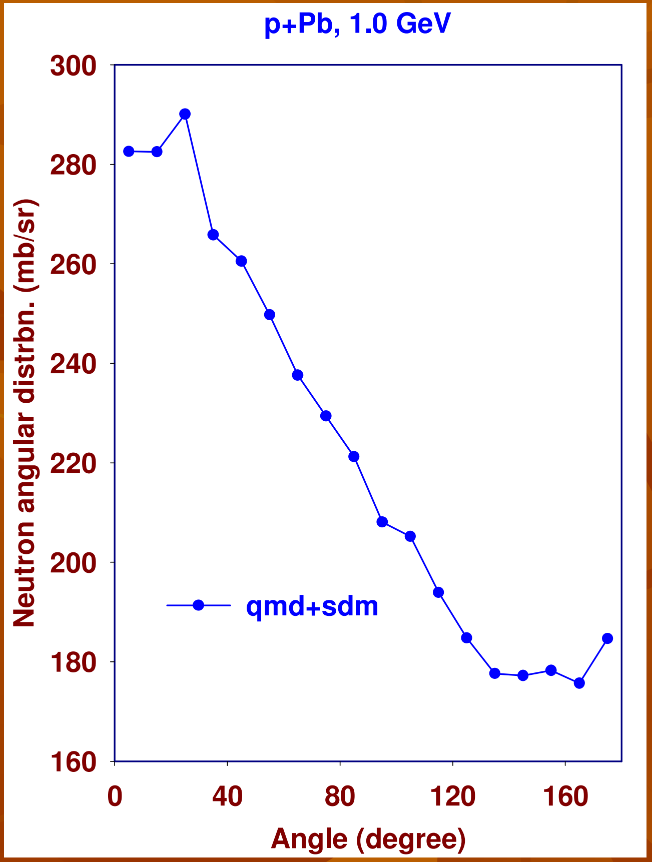


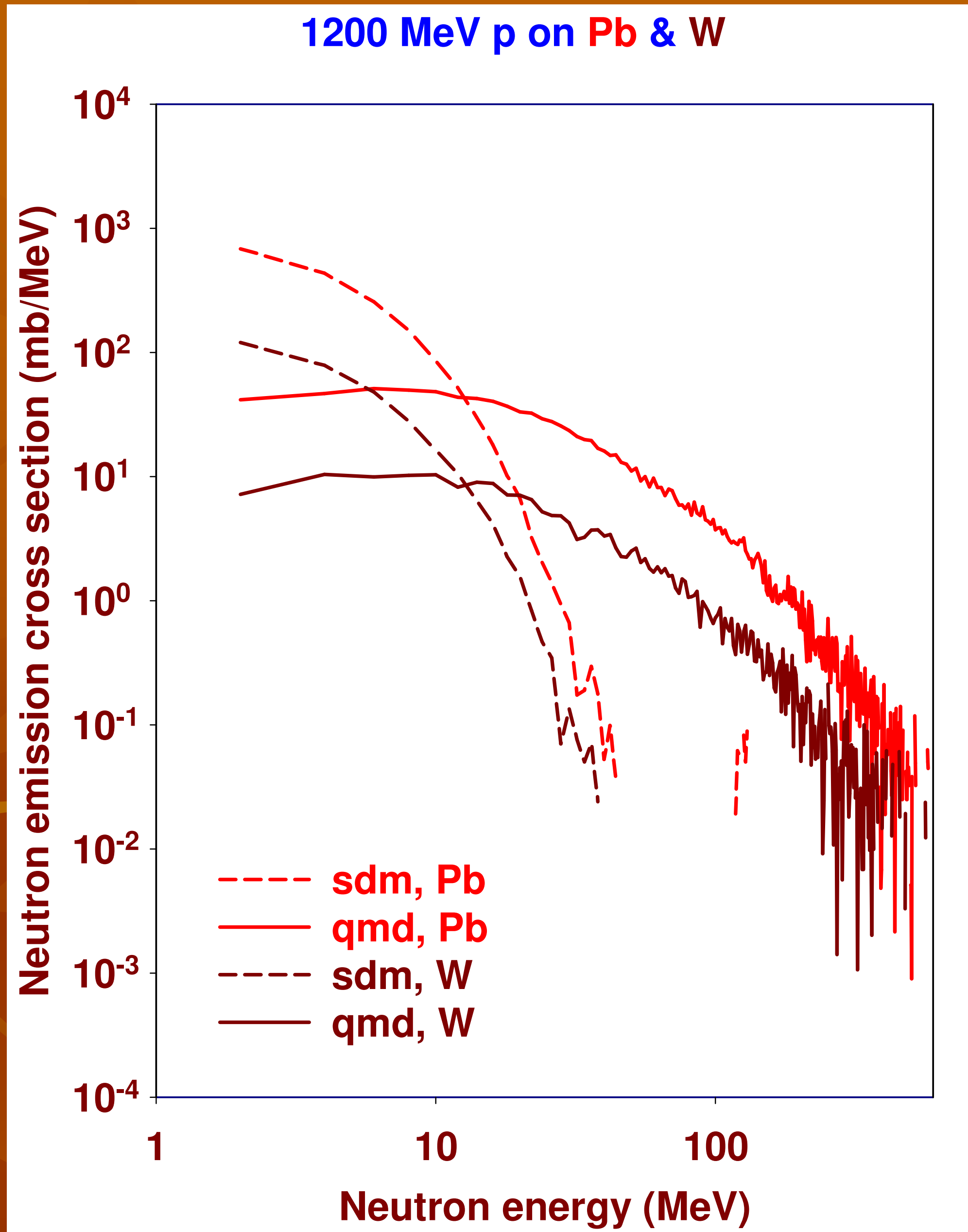
p+Pb, 800 MeV
sdm
qmd
total
dσ/dE (mb/MeV)
10⁴
10³
10²
10¹
10⁰
10⁻¹
10⁻²
10⁻³
0
100
200
300
400
Neutron energy (MeV)



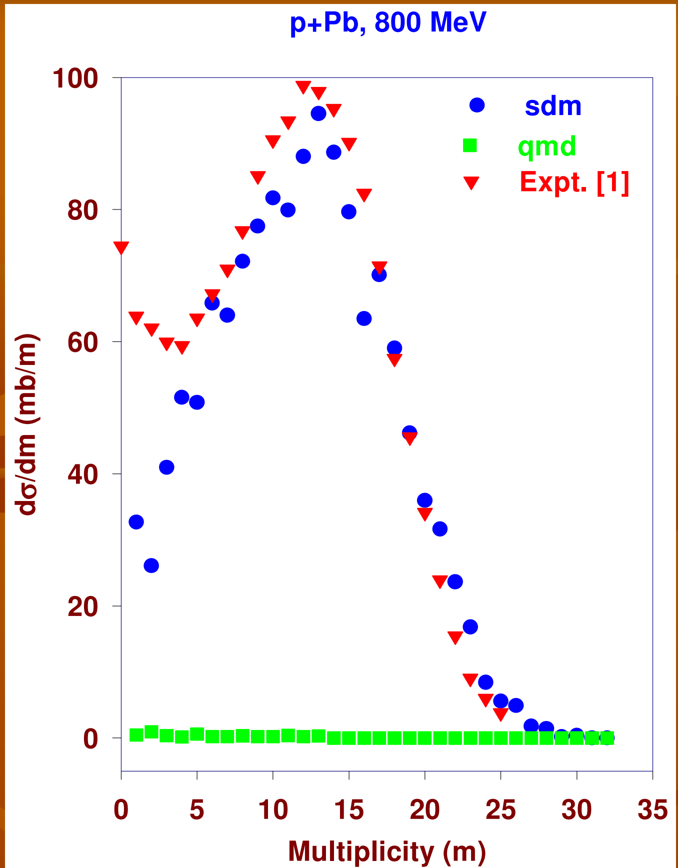
p+Pb, 800 MeV
sdm
qmd
dσ/dΩ (mb/sr)
1000
100
0
30
60
90
120
150
180
Angle (deg)


p+Pb, 1.0 GeV
qmd+sdm
Neutron emission cross section (mb/MeV)
Neutron energy (MeV)
0
200
400
600
800
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}

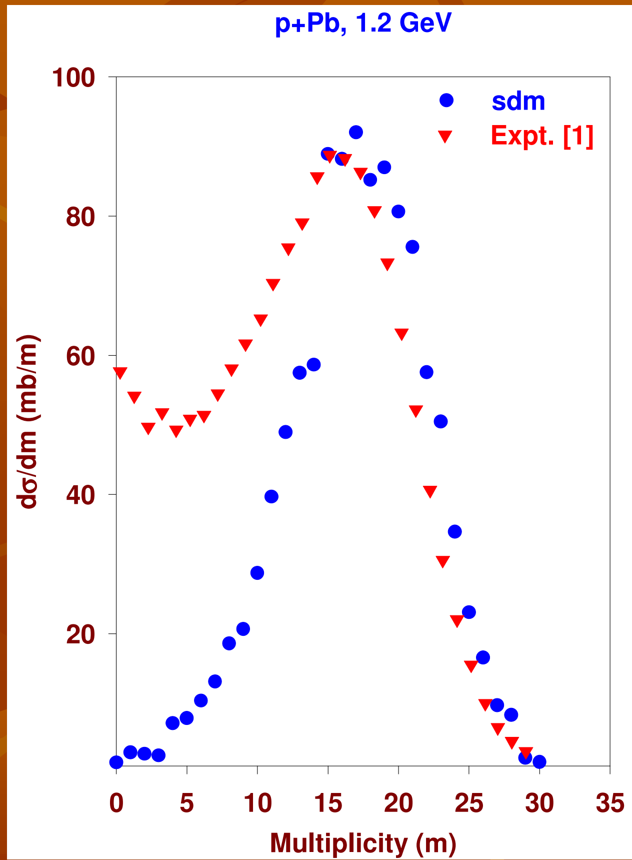

p+Pb, 1.0 GeV
qmd+sdm
Neutron angular distrbn. (mb/sr)
Angle (degree)
0
40
80
120
160
160
180
200
220
240
260
280
300



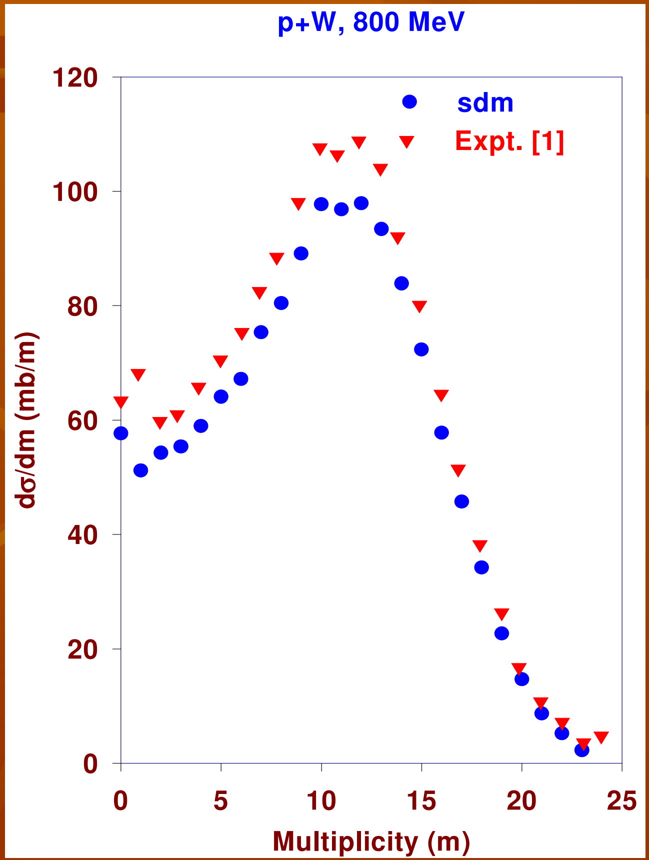
1200 MeV p on Pb & W
Neutron emission cross section (mb/MeV)
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
1
10
100
Neutron energy (MeV)
sdm, Pb
qmd, Pb
sdm, W
qmd, W

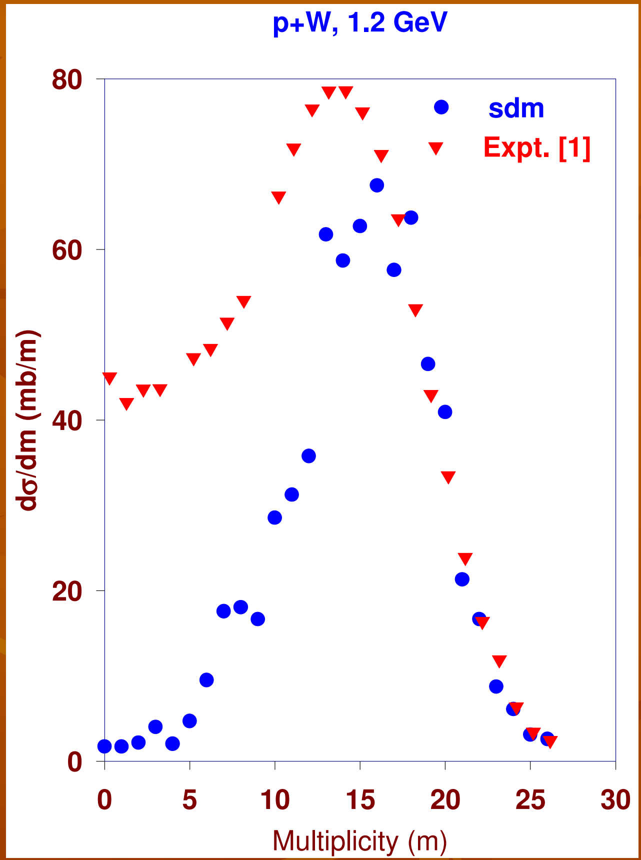


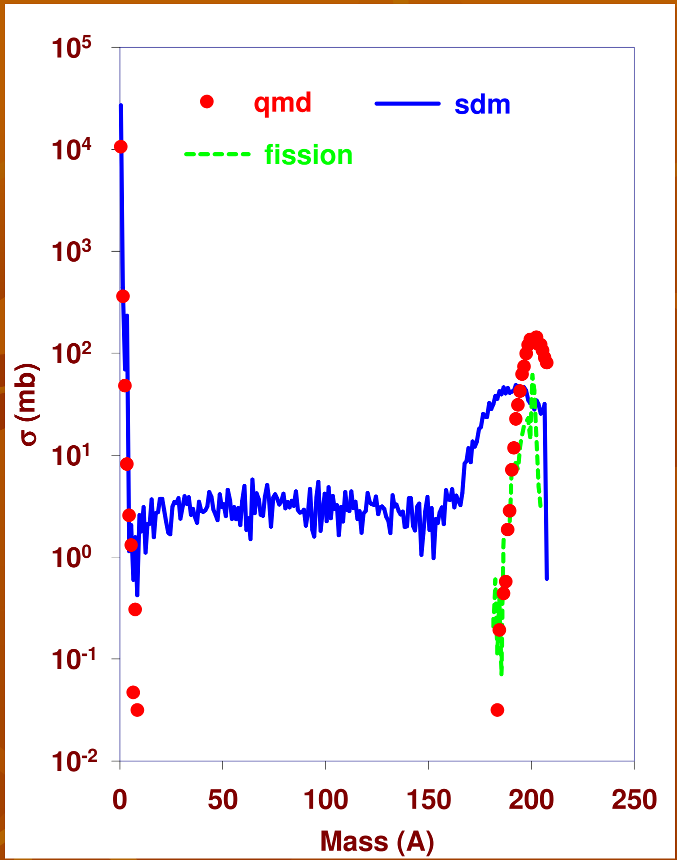
p+Pb, 800 MeV
sdm
qmd
Expt. [1]
dσ/dm (mb/m)
Multiplicity (m)
0
20
40
60
80
100
0
5
10
15
20
25
30
35

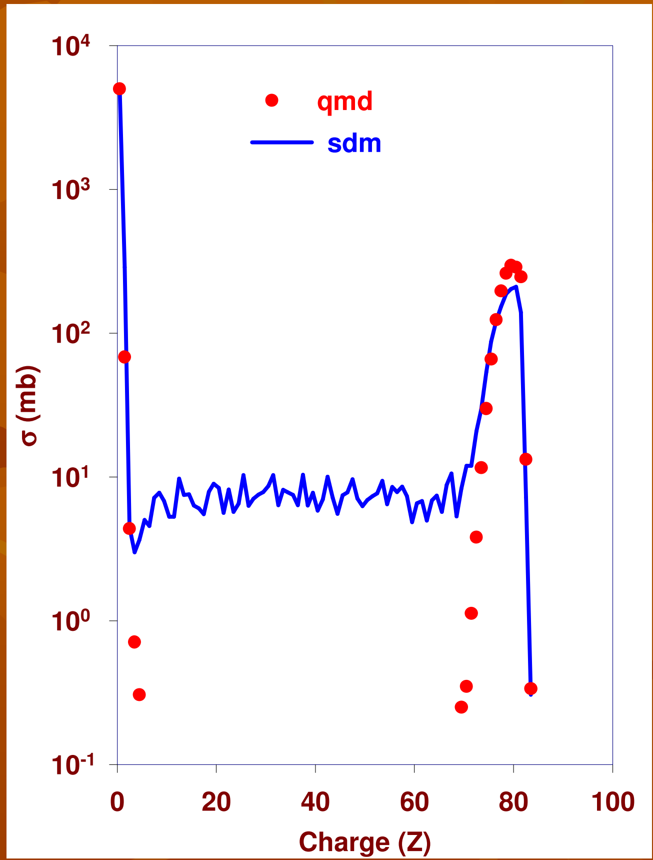


p+Pb, 1.2 GeV
sdm
Expt. [1]
dσ/dm (mb/m)
Multiplicity (m)
20
40
60
80
100
0
5
10
15
20
25
30
35

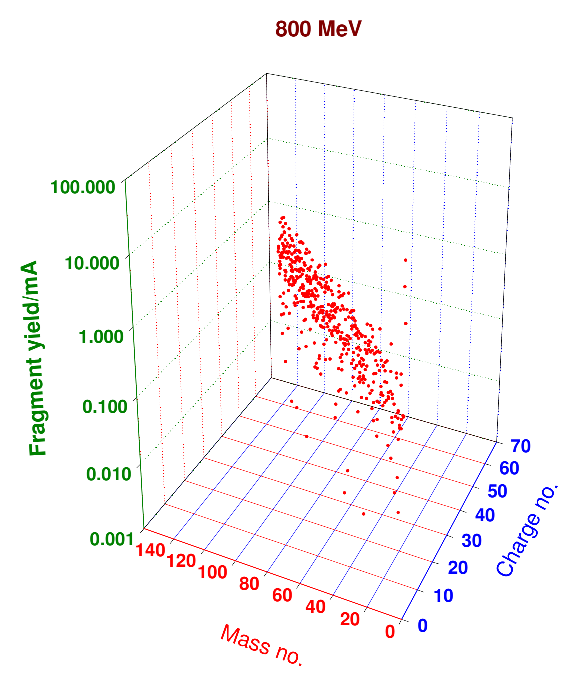

p+W, 800 MeV
dσ/dm (mb/m)
Multiplicity (m)
sdm
Expt. [1]
0
20
40
60
80
100
120
0
5
10
15
20
25

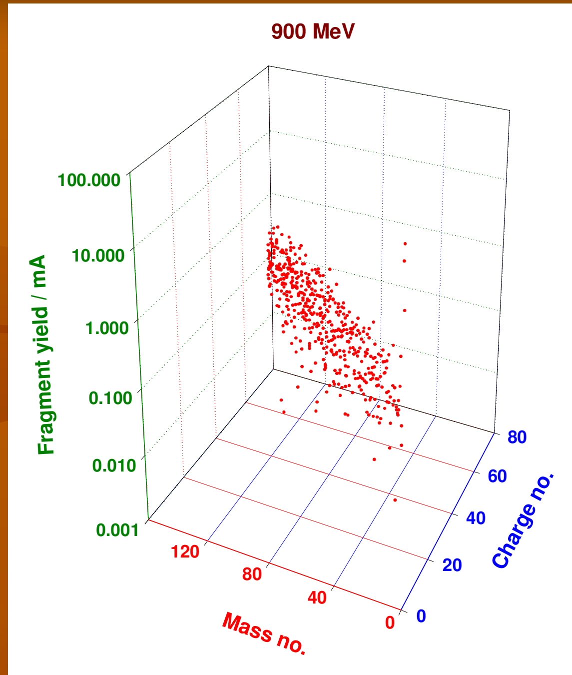

p+W, 1.2 GeV
dσ/dm (mb/m)
Multiplicity (m)
sdm
Expt. [1]
0
20
40
60
80
0
5
10
15
20
25
30

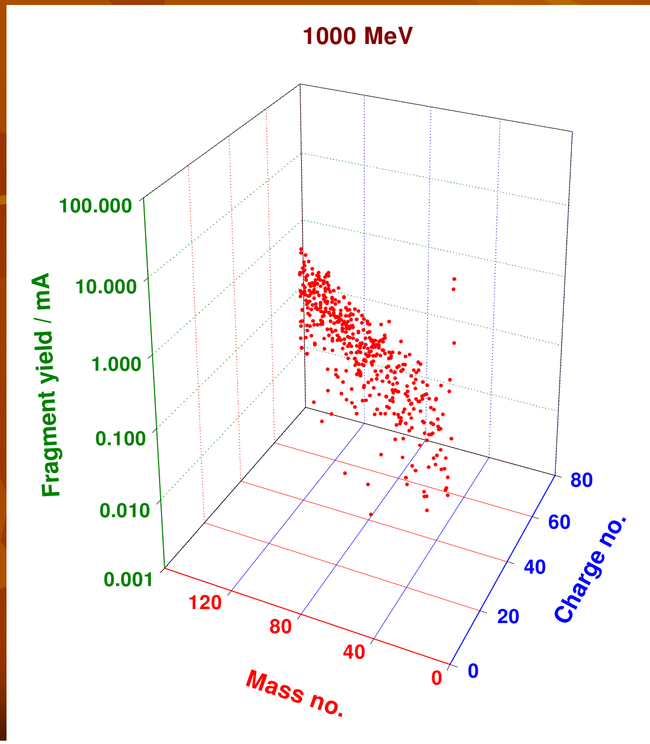

qmd
sdm
fission
σ (mb)
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
0
50
100
150
200
250
Mass (A)


qmd
sdm
σ (mb)
10^4
10^3
10^2
10^1
10^0
10^-1
0
20
40
60
80
100
Charge (Z)

p+ Pb, 800 MeV


800 MeV
Fragment yield/mA
100.000
10.000
1.000
0.100
0.010
0.001
140
120
100
80
60
40
20
0
Mass no.
70
60
50
40
30
20
10
0
Charge no.


900 MeV
Fragment yield / mA
100.000
10.000
1.000
0.100
0.010
0.001
120
80
40
0
Mass no.
80
60
40
20
0
Charge no.


1000 MeV
Fragment yield / mA
100.000
10.000
1.000
0.100
0.010
0.001
120
80
40
0
Mass no.
80
60
40
20
0
Charge no.