Applications of Monte Carlo method in Spallation Physics

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Introduction of spallation reaction mechanism

Physics Models

Intra-nuclear cascade model

Pre-equilibrium (exciton model)

Evaporation (Generalized Evaporation Model)

Fission model (Fong's Model)

Realization of the physics models in real problem

Define Geometry

Ionization loss

Tracing till stop/exit

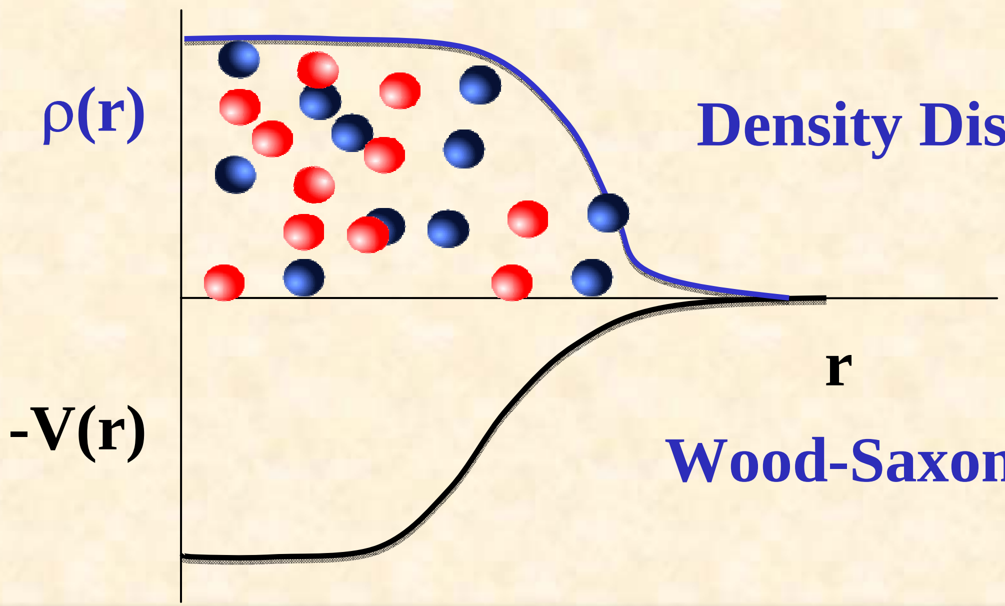
Intra-Nuclear Cascade model

What are the inputs we have?

Projectile: **Charge, mass, energy/momentum**

Target: **Charge, mass, nucleon density distribution**

Each nucleon is assigned position & momentum Using Random Numbers



Density Distribution

Wood-Saxon potential

$$\left\{ \begin{array}{ll} \rho(r) = \frac{\rho_0}{1+exp\frac{(r-r_0)}{a}} & \\ \text{where} & r_0 = 1.07A^{1/3}fm \\ a = 0.545fm & \text{For A} > 10 \\ \rho(r) = \rho_0 exp\frac{-r^2}{R^2} & \text{For A} \leq 10 \end{array} \right\}$$

$$\left\{ \begin{array}{l} P_F(r) = (\frac{3\pi^2\rho(r)}{2})^{1/3} \\ E_F(r) = \hbar^2\frac{(3\pi^2\rho(r))^{2/3}}{2m_N} \end{array} \right\}$$

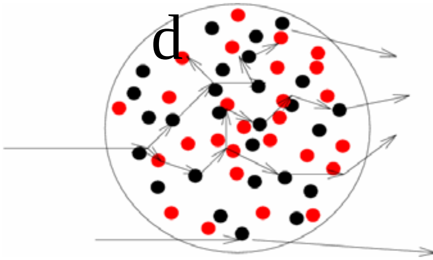
$$\left\{ \begin{array}{l} V \equiv V_N = E_F + \text{Bindinging energy} \\ V_\pi = 25\text{MeV} \end{array} \right\}$$

Quasi free scattering

$\bar{\lambda} << d$

$\bar{\lambda} << \Lambda$

λ=de-Broglie wavelength
d=distance between two nucleon
L=mean free path inside nucleus



Drawback of this theory

It is not self consistent theory

It is based on experimental knowledge

$$NN \to NN, \quad NN \to \pi NN, \quad NN \to \pi_1, \cdots, \pi_i NN$$
$$\pi N \to \pi N, \quad \pi N \to \pi_1, \cdots, \pi_i N \quad (i \geq 2)$$

Reactions

$$\begin{cases} cos(\theta) = 2\xi^{1/2}[\sum_{n=0}^{N} a_n \xi^n + (1 - \sum_{n=0}^{N} a_n)\xi^{N+1}] - 1 \\ a_n = \sum_{k=0}^{N} a_{nk} E^k \\ \text{N=3, M=3} \end{cases}$$

Angular distribution

Cross-section

$p + p = p + p$	Isotropic E $<$ 0.46 GeV
$p + p = p + p$	0.46 $<$ E $<$ 2.8 GeV
$p + p = p + p$	2.8 $<$ E $<$ 10.0 GeV
$p + n = p + n$	E $<$ 0.97 GeV
$\pi^+ + p = \pi^+ + p$	E $<$ 80.0 MeV
$\pi^+ + p = \pi^+ + p$	80 $<$ E $<$ 300.0 MeV
$\pi^+ + p = \pi^+ + p$	0.3 $<$ E $<$ 1.0 GeV
$\pi^+ + p = \pi^+ + p$	1.0 $<$ E $<$ 2.4 GeV

Pre-equilibrium model (Exciton model)

Cut off energy (7 MeV) is the criteria to close INC

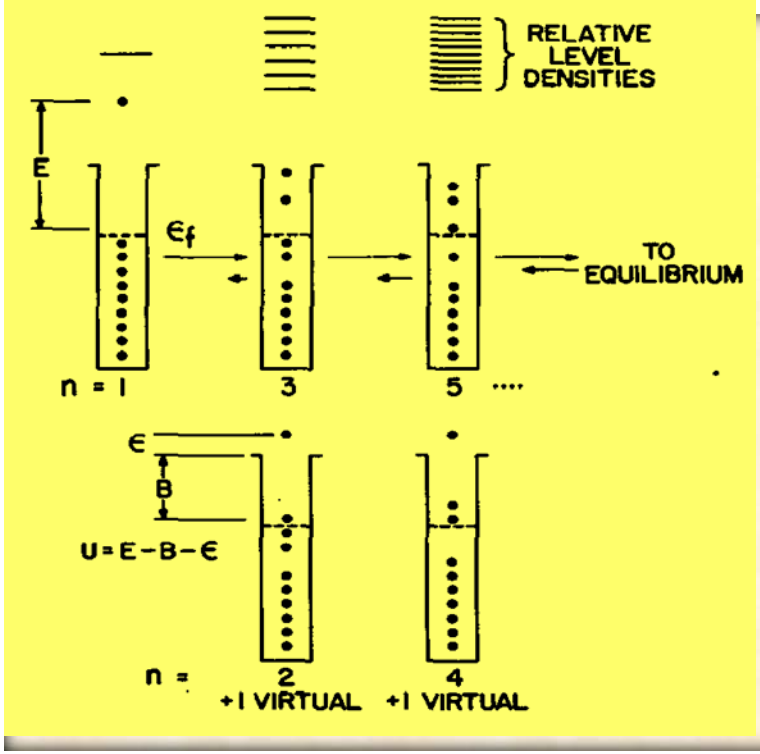
n, p, d, t, ^{3}He, and ^{4}He emission

Probability of emission is calculated as given below

$$\Gamma_j(p,h,E) = \int_{V_j^c}^{E-B_j} \lambda_c^j(p,h,E,T)\,dT \,,$$

$$\lambda_c^j(p,h,E,T) = \frac{2s_j+1}{\pi^2\hbar^3}\mu_j \Re_j(p,h)\frac{\omega(p-1,h,E-B_j-T)}{\omega(p,h,E)}T\sigma_{inv}(T)$$

p=particle, h=hole, n=p+h is exciton number, s=spin, σ_{inv}=cross-section, E=excitation energy, B=binding energy

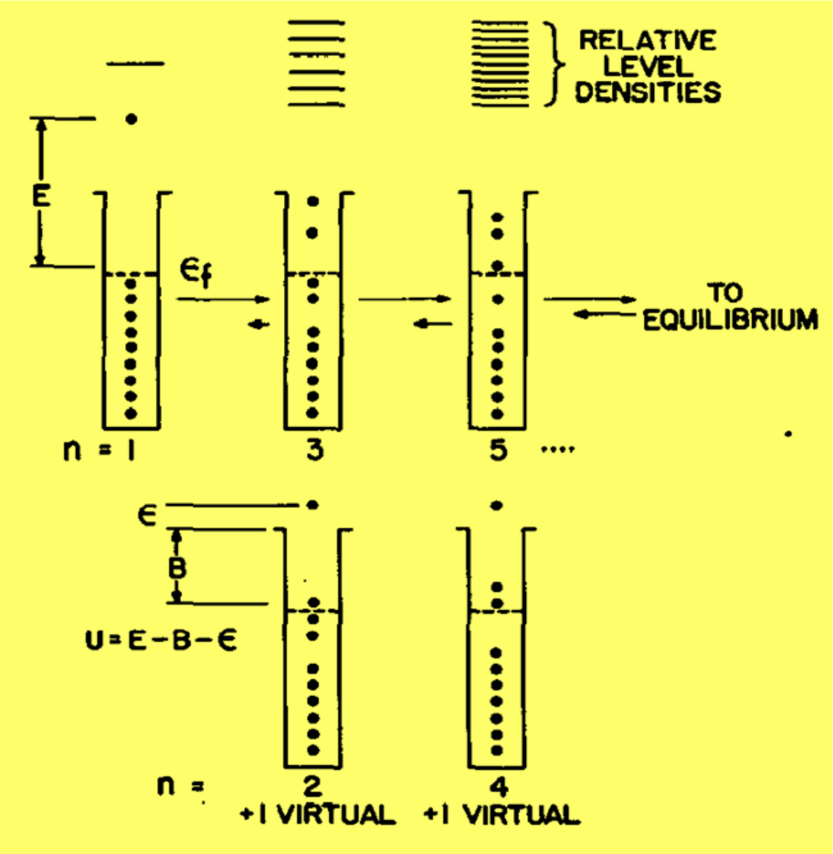


Normalize p, d, t, ^{3}He, and ^{4}He emission **probability to 1**

Generate random number

Select the probable one

How do we reach equilibrium



$$P_j(\epsilon)d\epsilon = g_j \sigma_{inv}(\epsilon) \frac{\rho_d(E-Q-\epsilon)}{\rho_i(E)} \epsilon d\epsilon$$

Z_j	Ejectiles						
0	n						
1	p	d	t				
2	^{3}He	^{4}He	^{6}He	^{8}He			
3	^{6}Li	^{7}Li	^{8}Li	^{9}Li			
4	^{7}Be	^{9}Be	^{10}Be	^{11}Be	^{12}Be		
5	^{8}B	^{10}B	^{11}B	^{12}B	^{13}B		
6	^{10}C	^{11}C	^{12}C	^{13}C	^{14}C	^{15}C	^{16}C
7	^{12}N	^{13}N	^{14}N	^{15}N	^{16}N	^{17}N	
8	^{14}O	^{15}O	^{16}O	^{17}O	^{18}O	^{19}O	^{20}O
9	^{17}F	^{18}F	^{19}F	^{20}F	^{21}F		
10	^{18}Ne	^{19}Ne	^{20}Ne	^{21}Ne	^{22}Ne	^{23}Ne	^{24}Ne
11	^{21}Na	^{22}Na	^{23}Na	^{24}Na	^{25}Na		
12	^{22}Mg	^{23}Mg	^{24}Mg	^{25}Mg	^{26}Mg	^{27}Mg	^{28}Mg

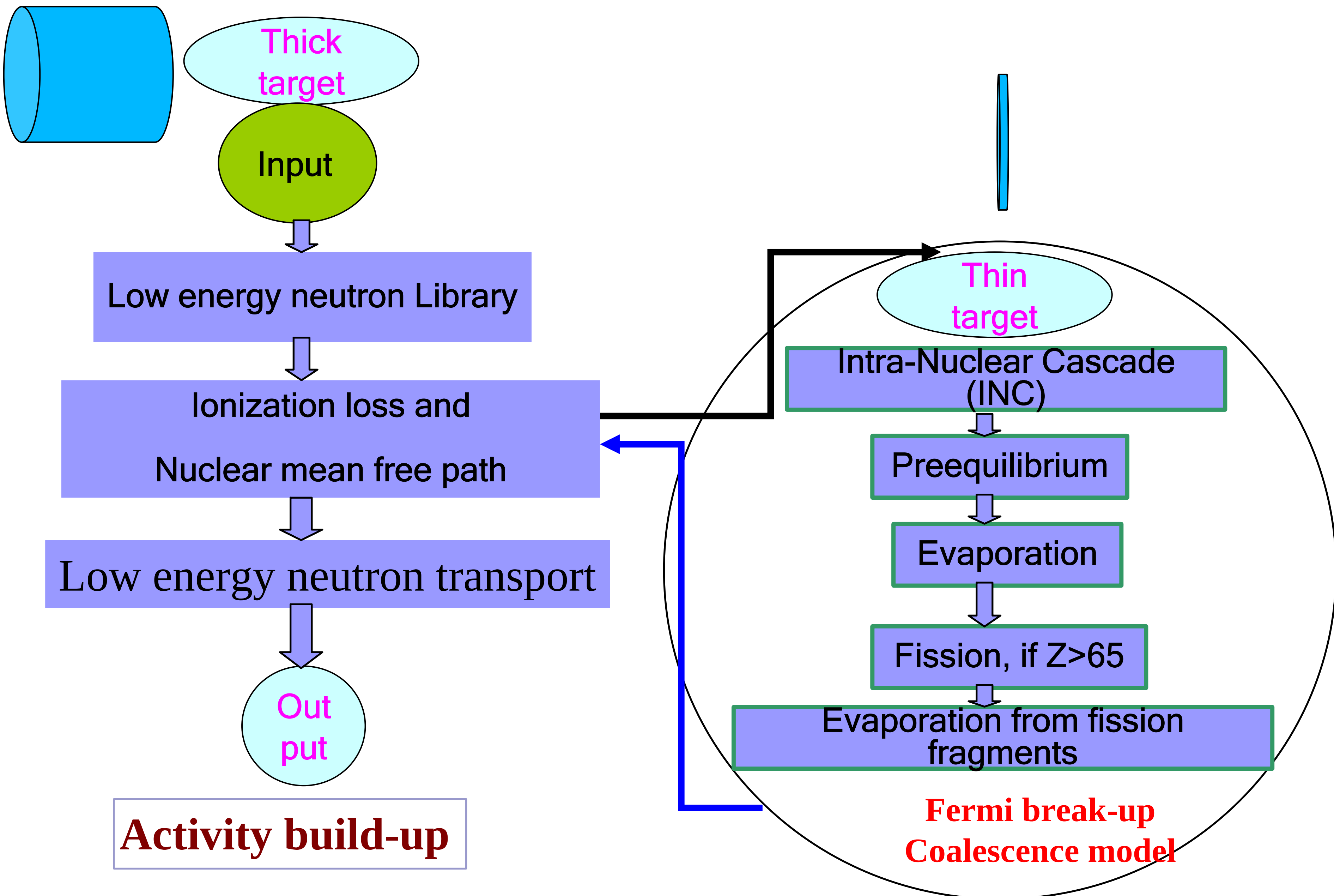
$$\lambda_+(n_{eq}, E) = \lambda_-(n_{eq}, E)$$

$$n_{eq} \simeq \sqrt{2gE}$$

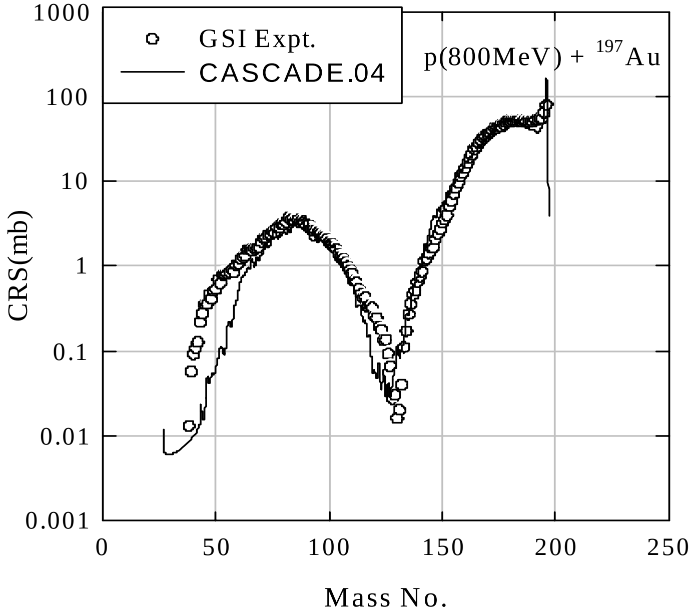
$$\rho(E) = \frac{c_1 exp(2\sqrt{a(E-\delta)})}{a^{1/4}(E-\delta)^{5/4}}$$

$$a(A_d, Z_d, E) = A_d(0.134 - 1.2110^{-04} A_d)(1 + \frac{S}{E}(1 - exp(-0.061E)))$$

CASCADE.04 general scheme



Results, Benchmark



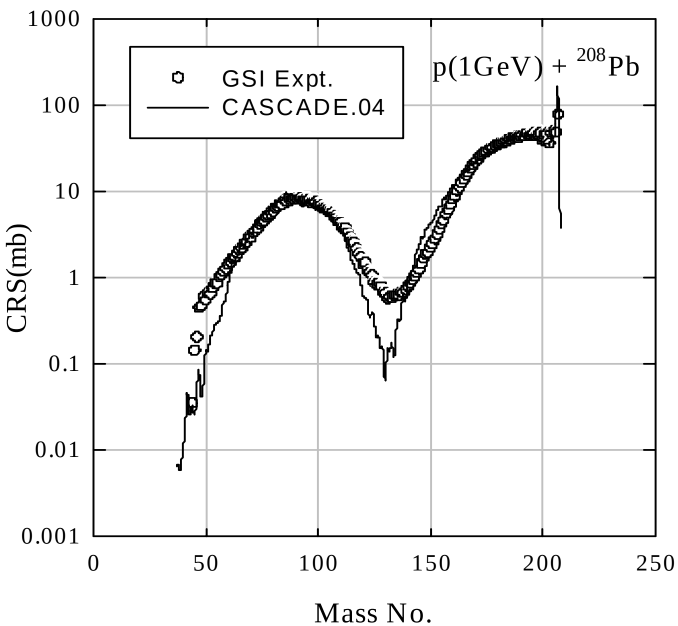
Mass Distributions

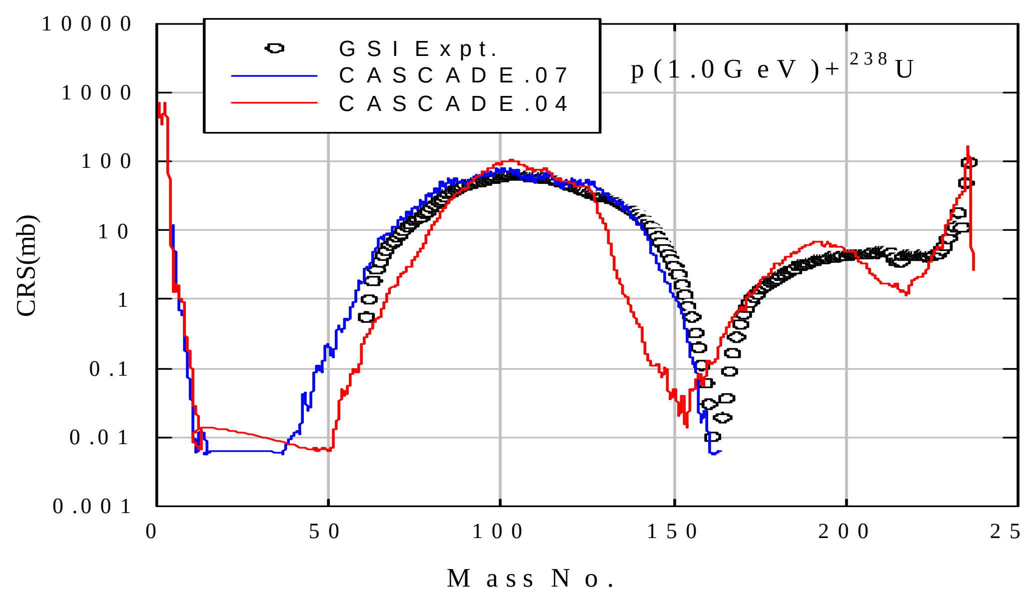
Isotope distribution

Excitation function

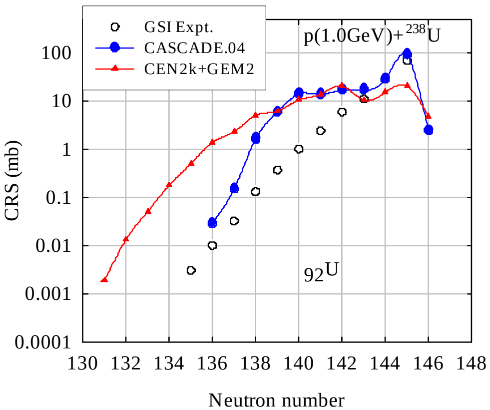
n,p,d,t,^{3}He,^{4}He, p ,0

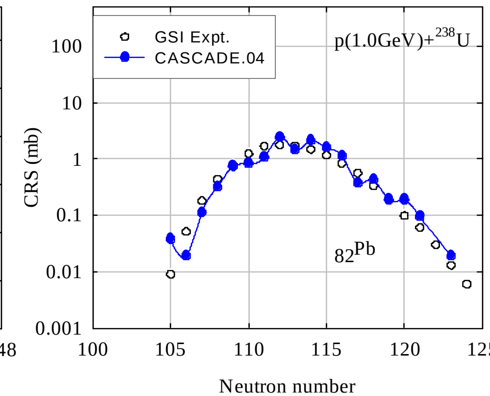
Thick target simulation

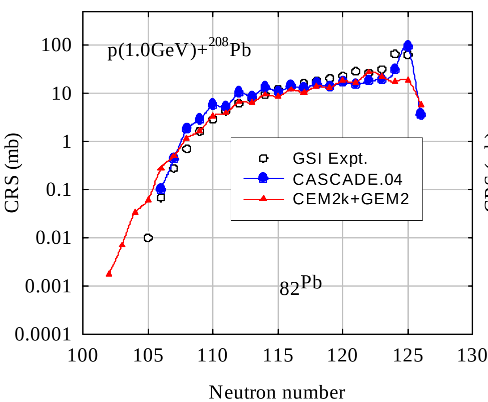


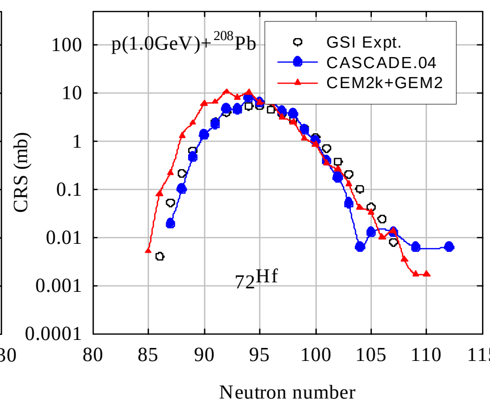


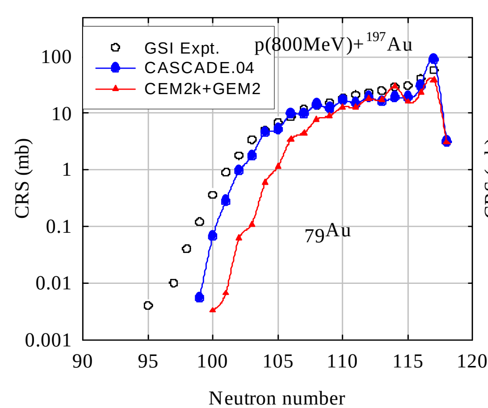
Spallation Evaporation and Fission Residues

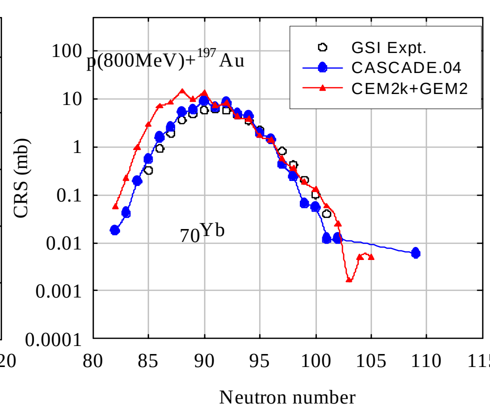


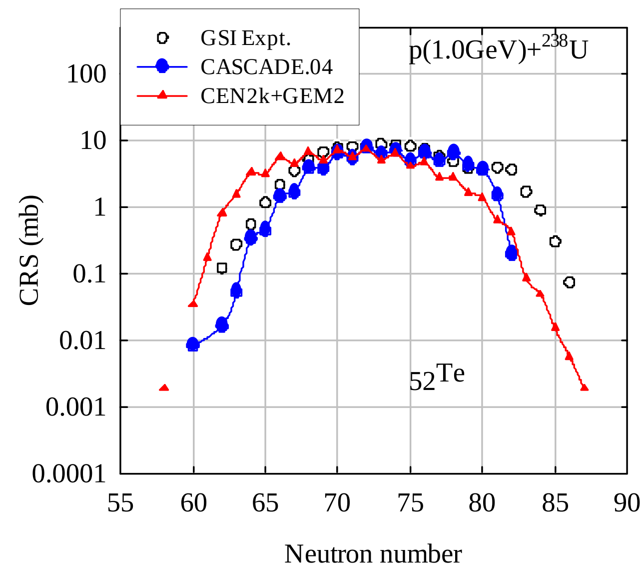


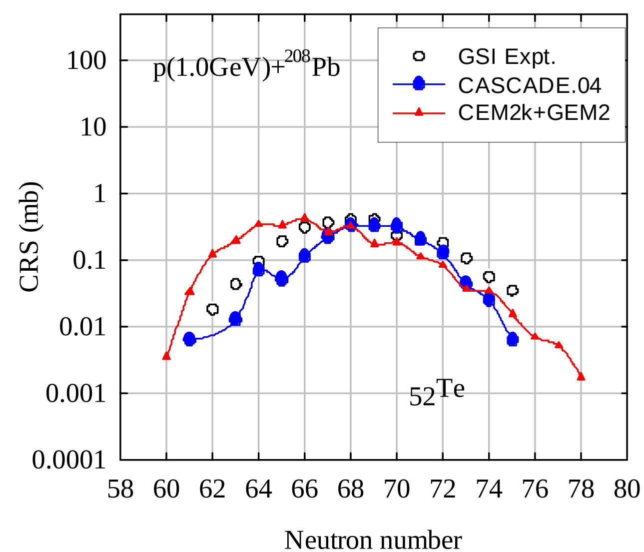


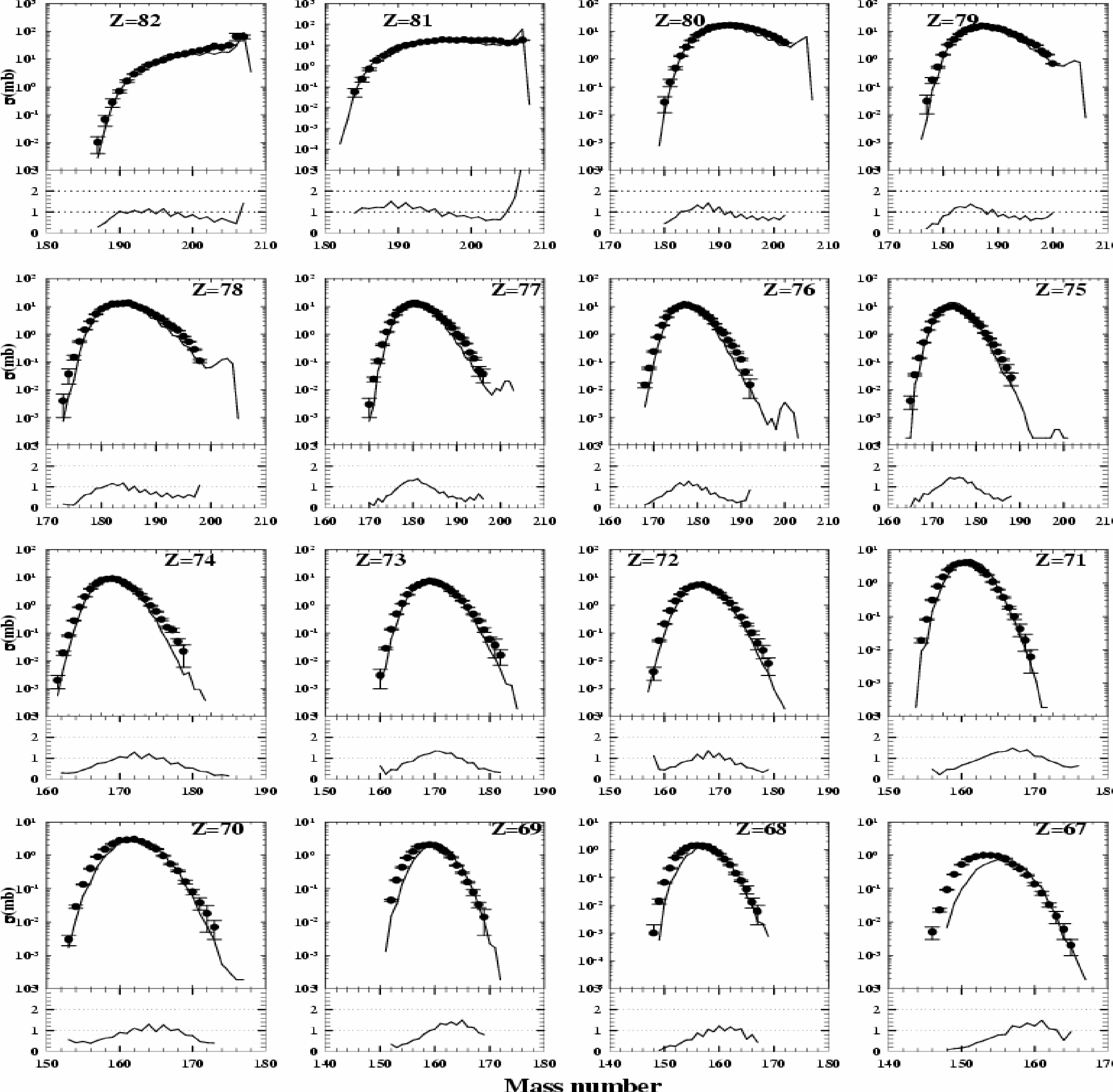




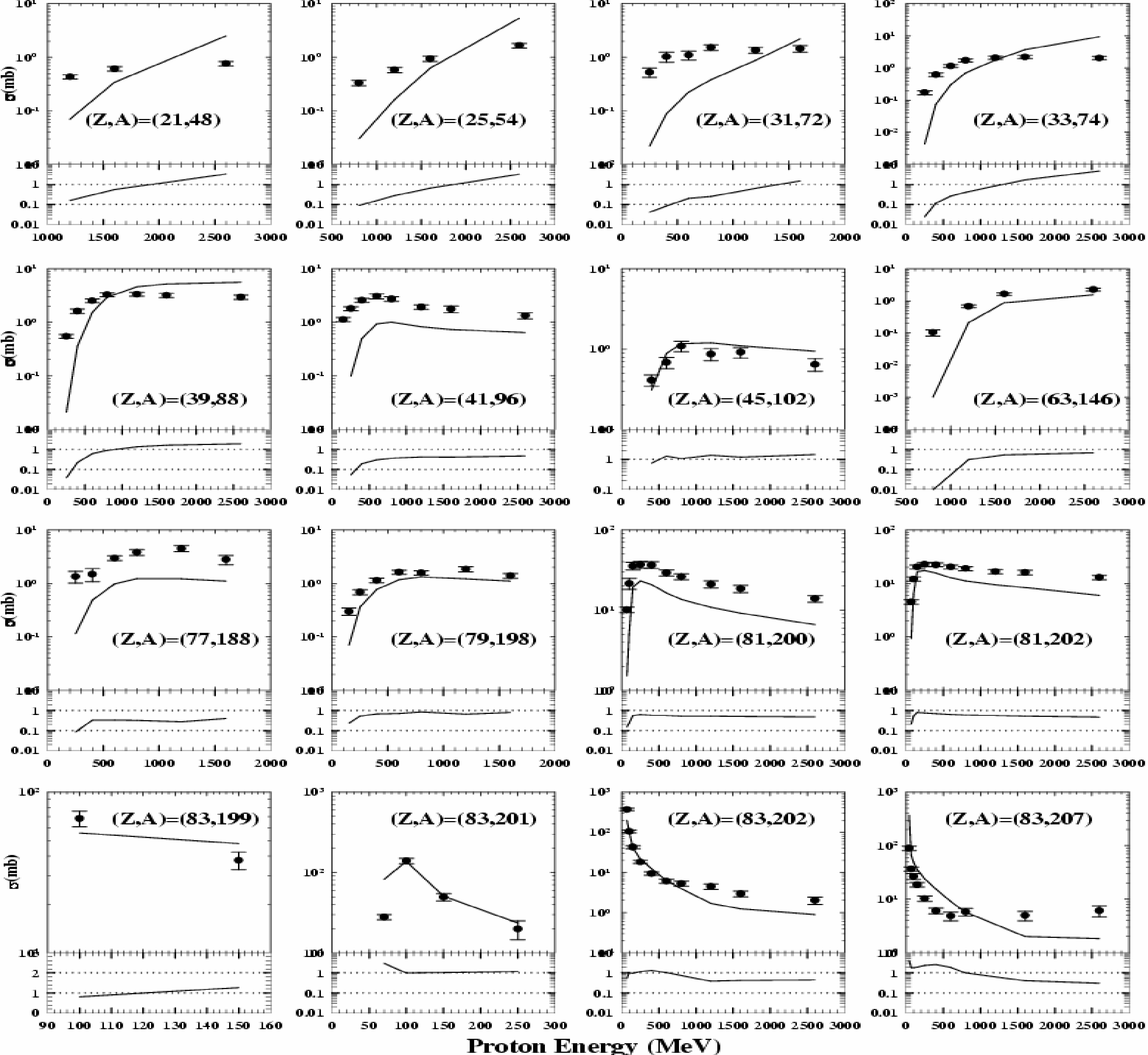




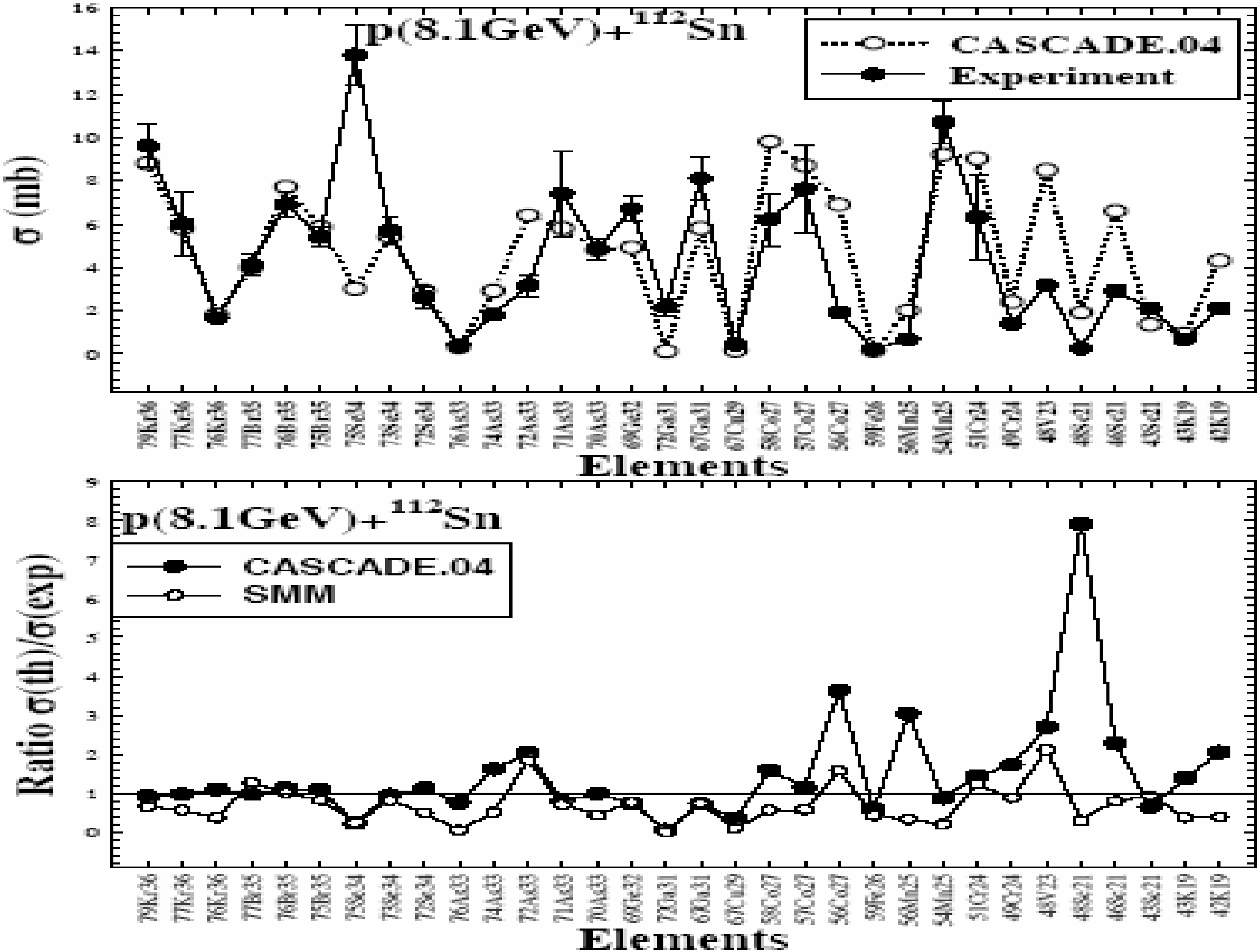




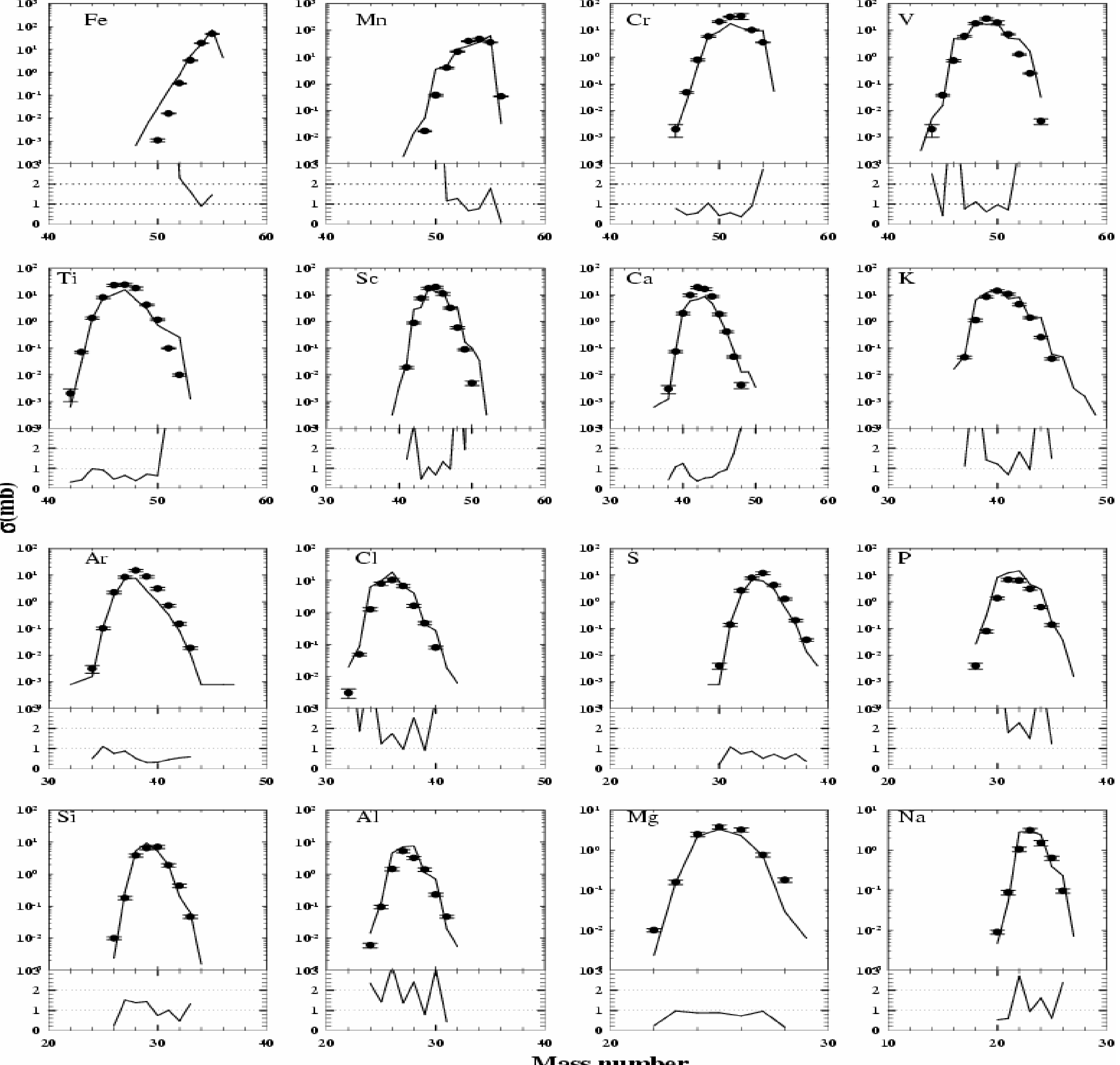
Different Isotopes From p(1GeV)+Pb208 system



Cross-section For p+208Pb

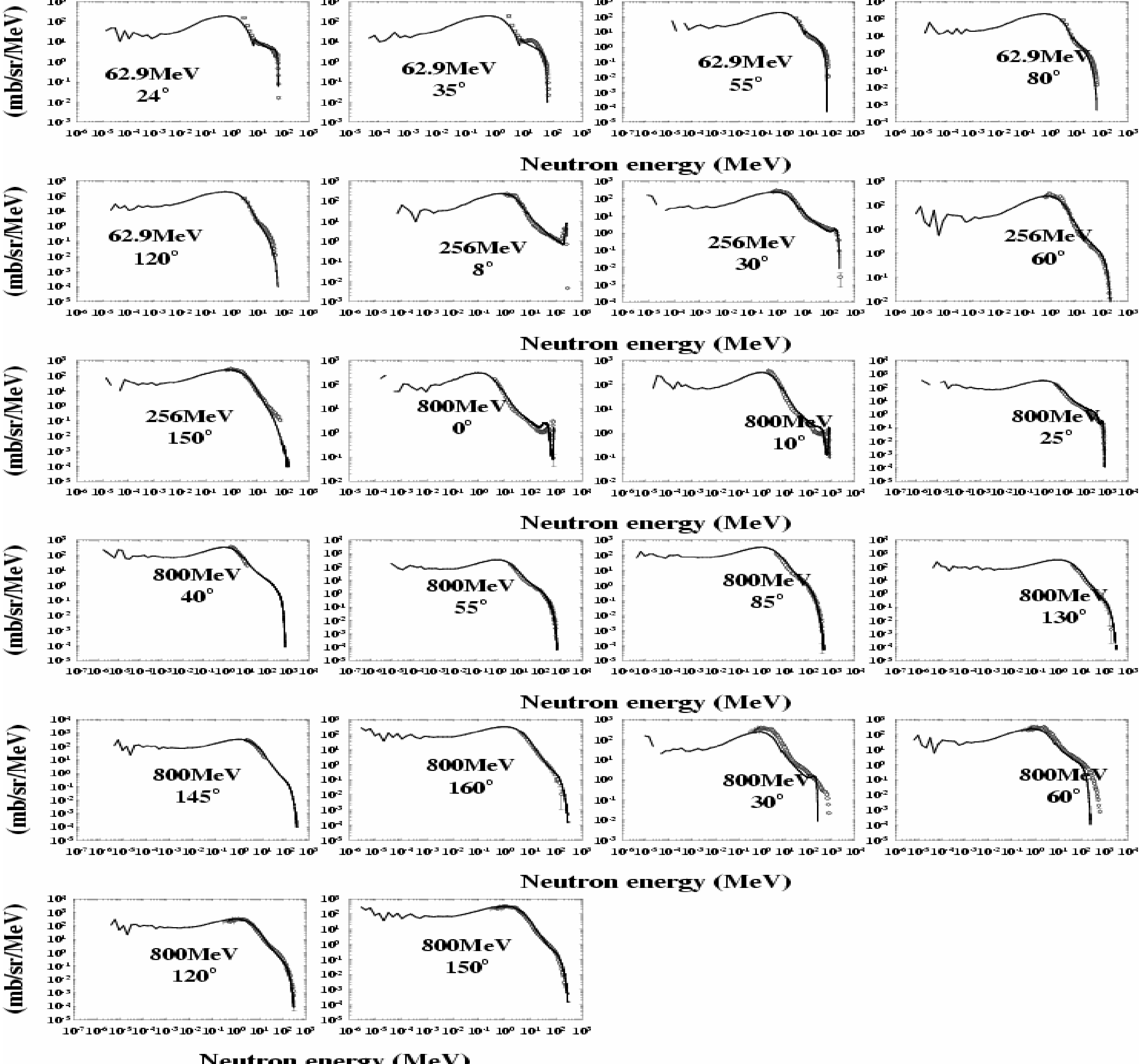


p(8.1GeV)+^{112}Sn
CASCADE.04
Experiment
σ (mb)
Elements
p(8.1GeV)+^{112}Sn
CASCADE.04
SMM
Ratio σ(th)/σ(exp)
Elements

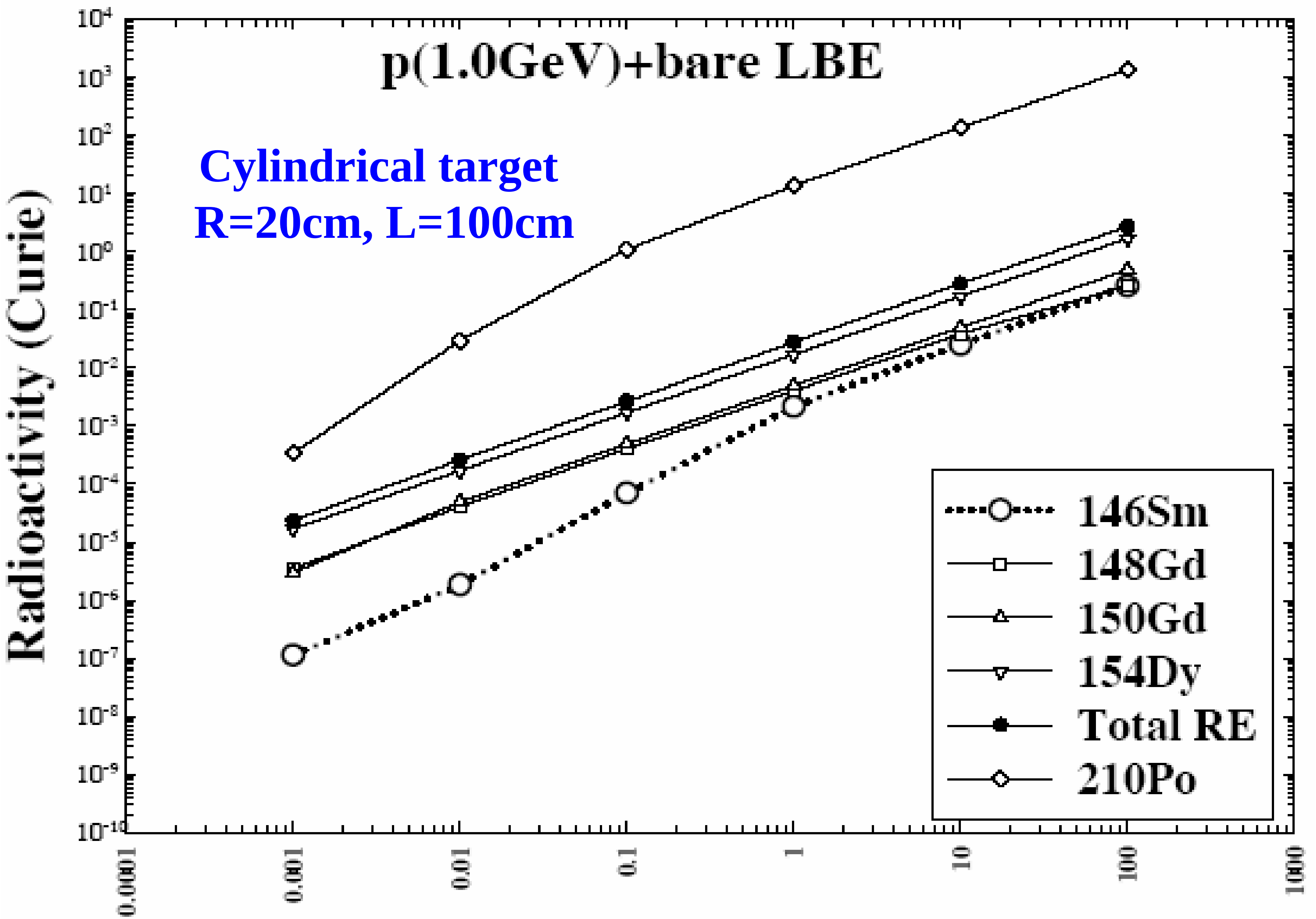


Different Isotopes From p(1GeV)+Fe56 system

Double Differential Neutron Production Cross-section For p+Pb208 system



Alpha radio-activity in LBE due to Rare earth and ^{210}Po



Thick target simulation

Pre-defined geometries:

Spherical, cylindrical, conical, hexagonal, elliptical, hemi-sphere, hemi-elliptical, cubic ..

Low energy data library

26-group data library

ENDFVII.0 is implemented for Pb^{208} more to be done

Ionization/Stopping power calculation is implemented up to 100GeV

Coupled with burnup code ☺

Thick target simulation Results

Heat deposition due to primary and secondaries

Neutron yield, Angular /energy spectra, spatial and radial flux distribution

Isotope buildup

Burnup, k_{eff}?

Biasing:

Weight cutoff, energy cuttoff, geometry splitting and exponential method