The Abdus Salam
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IAEA
International Atomic Energy Agency

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Joint ICTP-IAEA Advanced Workshop on Model Codes for Spallation Reactions

4 - 8 February 2008

Nuclear Reaction Models (JAM and JQMD) in PHITS

Koji Niita

RIST
Ibaraki
Japan

Reaction Models (JAM and JQMD) in Particle and Heavy Ion Transport code System

PHITS

Koji Niita: RIST, Japan

Hiroshi Iwase: KEK, Japan

Tatsuhiko Sato: JAEA, Japan

Yousuke Iwamoto, Norihito Matsuda,
Yukio Sakamoto, Hiroshi Nakashima: JAEA, Japan

Davide Mancusi, Lembit Sihver: Chalmers, Sweden

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PHITS : Particle and Heavy Ion Transport code System

PHITS is a multi-purpose 3D Monte Carlo transport code system for all particles and Heavy ions with all energies from meV up to 200 GeV.

5 major codes for all particle transport in a world

	MCNPX	GEANT4	FLUKA	MARS	PHITS
Lab. Affiliation	LANL	CERN,IN2P3 INFN,KEK,ESA, SLAC,TRIUMF	CERN INFN	FNAL	JAEA,RIST GSI,KEK Chalmers Univ.
Language	Fortran 90/C	C++	Fortran 77	Fortran 95/C	Fortran 77
Release Format	Source & binary	Source & binary	Source & binary	Binary	Source & binary
Users	~2000	~1000	~1000	220	220
Parallel Exec.	Yes	Yes	No	Yes	Yes

By G. W. McKinney in FNDA (Fast Neutron Detectors and Applications Conference) April 2006
Revised by L. Waters in HSS06 (Hadronic Shower Simulation Workshop) Sep. 2006

Physics Capabilities

Physics	MCNPX	GEANT4	FLUKA	MARS	PHITS
Particles	34	68	68	41	38
Charged particles Energy loss Scatter Straggling XTR/Cheren.	CSDA Bethe-Bloch Rossi Vavilov No	CSDA Bethe-Bloch Lewis Urban Yes	CSDA Bethe-Bloch Moliere improved Custom No/yes	CSDA Bethe-Bloch Moliere improved Custom No	CSDA Bethe-Bloch Moliere Vavilov No
Baryons Neutron Low High Proton Low High Other	 Cont. (ENDF) Models Cont. (ENDF) Models Model List: Bertini ISABEL CEM INCL FLUKA89>3 GeV LAQGSM (2.6.C)	 Cont. (ENDF) Models Models Models Model list: Hadron-nucleous GHEISHA* INUCL(Bertini) BIC CHIPS QGS/FTF>8 GeV	 Multigroup(72) Models Models Models Model list: PEANUT(GINC) +DPM+Glauber	 Cont. (ENDF) Models Models Models Model list: Custom CEM LAQGSM DPMJET	 Cont. (ENDF) Models Models Models Model list: Bertini JAM>3 GeV
Leptons Electrons Muon Neutrino Other	 ITS 3.0 CSDA/decay Production Decay	 Models/EEDL, EADL Models Production Decay	 Custom Models Models Decay	 Custom Models Models Models	 ITS 3.0 CSDA/decay Models Models

Mesons	Models	Models	Models	Models	Models
Photons Optical x-ray/g Photonuclear	No ITS 3.0 Libraries (IAEA) CEM	Yes Models or EPDL97, EADL CHIPS	Yes Custom+EPDL97 PEANUT VMDM	No Custom Custom CEM	No ITS 3.0 No
Ions	ISABEL LAQGSM (2.6.C)	AAM EDM BLIC	RQMD-2.4 DPMJET-3	LAQGSM	JQMD JAMQMD > 3 GeV/u
Delayed	n,γ (2.6.C)	α,β,γ?	β,γ	γ	n

Overview of PHITS (Particle and Heavy Ion Transport code System)

1951	1983	1997	2001	2003
NMTC	NMTC/JAERI	NMTC/JAERI97	NMTC/JAM	PHITS
(ORNL)	High Energy Fission	CG geometry	JAM, GG Magnetic Field	JQMD, MCNP Gravity

PHITS = MCNP + JAM + JQMD

MCNP	Neutron, Photon, Electron Transport by Nuclear Data
JAM	Hadron-Nucleus Collisions up to 200 GeV
JQMD	Nucleus-Nucleus Collisions by Molecular Dynamics

Transport Particle and Energy

Proton	0 ~ 200 GeV
Neutron	10^{-5} eV ~ 200 GeV
Meson	0 ~ 200 GeV
Barion	0 ~ 200 GeV
Nucleus	0 ~ 100 GeV/u
Photon	1 keV ~ 1 GeV
Electron	1 keV ~ 1 GeV

External Field: Magnetic Field, Gravity
Optical and Mechanical devices

Language and Parallelism

- FORTRAN 77
- MPI

Geometry: CG and GG

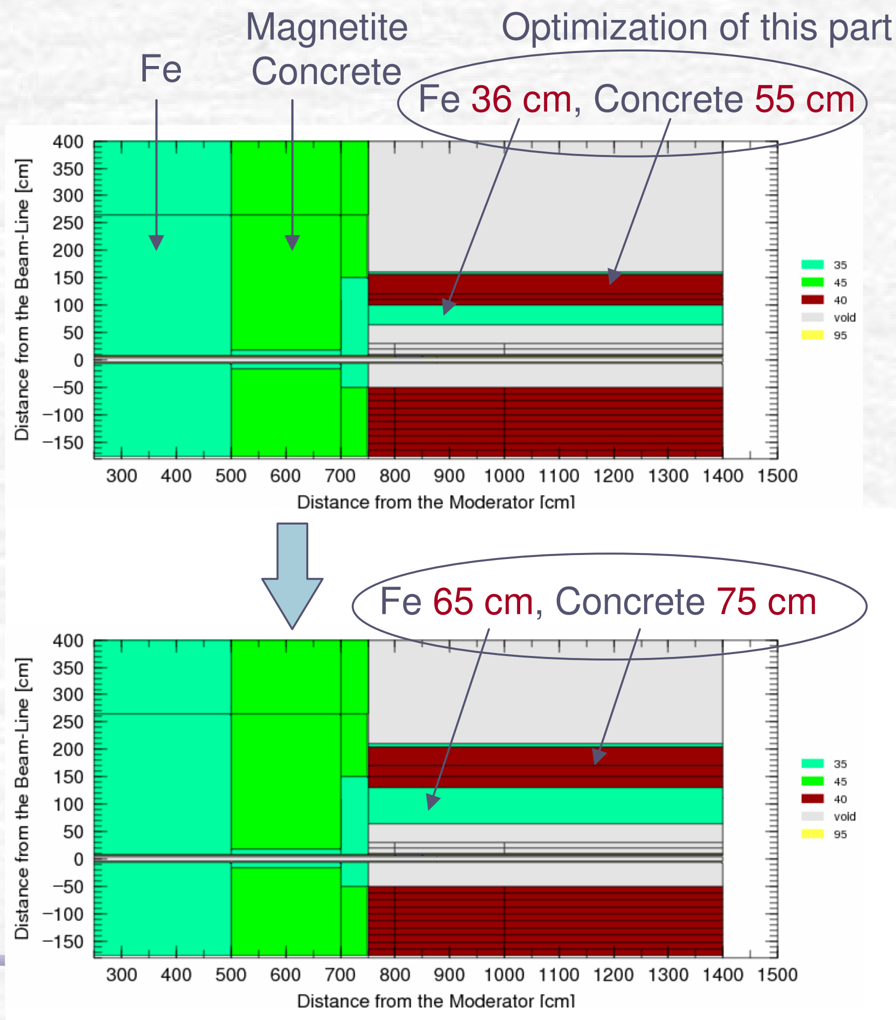
Tally, Mesh and Graphic

- Tally: Track, Cross, Heat, Star, Time, DPA, Product, LET
- Mesh: cell, r-z, xyz
- Counter:
- Graphic: ANGEL (PS generator)

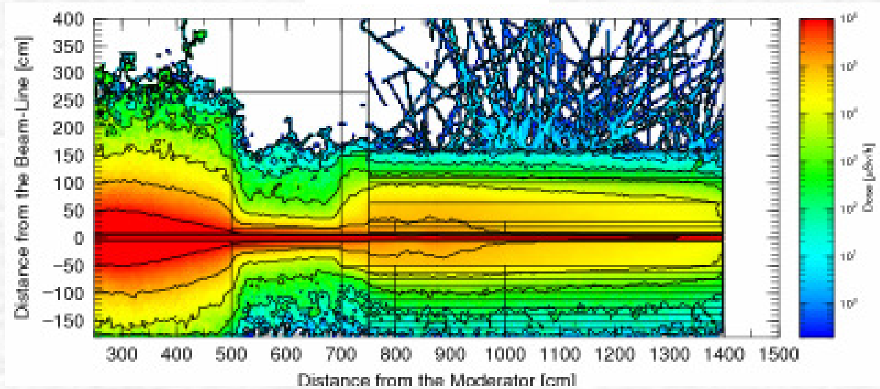
PHITS : H. Iwase et.al. *J. Nucl. Sci.Technol.* **39** (2002) 1142

User Interfaces of PHITS

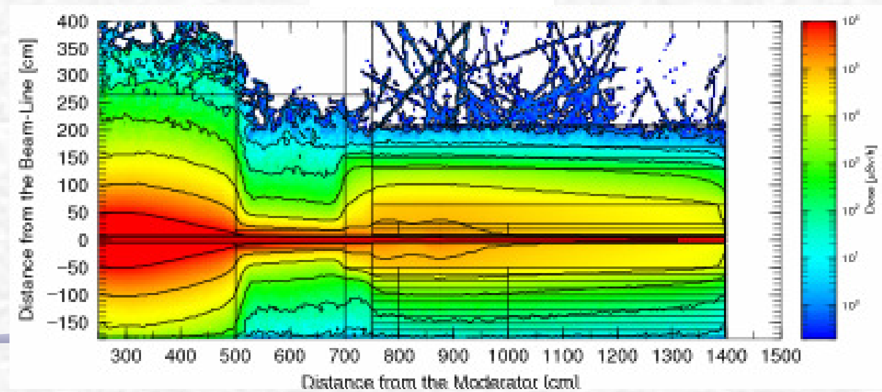
2D output of the intermediate results of a certain interval of histories.
This function is very powerful for optimization study !!!



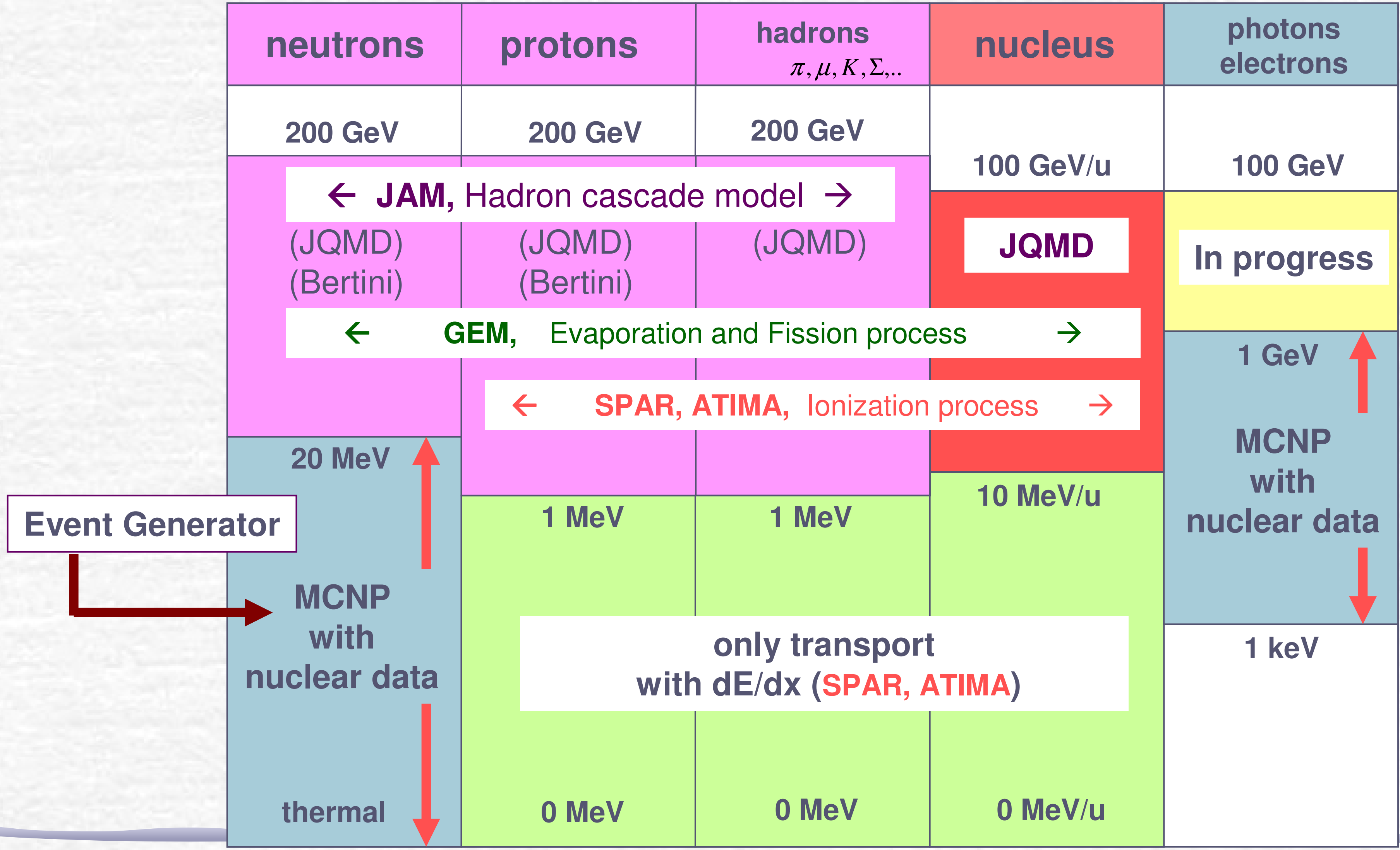
1 hour



20 hours



Map of Models, transport particles and energies in PHITS



What are we doing in Monte Carlo calculations for particle transport ?

- Solving one-body Boltzmann equation by using the evaluated nuclear data.
  - MCNP type code → Only one-body observables

    energy is conserved in average.
    no correlations

- Simulating real phenomena by using event generators.
  - PHITS for high energy by JAM, JQMD. → Any observables

    treat all ejectiles of collisions.
    energy and momentum are conserved in each collision.

Event Generator

Observables beyond one-body quantities are often required.

We have developed the event generator mode in PHITS for all energy.

Event Generator Mode for low energy neutrons in PHITS

Neutron data + Special Evaporation Model

We use the channel cross sections and neutron energy spectrum of the first neutron and assume the binary decay of recoiled nucleus.

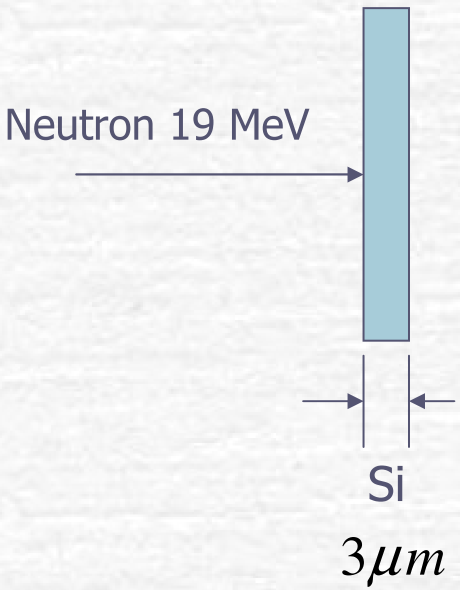
Neutron channels			
	capture	$\Gamma_n = 0$	charged particle and photon decay
	elastic		final state is uniquely determined
	(n,n′)	$\Gamma_n = 0$	charged particle and photon decay after the first neutron emission
	(n,Nn′)	$\Gamma_n \neq 0$	all particle and photon decay after the first neutron emission

By this model, we can determine all ejectiles (neutrons, charged particles, nucleus and photons) with keeping energy and momentum conservation.

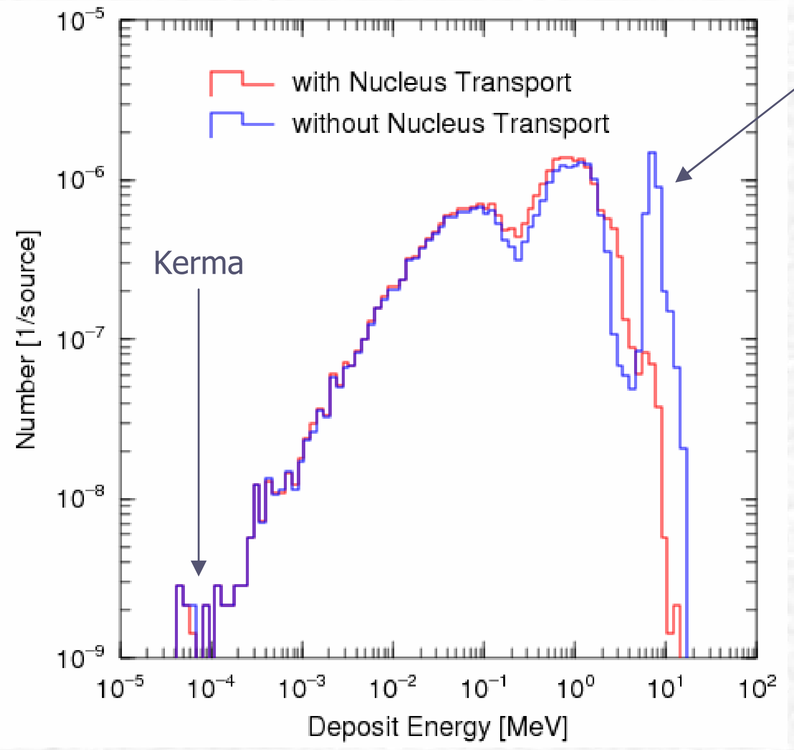
PHITS can transport all charged particle and nucleus down to zero energy and estimate deposit energy without local approximation (kerma factor).

*An example of **Event Generator Mode***

Neutron-induced semiconductor soft error
SEU: single event upset



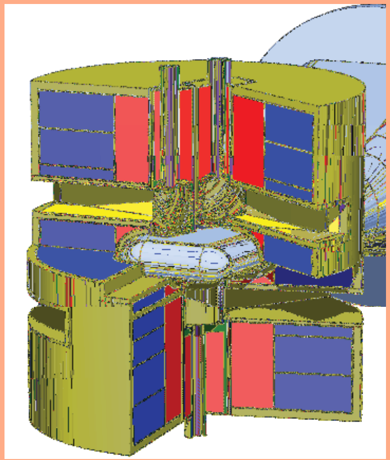
Deposit Energy Distribution by PHITS



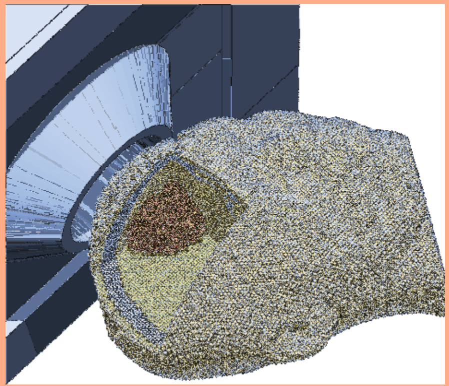
Leakage of recoil nucleus from Si

Application Fields of PHITS

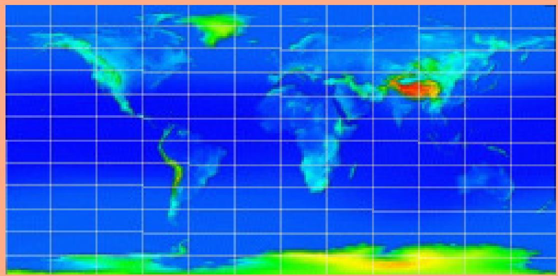
Accelerator



Cancer Therapy



Space Technology

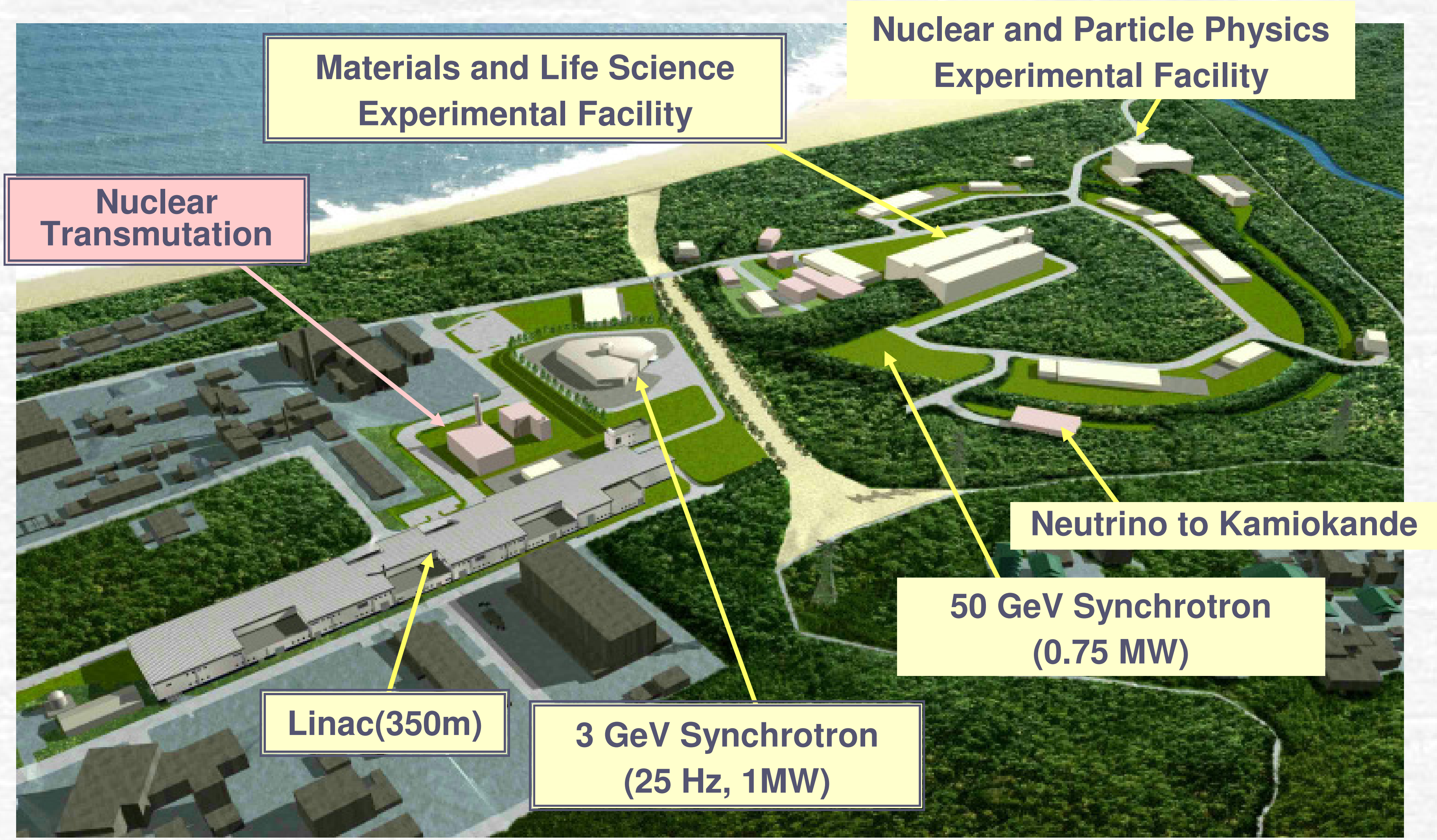


J-PARC
Spallation Neutron Source
Neutron Optics
Heavy Ion Facilities

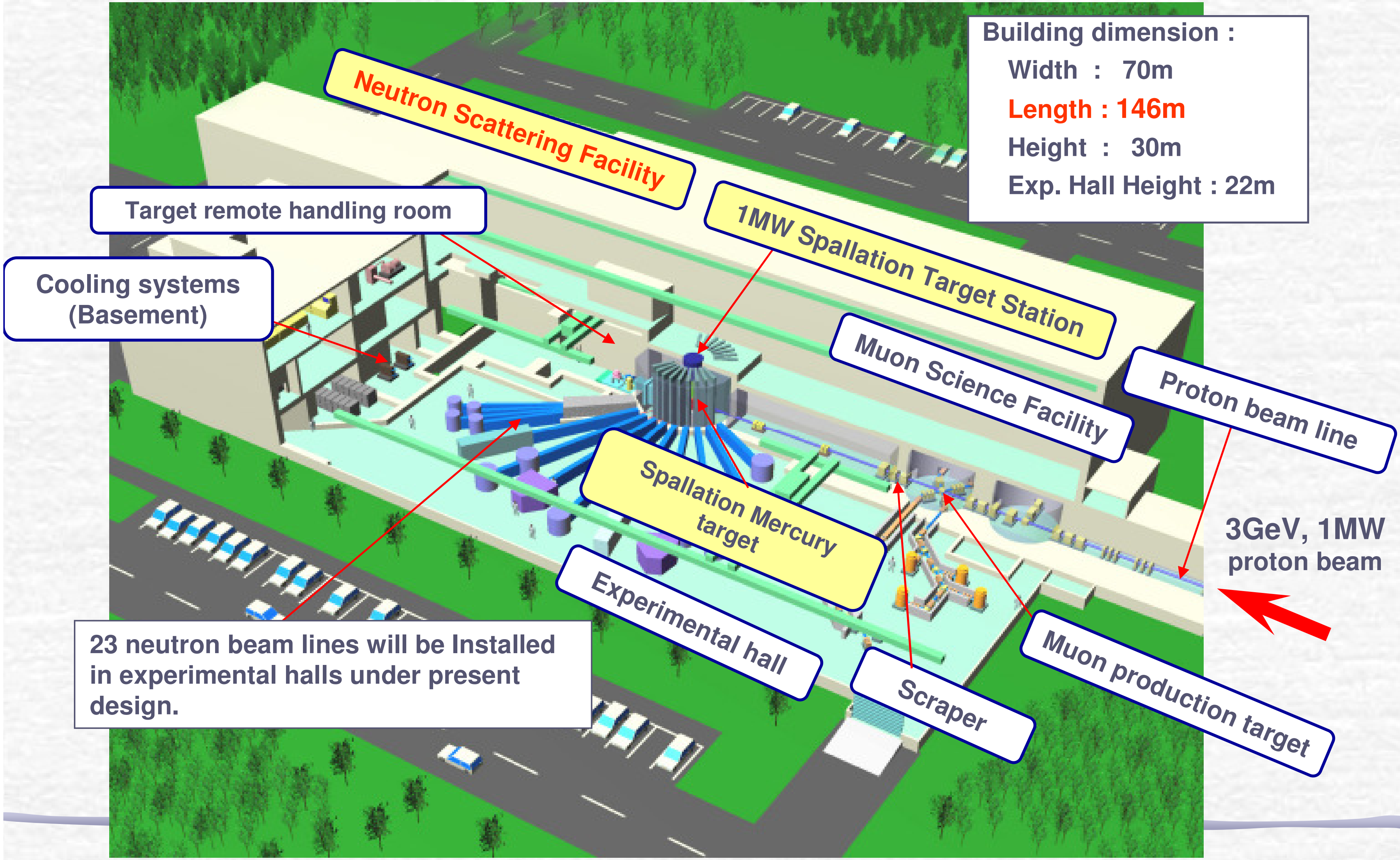
BNCT
Proton and
Heavy Ion Therapy

Dose in Space Shuttle
Atmospheric Cosmic-Ray

J-PARC = Japan Proton Accelerator Research Complex



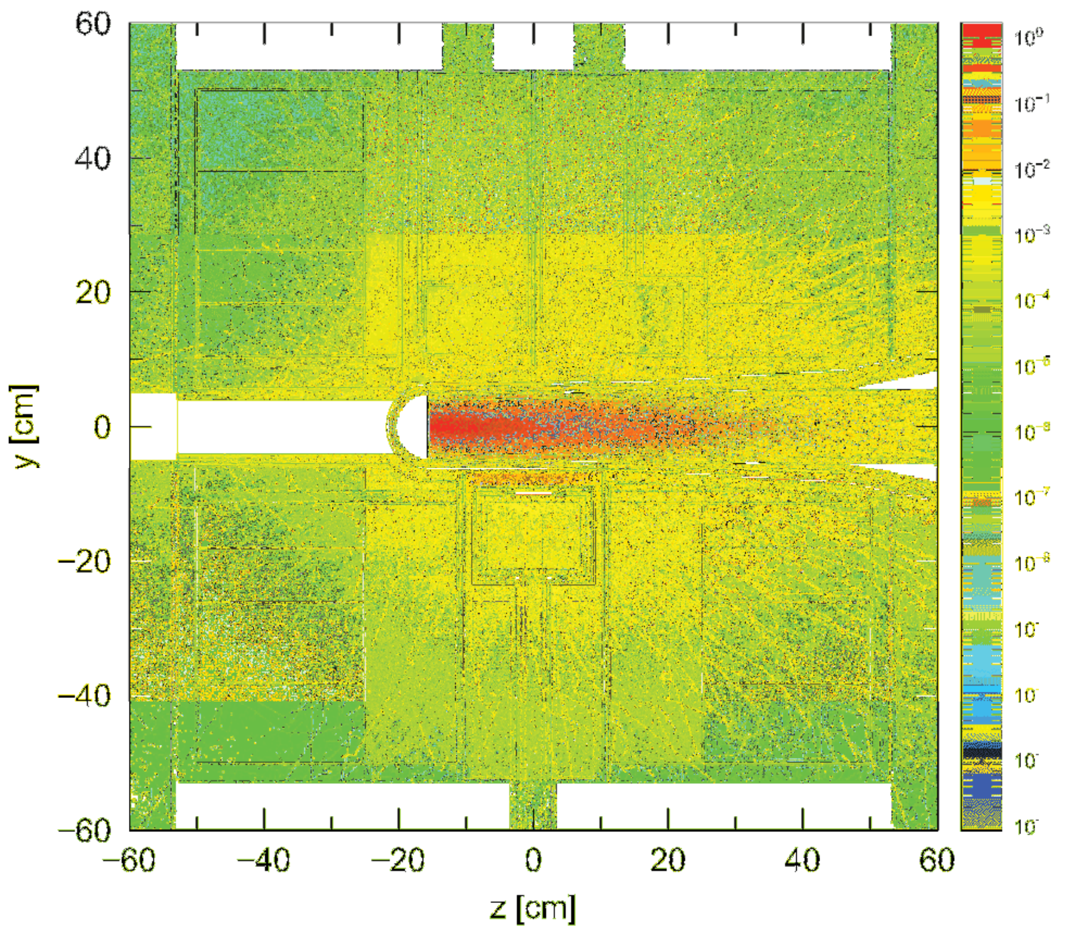
Materials and Life Science Experimental Facility

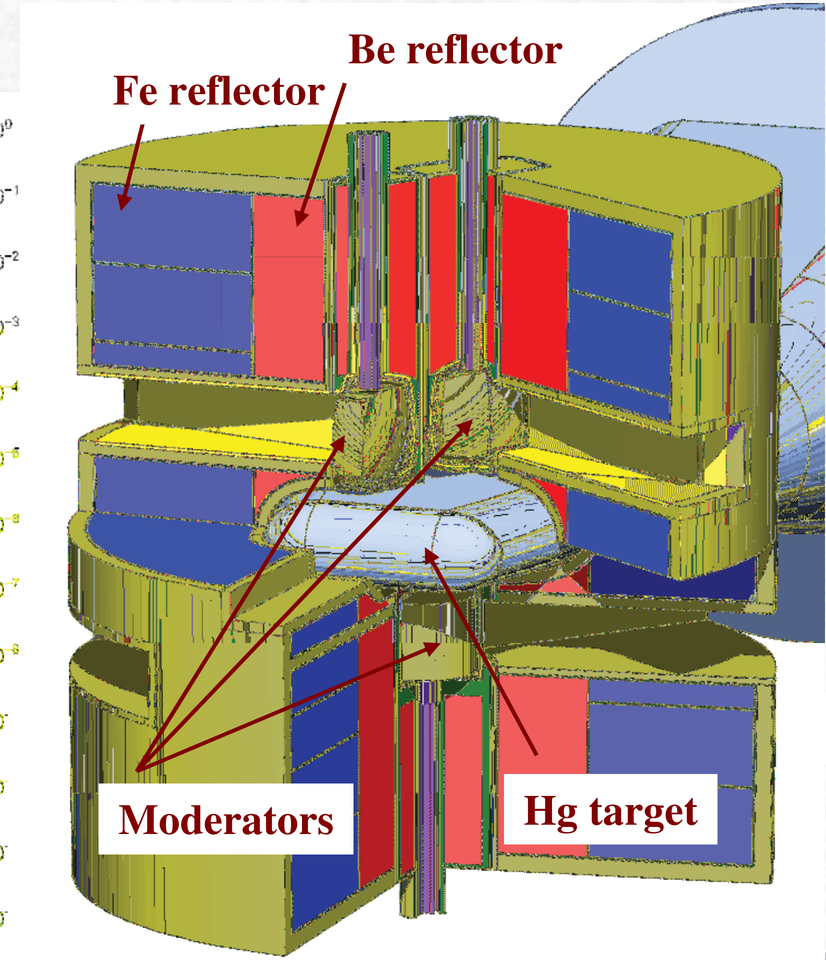


Spallation Neutron Source in Proton Accelerator Facilities

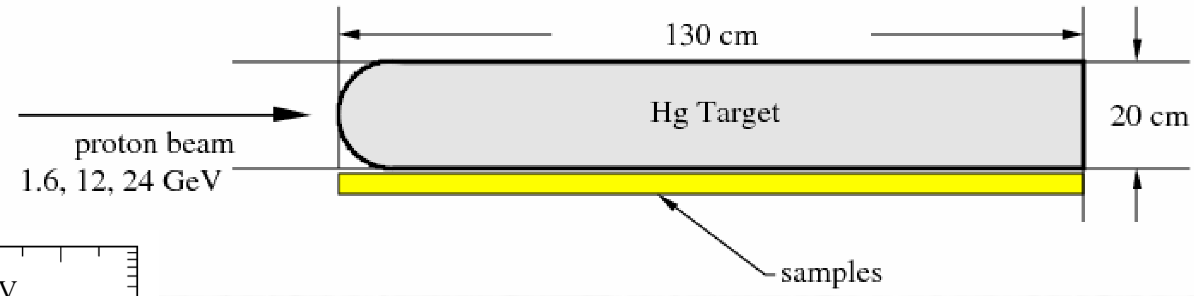
PHITS has been extensively used for
Optimization and Shielding design around Hg target of J-PARC

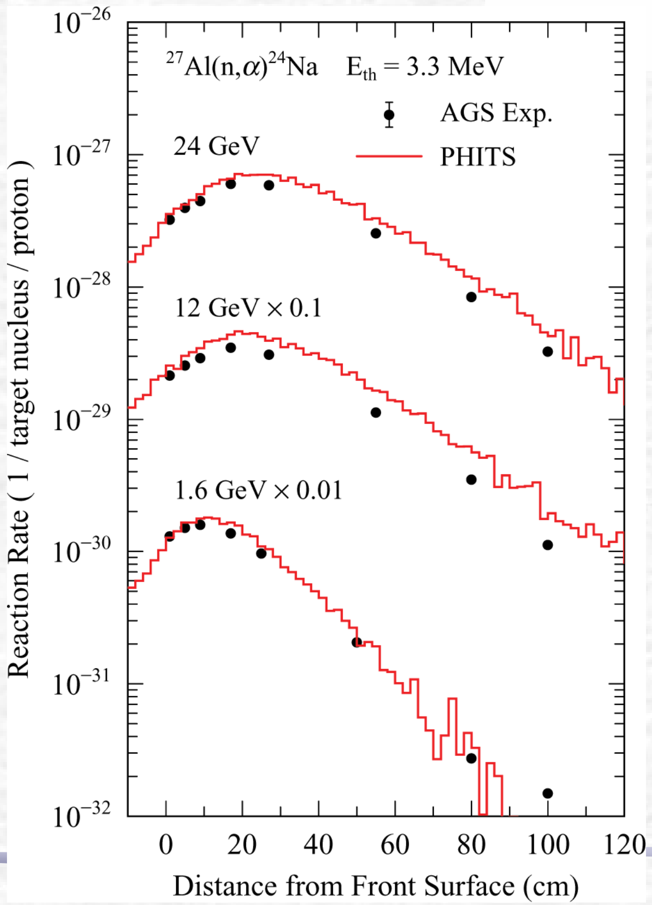
Energy Deposition

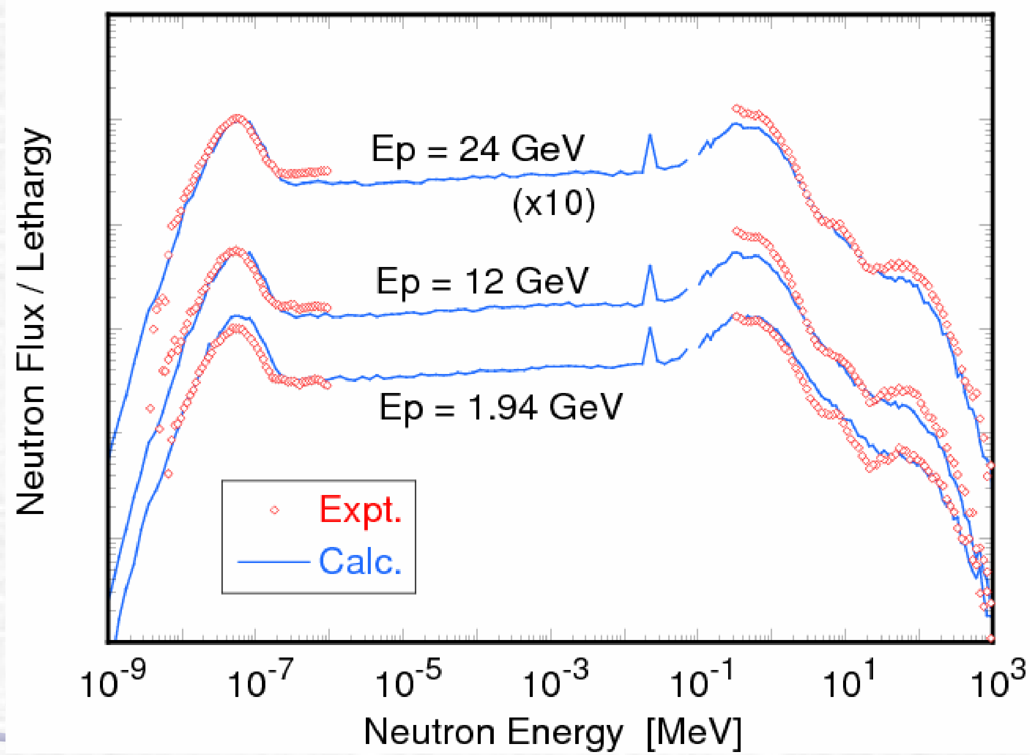




AGS Benchmark Experiments for Spallation Neutron Source

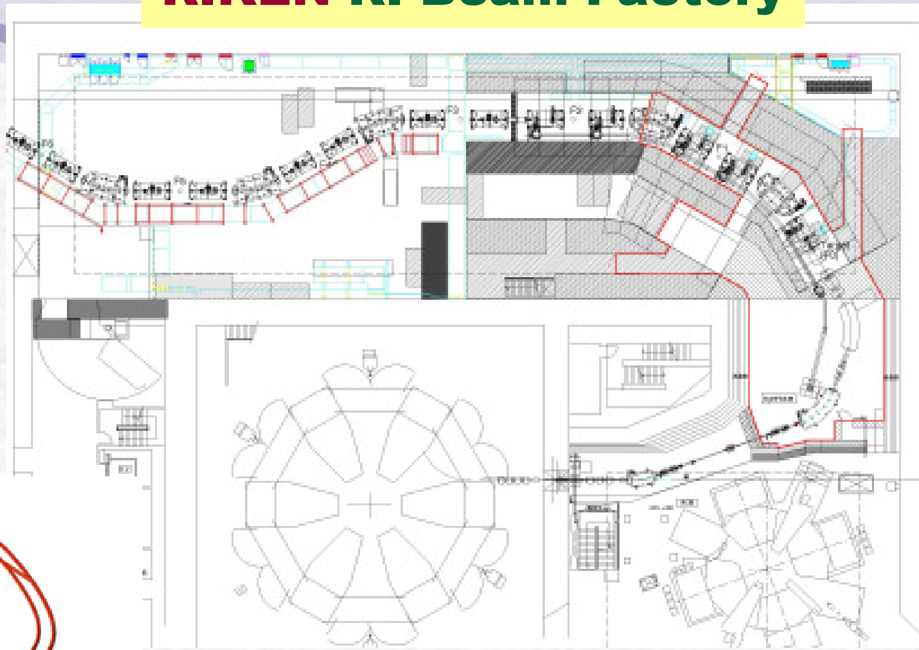




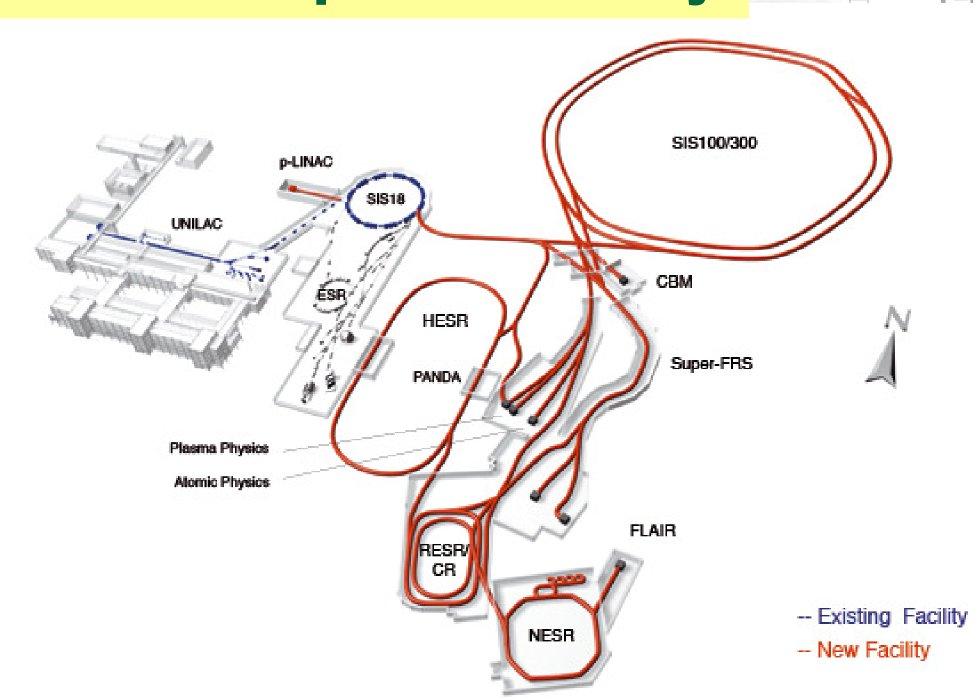


PHITS for High Intensity Heavy Ion facilities

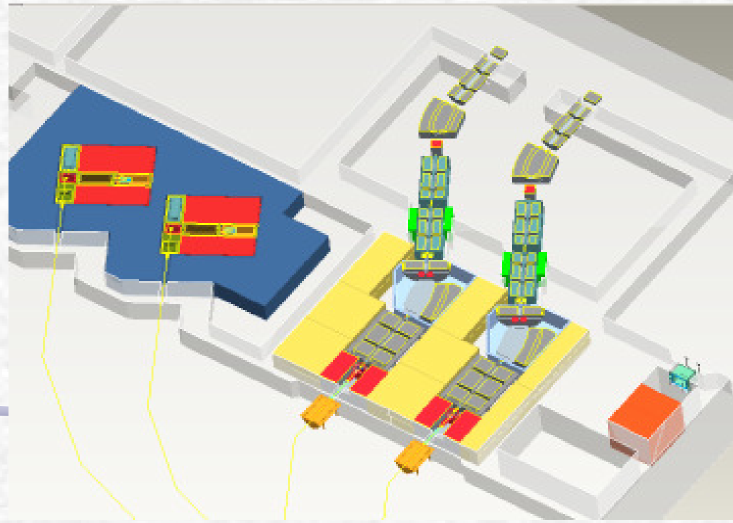
RIKEN RI Beam Factory



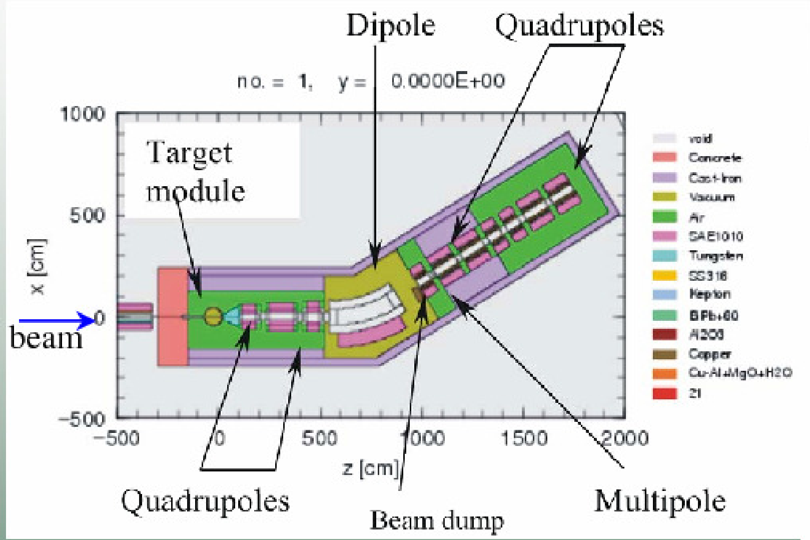
GSI FAIR : Super-FRS facility

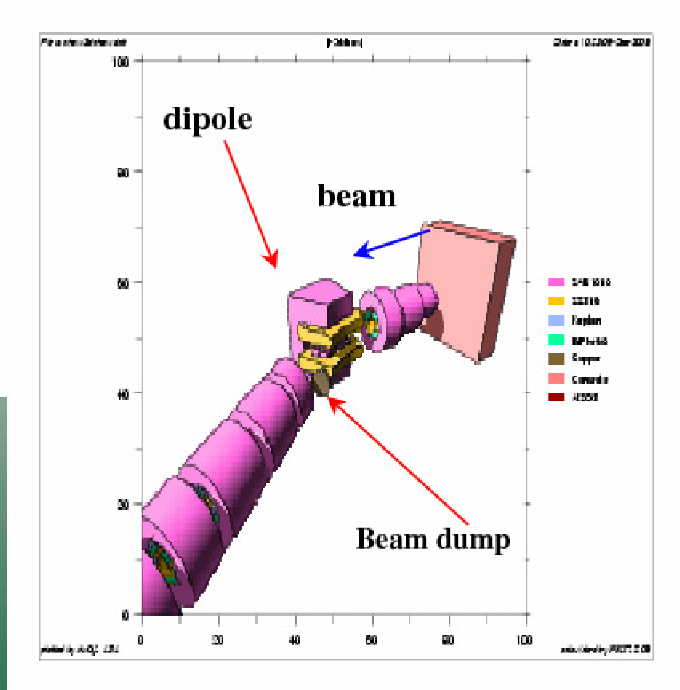


RIA Beam production area



Fragmentation Pre-Separator in PHITS (Inseok Baek, NSCL/MSU)

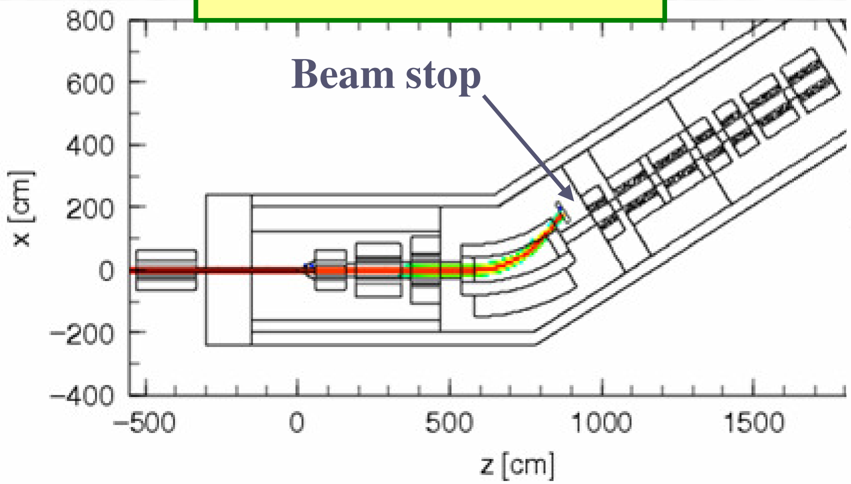




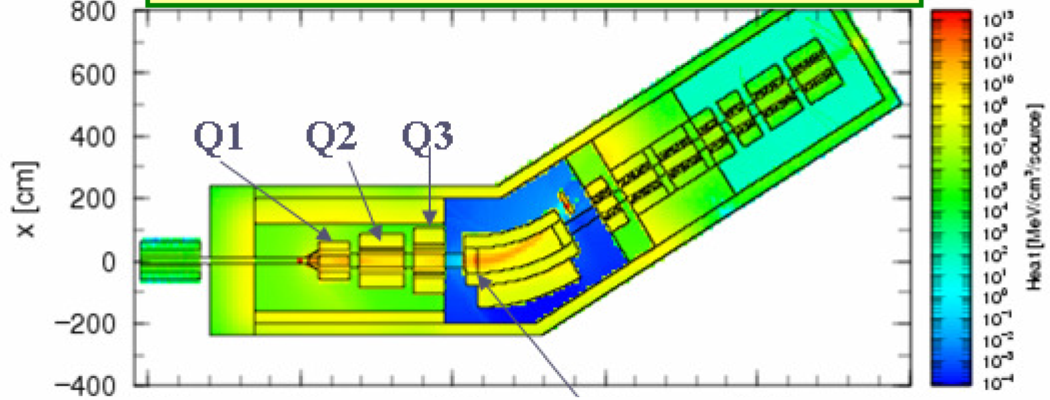
The NSCL is funded in part by the National Science Foundation and Michigan State University.

RIA Beam production area

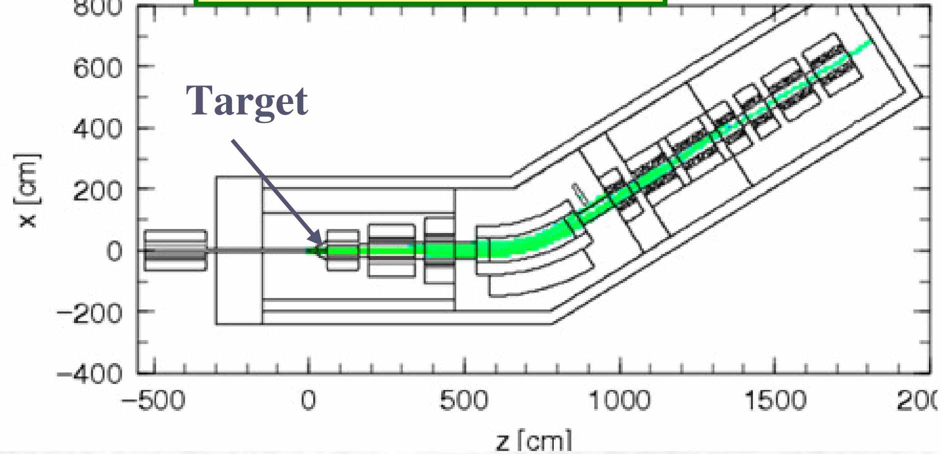
^{48}Ca beam track



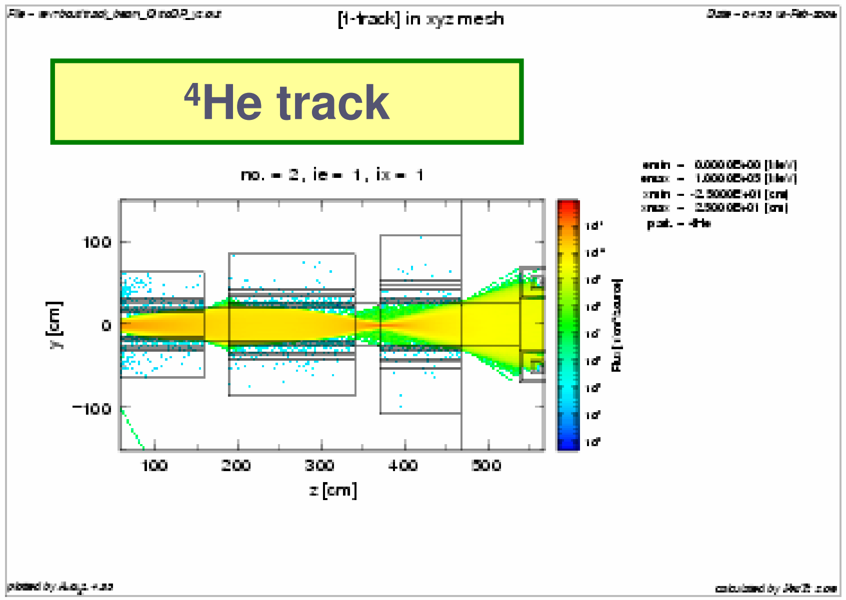
Heating in whole system



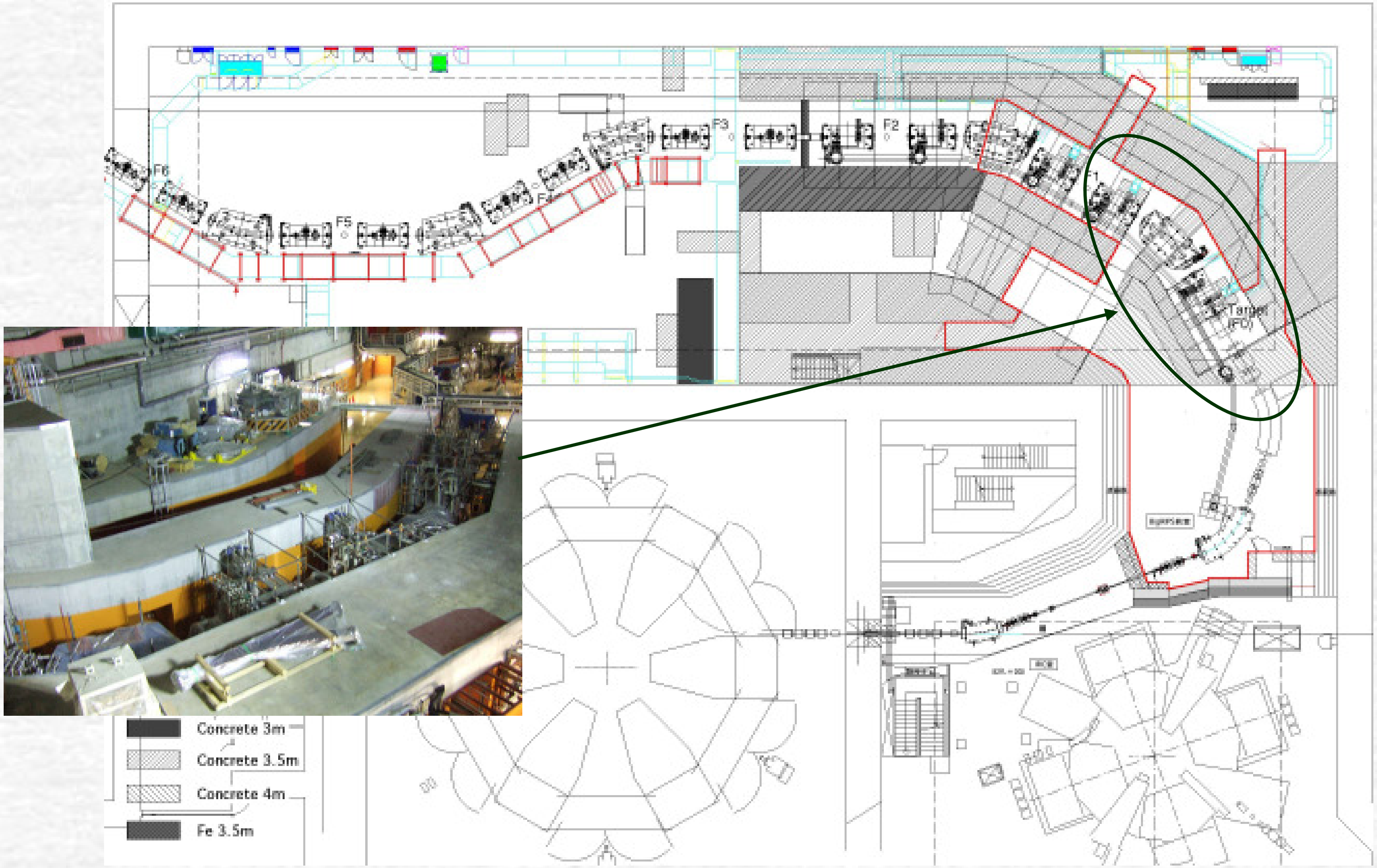
^{22}C track



^{4}He track



RIKEN RIBF: RI Beam Factory

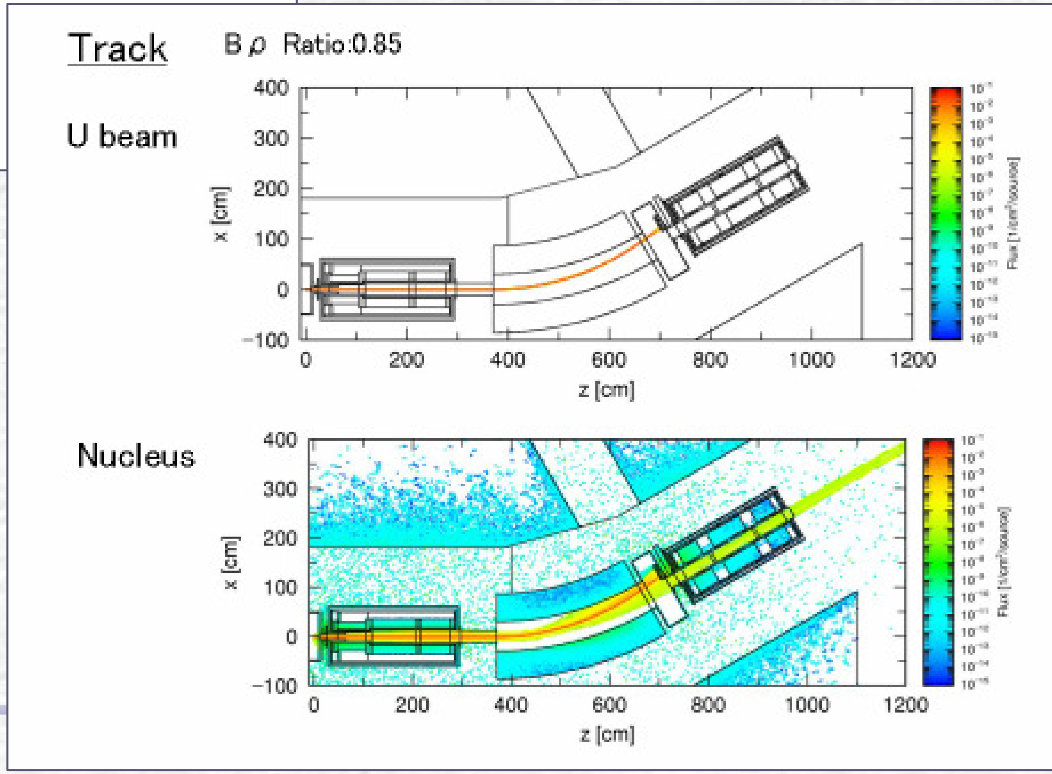


PHITS Simulation for BigRIPS

2006/5 Expert-Meeting at RIKEN

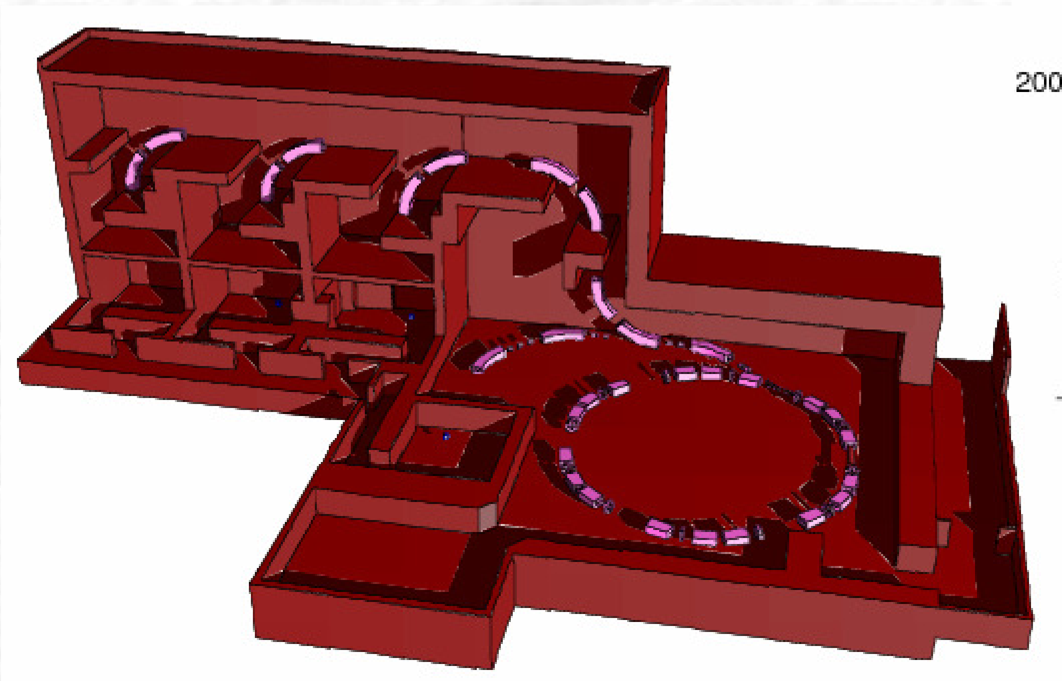
BigRIPS Team

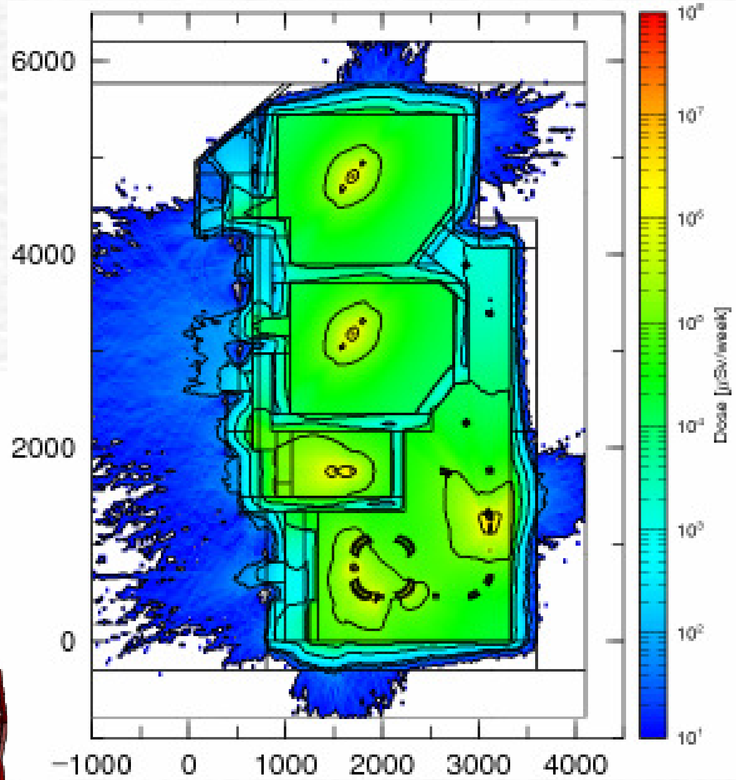
1. Heat load
2. Radiation damage
3. DPA



PHITS for Shielding of Proton and Carbon Therapy Facilities

3D view by PHITS



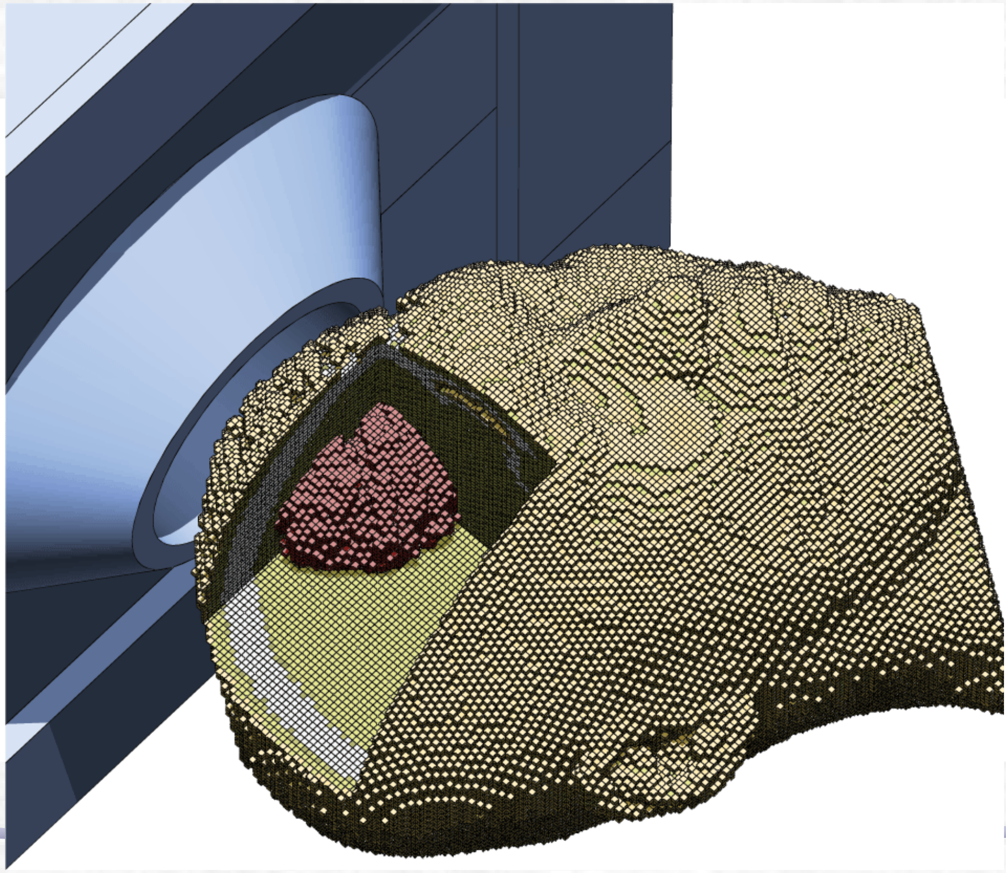


Dose distribution

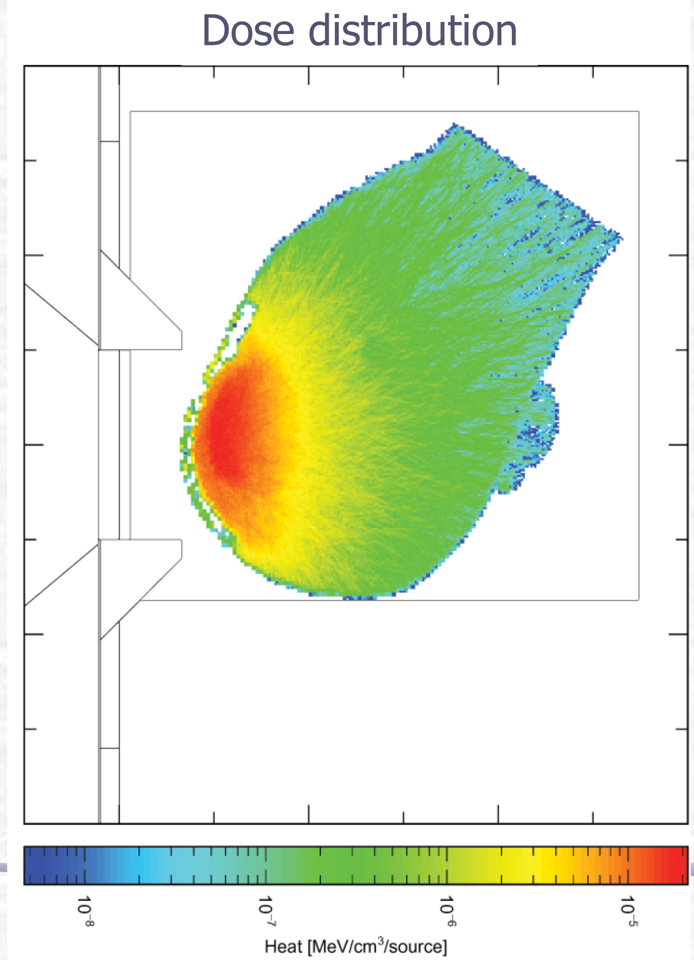
PHITS for planning system for radiotherapy

Boron Neutron Capture Therapy
at Dept. Research Reactor, JAERI

3D view by PHITS



JCDS (Jaeri Computational Dosimetry System)
creates the Voxel data from CT and MRI data for MCNP (PHITS) calculation.

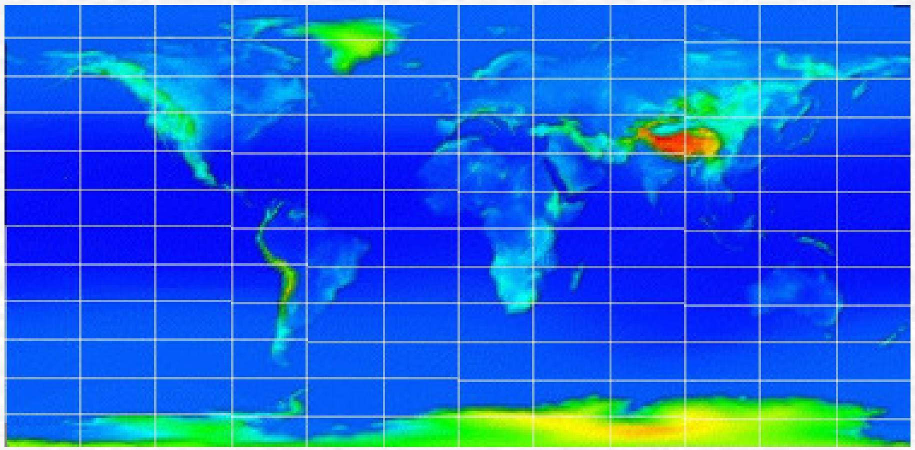


PHITS for neutron spectrum in atmosphere

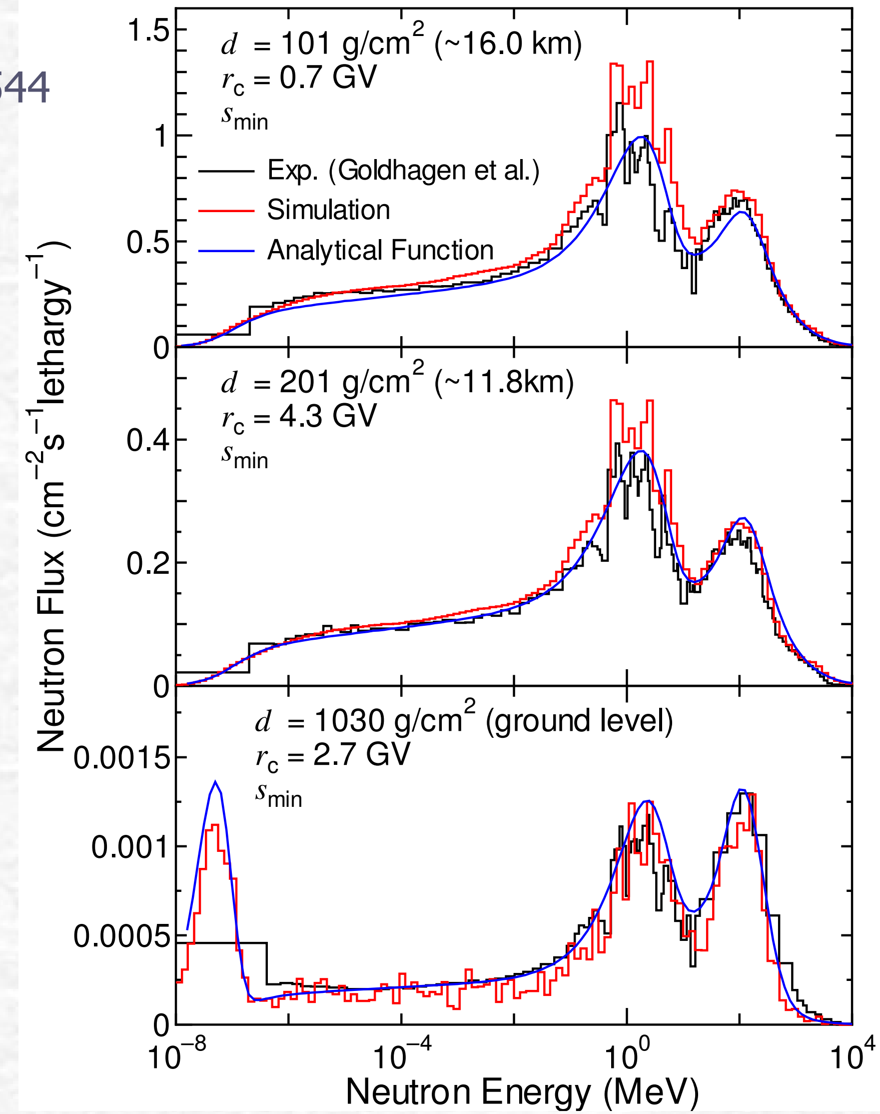
T. Sato and K. Niita, *Radiat. Res.,* **166** (2006) 544

Galactic Cosmic Ray

Neutron spectrum in any height of atmosphere even at ground level



dose map on ground level



http//www3.tokai-sc.jaea.go.jp/rphpwww/radiation-protection/expacs/expacs.html

JENDL High Energy File 2007

JENDL/HE-2007 neutron and proton ~ 3GeV, 106 nuclei

H-1, C-12,13, N-14, O-16, F-19, Na-23, Mg-24,25,26, Al-27, Si-28,29,30,
Cl-35,37, Ar-36,38,40, K-39,41, Ca-40,42,43,44,46,48, Ti-46,47,48,49,50,
V-51, Cr-50,52,53,54, Mn-55, Fe-54,56,57,58, Co-59, Ni-58,60,61,62,64,
Cu-63,65, Zn-64,66,67,68,70, Ga-69,71, Ge-70,72,73,74,76, As-75,
Zr-90,91,92,94,96, Nb-93, Mo-92,94,95,96,97,98,100, Ta-181,
W-180,182,183,184,186, Au-197, Hg-196,198, 199,200,201,202,204,
Pb-204,206,207,208, Bi-209, U-235,238, Np-237, Pu-238,239,240,241,242,
Am-241,242,242m

http://wwwndc.tokai-sc.jaea.go.jp/ftpnd/jendl/jendl-he-2007.html

Physical Processes included in PHITS

- **Transport** *between collisions*
  - **External Field** *and Optical devices*
    - Magnetic Field
    - Gravity
    - Super mirror (reflection)
    - Mechanical devices, T0 chopper
  - **Ionization process** *for charge particle*
    - SPAR, ATIMA code
    - Energy straggling
    - Angle Straggling
- **Collisions** *with nucleus*
  - **Nuclear Data** ENDF-B/VI, LA150, …..
    - MCNP code
  - **Particle Induced Collisions**
    - JAM code
  - **Heavy Ion Collisions**
    - JQMD code

Nuclear Reaction Models

MCNP code *for Neutron Transport below 20 MeV with Nuclear Data*

Monte Carlo N-Particle Transport Code System *developed by*
Los Alamos National Lab.

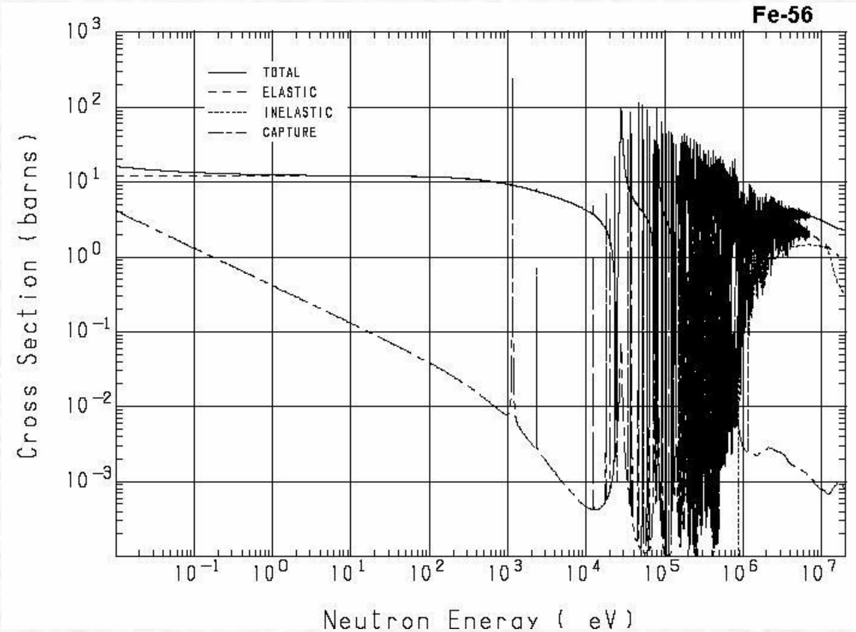
for Neutrons, Photons, Electrons

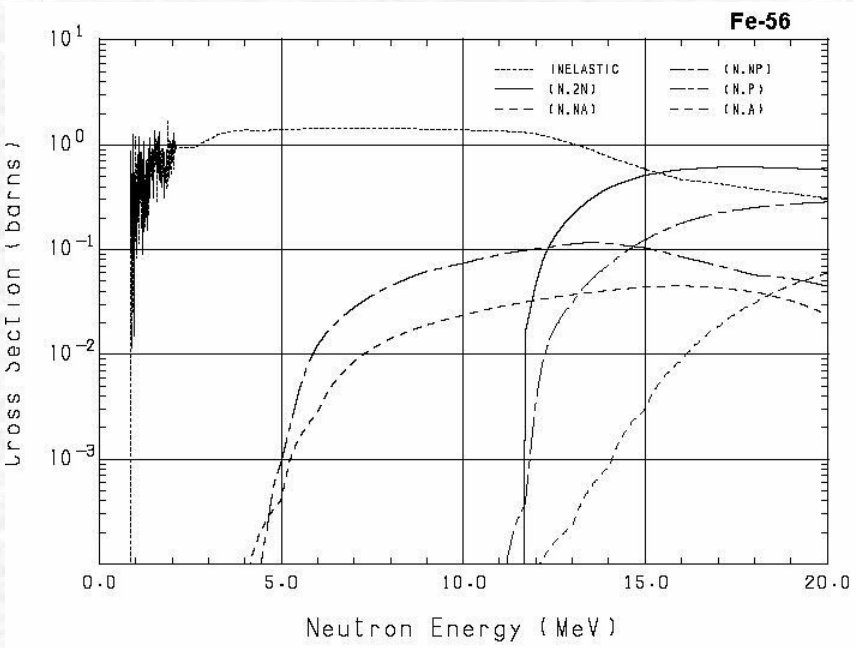
by using Evaluated Nuclear Data, such as **ENDF, JENDL, …**

Applications:

Nuclear Criticality Safety, Radiation Shielding, Fission Reactor Design, …

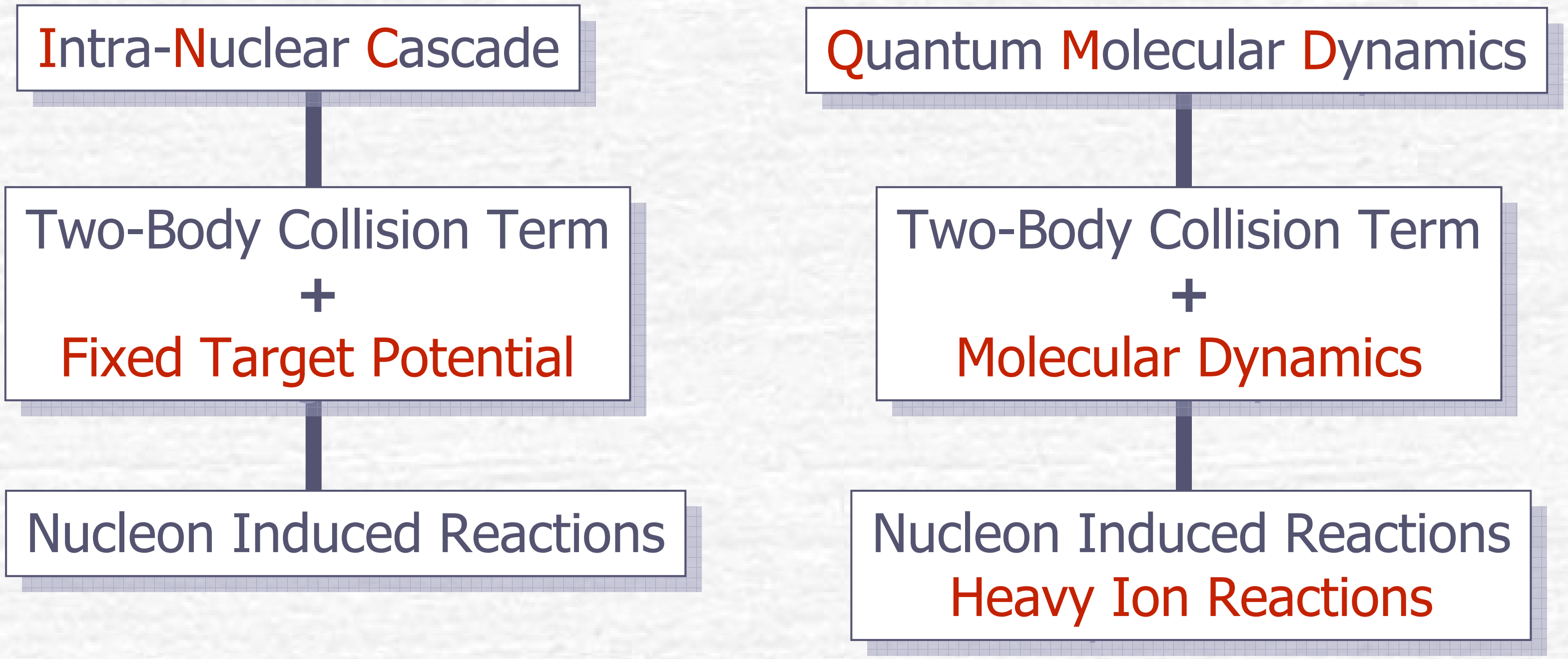
n-56Fe Reaction Cross Sections





Numerical Simulation *for high energy nuclear reactions*

1. Tow-Body Collision (hard interaction)
   - elementary cross sections for hadrons
2. Potential (soft interaction)
   - ground state, residual nucleus, excitation energy, recoil energy

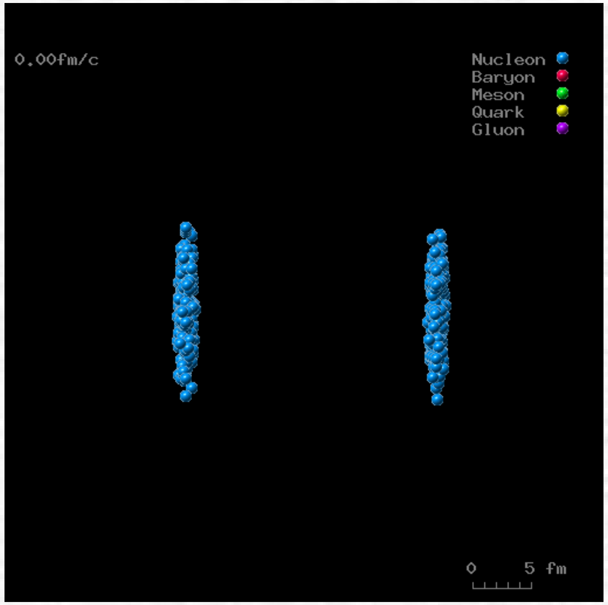


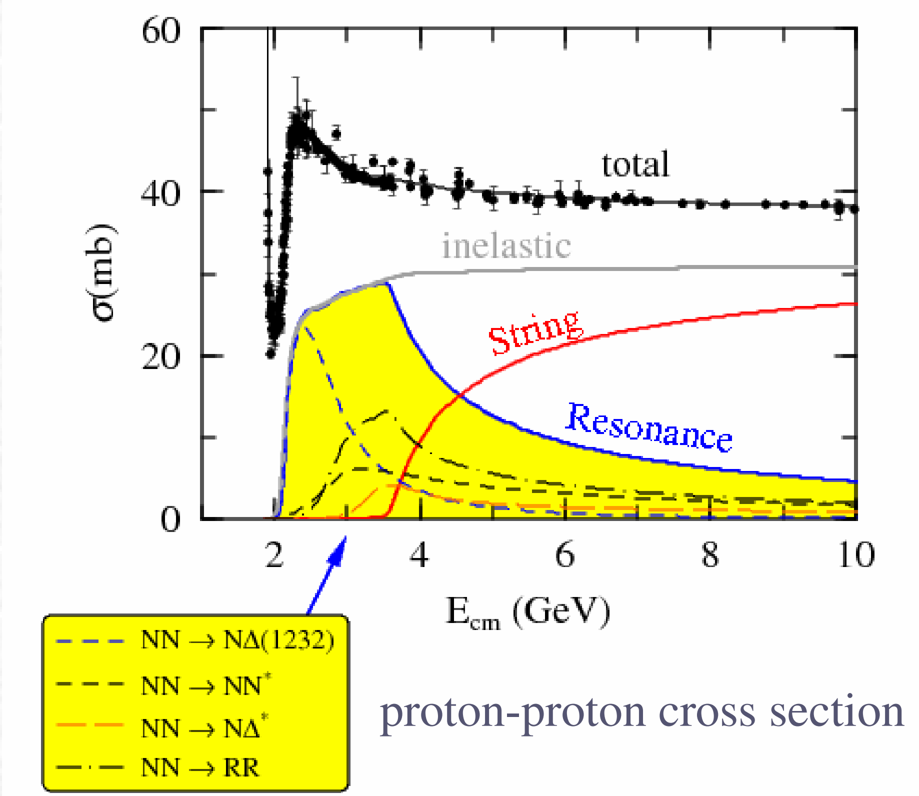
JAM code *for Hadron Nucleus Collisions up to 200 GeV*

Introducing JAM *(Jet AA Microscopic Transport Model)*   Y. Nara et.al. *Phys. Rev.* **C61** (2000) 024901

JAM is a ***Hadronic Cascade Model***, which explicitly treats all established hadronic states including resonances with explicit spin and isospin as well as their anti-particles.
We have parameterized all ***Hadron-Hadron Cross Sections***, based on ***Resonance Model*** and ***String Model*** by fitting the available experimental data.

Au+Au 200GeV/u in cm



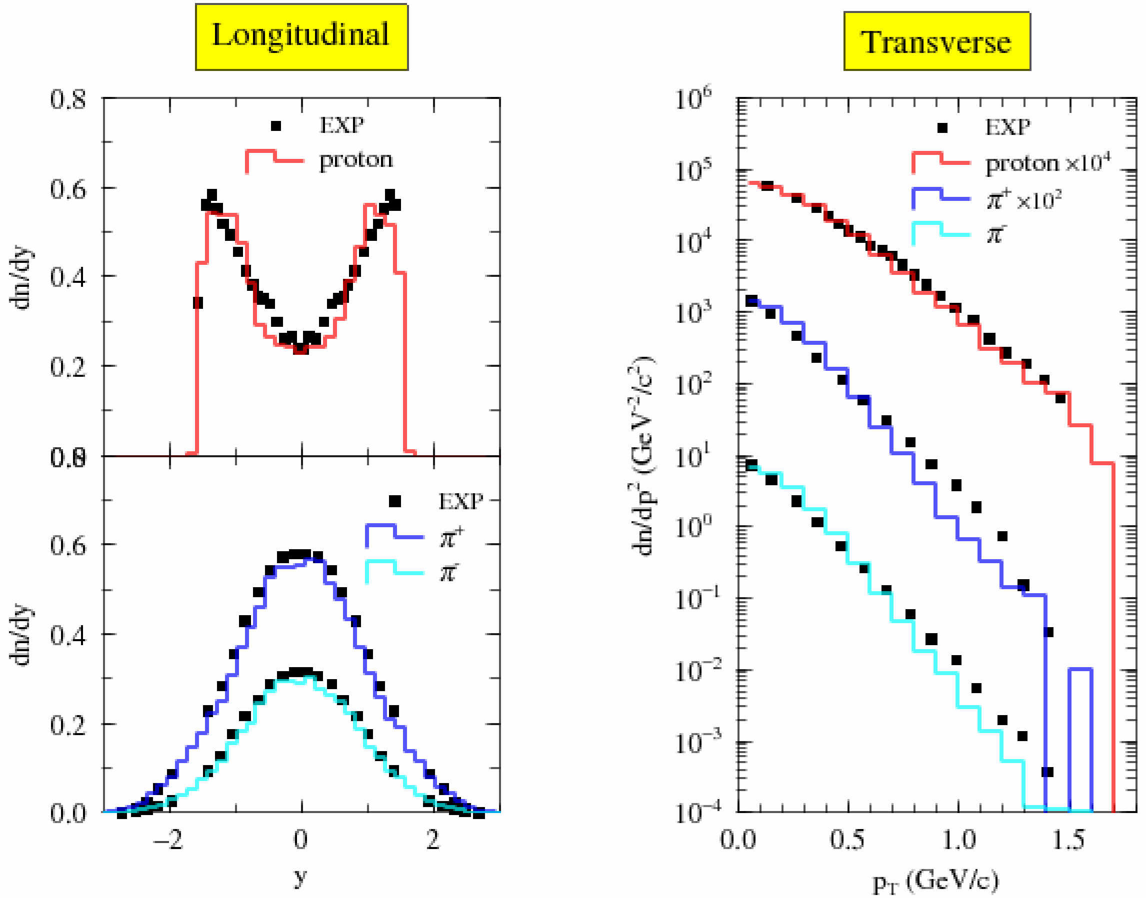


proton-proton cross section

119 kinds of Mesons
170 kinds of Baryons

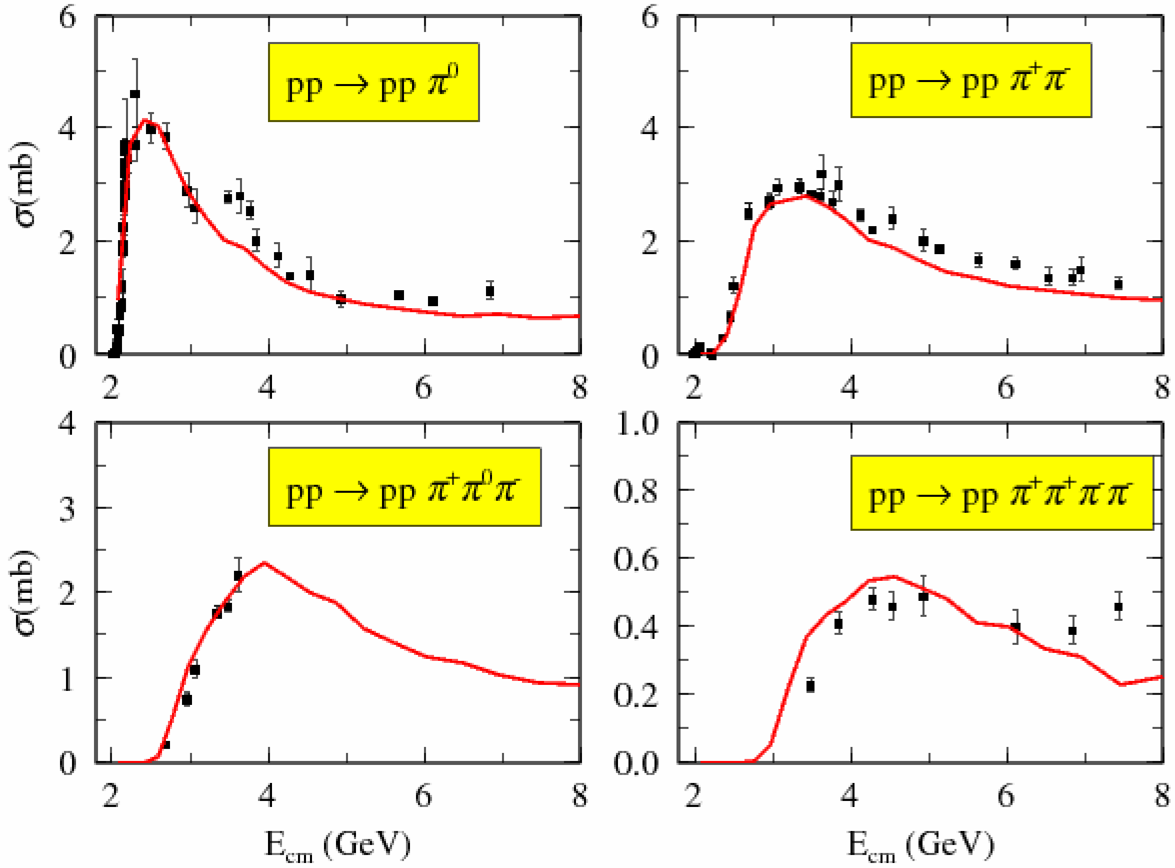
Proton-Proton (12GeV/c) Inclusive Spectra

Rapidity y distributions (left panel) and the transverse momentum distributions (right panel) of proton, π^+ and π^- in pp collisions at 12 GeV/c.



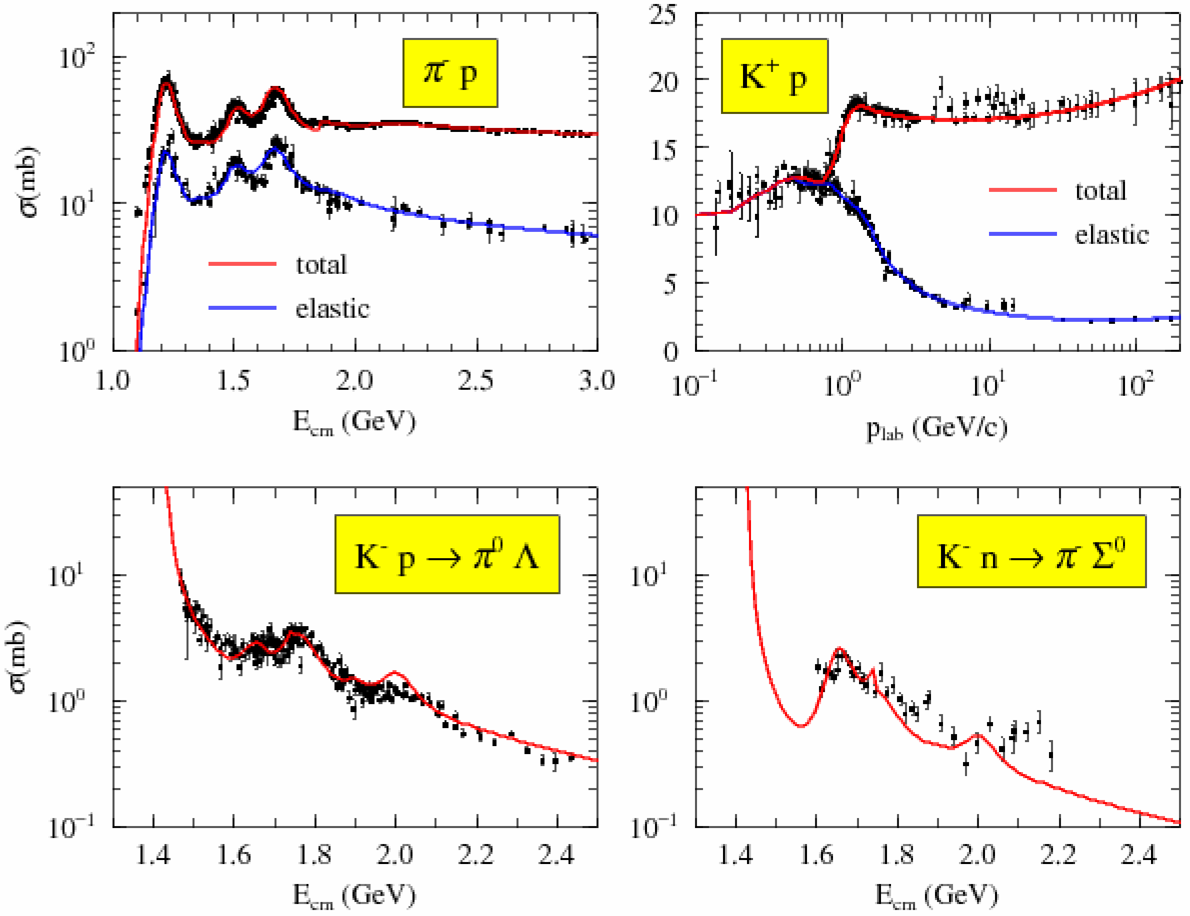
Proton-Proton Exclusive Cross Sections

Energy dependence of the exclusive pion production cross sections for proton-proton reactions as a function of c.m. energy.



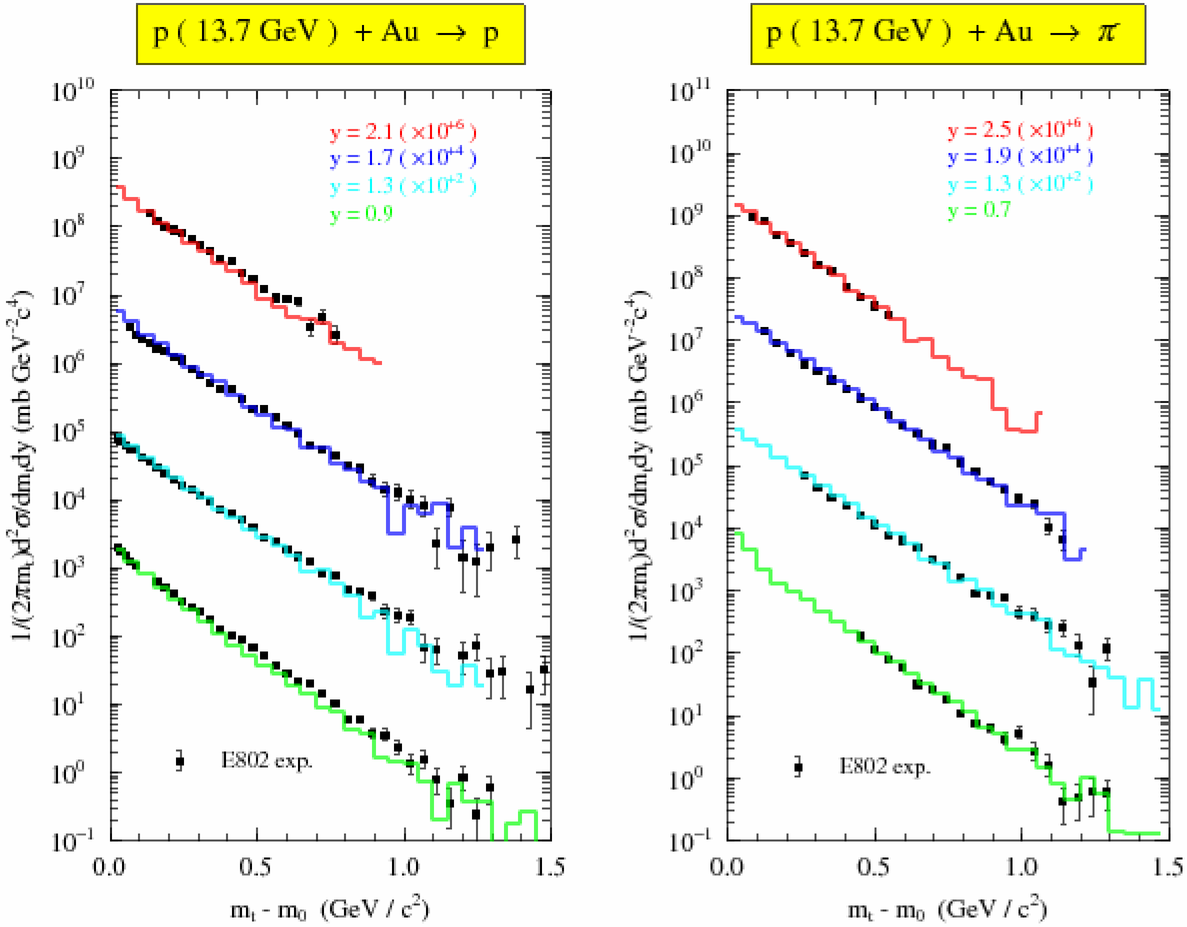
Other Hadron-Hadron Cross Sections

Parameterization of the total and elastic π–p and K^+p cross sections (upper panel), and the energy dependence of the exclusive cross sections of $K^-p \rightarrow \pi^0\Lambda$ and $K^-n \rightarrow \pi^-\Sigma^0$ (lower panel).



DDX of Nucleons and Pions from p-A Reactions

Invariant transverse mass distribution of proton (left panel) and π^- (right panel) from proton on thin Au target reaction at 13.7 GeV.



1. Two-body collision

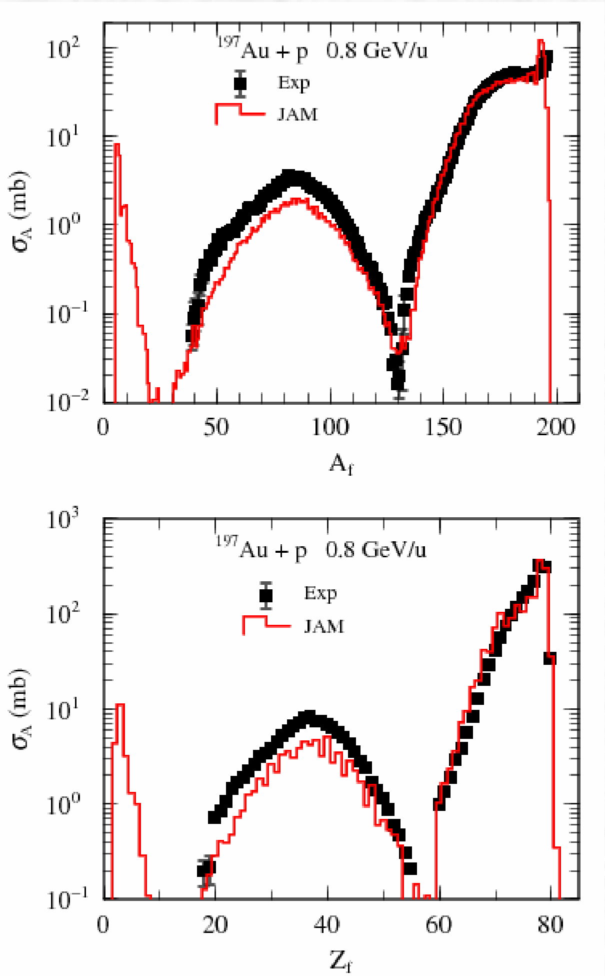
2. Potential

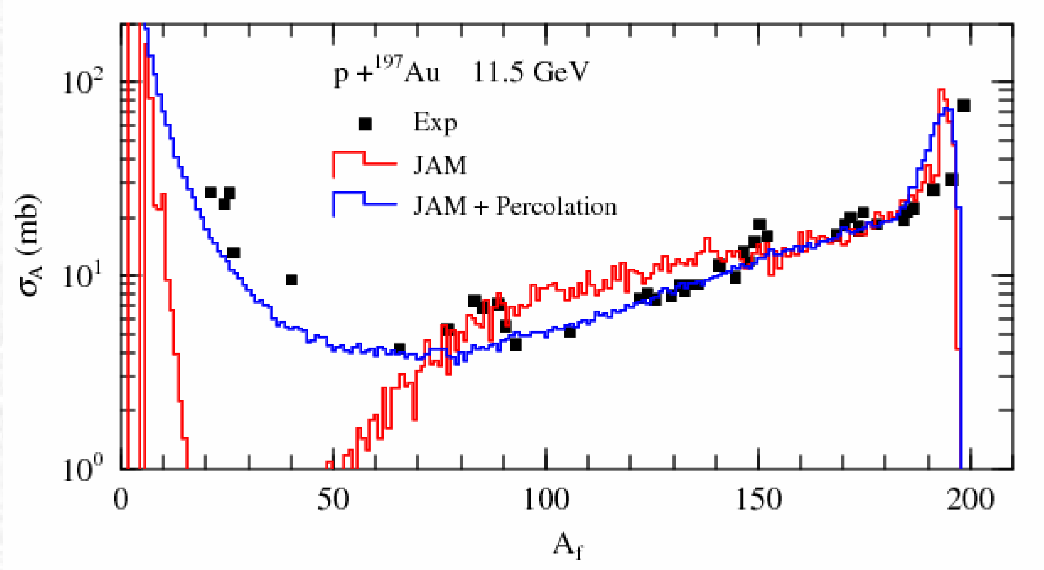
   1). Initial ground state of target

   - Woods-Saxon for coordinates
   - Local Thomas-Fermi for momentum

   2). Frozen until participated
   3). Fixed square-well potential
   4). no reflection, no refraction

Fragment Mass Distribution





JAM + Percolation

Y. Hirata, et.al.; *Nucl. Phys*. **A707** (2002) 193.

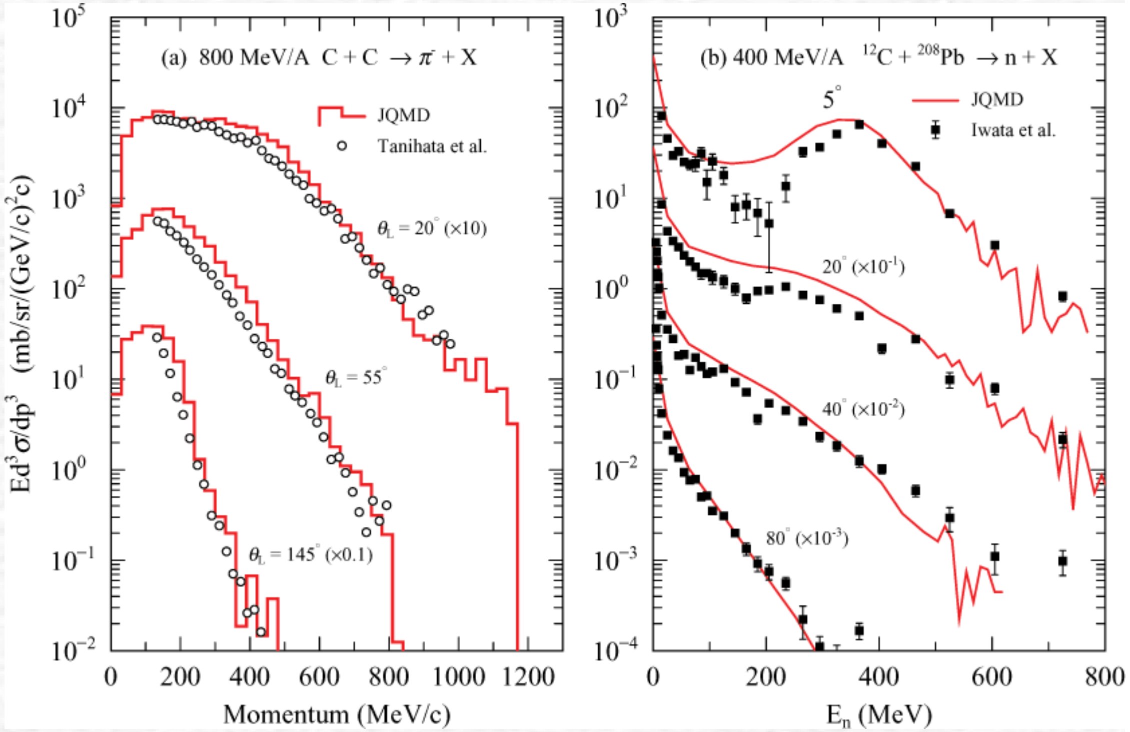
JAM + SDM

JQMD code *for Nucleus-Nucleus Collisions up to 100 GeV/u*

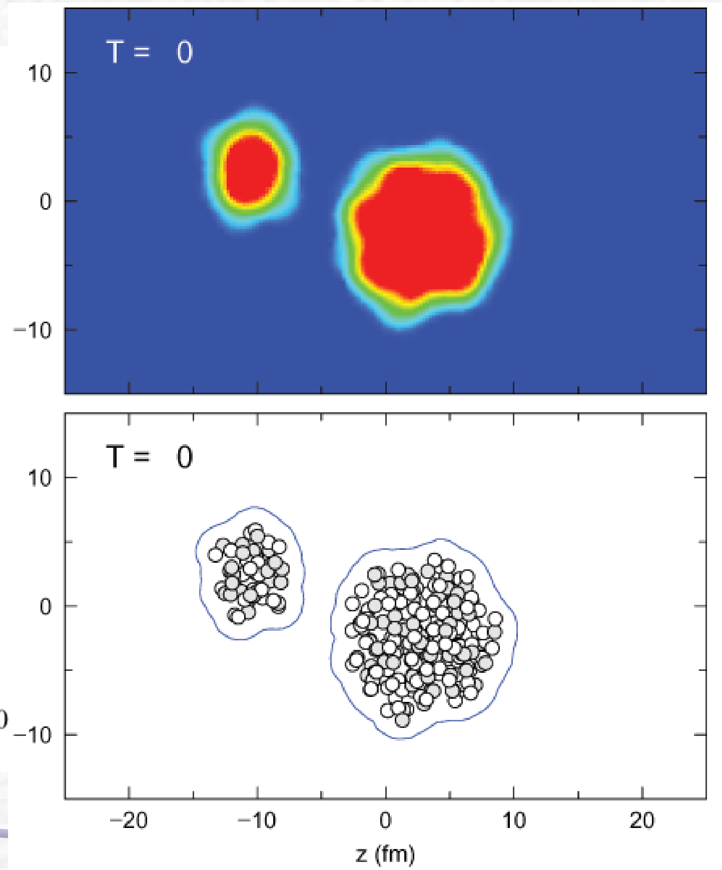
JQMD *(Jaeri Quantum Molecular Dynamics)* *for Simulation of Nucleus-Nucleus Collisions*

K. Niiita et.al. *Phys. Rev*. **C52** (1995) 2620 *http://hadron31.tokai.jaeri.go.jp/jqmd/*

Analysis of Nucleus-Nucleus Collisions by ***JQMD***



^{56}Fe 800 MeV/u on ^{208}Pb



Basic Equations of QMD

Nucleon state (i) is represented by a Gaussian wave packet.

$$\phi_i(\boldsymbol{r}) = \frac{1}{(2\pi L)^{3/4}} \exp\left[-\frac{(\boldsymbol{r}-\boldsymbol{R}_i)^2}{4L} + \frac{i}{\hbar} \boldsymbol{r}\cdot\boldsymbol{P}_i \right].$$

The one-body distribution function is obtained by the Wigner transform of the wave function,

$$f_i(\boldsymbol{r},\boldsymbol{p}) = 8 \cdot \exp\left[-\frac{(\boldsymbol{r}-\boldsymbol{R}_i)^2}{2L} - \frac{2L(\boldsymbol{p}-\boldsymbol{P}_i)^2}{\hbar^2} \right].$$

The equation of motion of $\boldsymbol{R}_i$ and $\boldsymbol{P}_i$ is given by the time-dependent variational principle,

$$\dot{\boldsymbol{R}}_i = \frac{\partial H}{\partial \boldsymbol{P}_i}, \qquad \dot{\boldsymbol{P}}_i = -\frac{\partial H}{\partial \boldsymbol{R}_i}.$$

Hamiltonian H is given by

$$H = \sum_i (m_i^2 + \boldsymbol{P}_i^2)^{1/2}$$: Relativistic Energy

$$+ \frac{1}{2}\frac{A}{\rho_0}\sum_i \langle \rho_i \rangle + \frac{1}{1+\tau}\frac{B}{\rho_0^\tau}\sum_i \langle \rho_i \rangle^\tau$$: Skyrme Terms

$$+ \frac{1}{2}\sum_{i,j(\neq i)} \frac{e_i e_j}{|\boldsymbol{R}_i-\boldsymbol{R}_j|} \mathrm{erf}(\, |\boldsymbol{R}_i-\boldsymbol{R}_j| / \sqrt{4L}\,)$$: Coulomb Potential

$$+ \frac{C_s}{2\rho_0}\sum_{i,j(\neq i)} c_i c_j \rho_{ij}, \quad c_i = \begin{cases} 1 & \text{for proton} \\ -1 & \text{for neutron} \end{cases}$$: Symmetry Term

The density is given by

$$\rho_i(\boldsymbol{r}) \equiv \int \frac{d\boldsymbol{p}}{(2\pi\hbar)^3} f_i(\boldsymbol{r},\boldsymbol{p}) = \frac{1}{(2\pi L)^{3/2}} \exp\left[-\frac{(\boldsymbol{r}-\boldsymbol{R}_i)^2}{2L} \right].$$

The overlap function is defined by

$$\langle \rho_i \rangle \equiv \sum_{j\neq i} \rho_{ij} \equiv \sum_{j\neq i} \int d\boldsymbol{r}\, \rho_i(\boldsymbol{r})\, \rho_j(\boldsymbol{r}) = \sum_{j\neq i} \frac{1}{(4\pi L)^{3/2}} \exp\left[-\frac{(\boldsymbol{R}_i-\boldsymbol{R}_j)^2}{4L} \right].$$

The saturation condition of nuclear matter ($\rho_0 = 0.168\ \mathrm{fm}^{-3}$, $E_b = 16$ MeV)

$A = -219.4$ MeV
$B = 165.3$ MeV

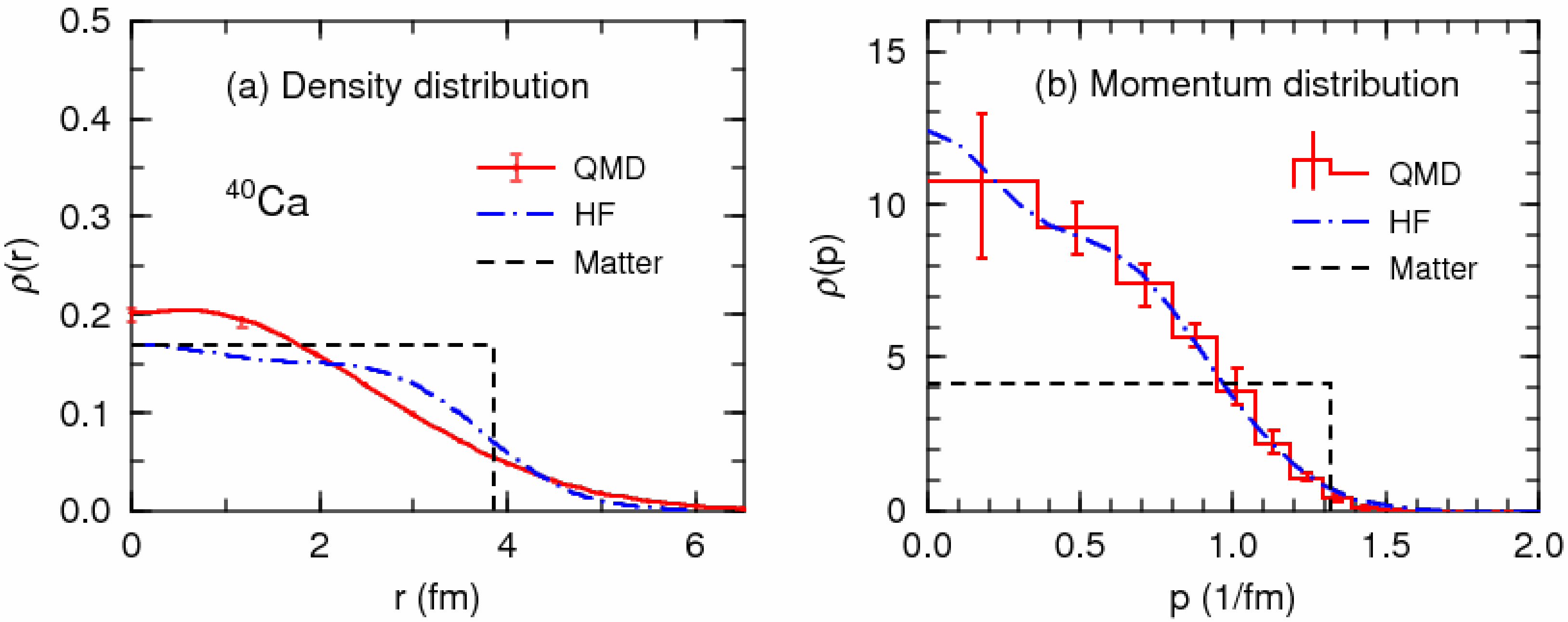
compressibility ($K = 237.3$ MeV)
$\tau = 4/3$

symmetry energy
$C_s = 25$ MeV

width of Gaussian (free parameter)
$L = 2\ \mathrm{fm}^2$

Ground State of QMD

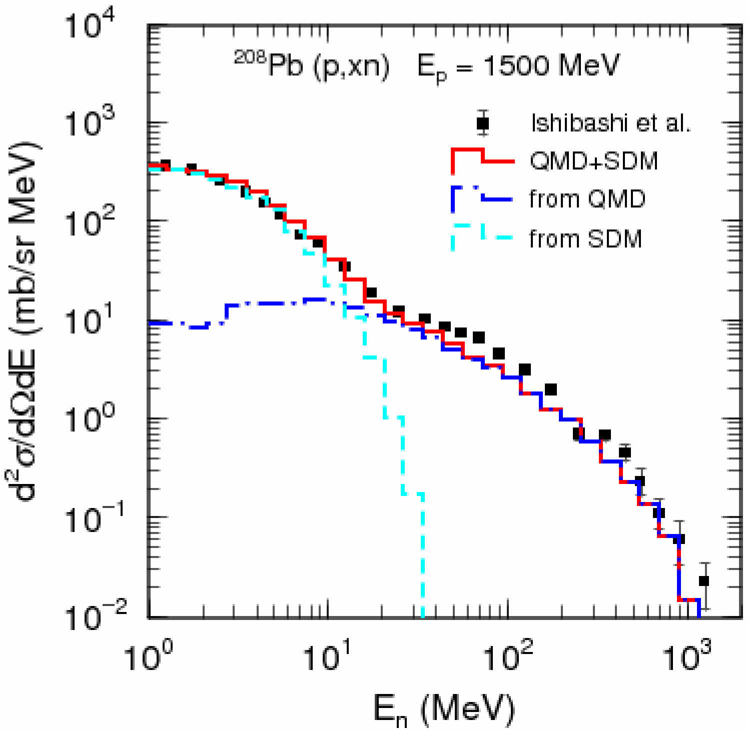
The ground state is generated by packing $\boldsymbol{R}_i$ and $\boldsymbol{P}_i$ randomly based on the Woods-Saxon distribution in the coordinate space and local Thomas-Fermi approximation in the momentum space. The ground state is a self-bind system and stable up to the time 200 fm/c.

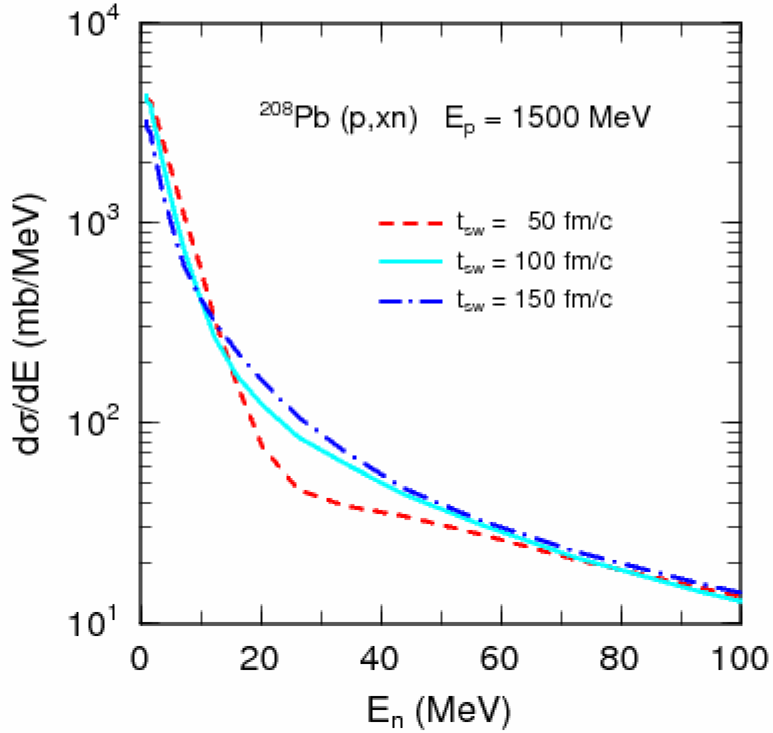


This state is not a energy minimum state !!

QMD + SDM (Statistical Decay Model)

At the end of the dynamical stage, the QMD simulation yields many nucleons and fragments which are normally in highly excited states. We stop the QMD calculation and switch to the statistical decay model (SDM) at the end of the dynamical stage.
The final results are not sensitive to the switching time if we use the switching time from 100 fm/c to 150 fm/c.

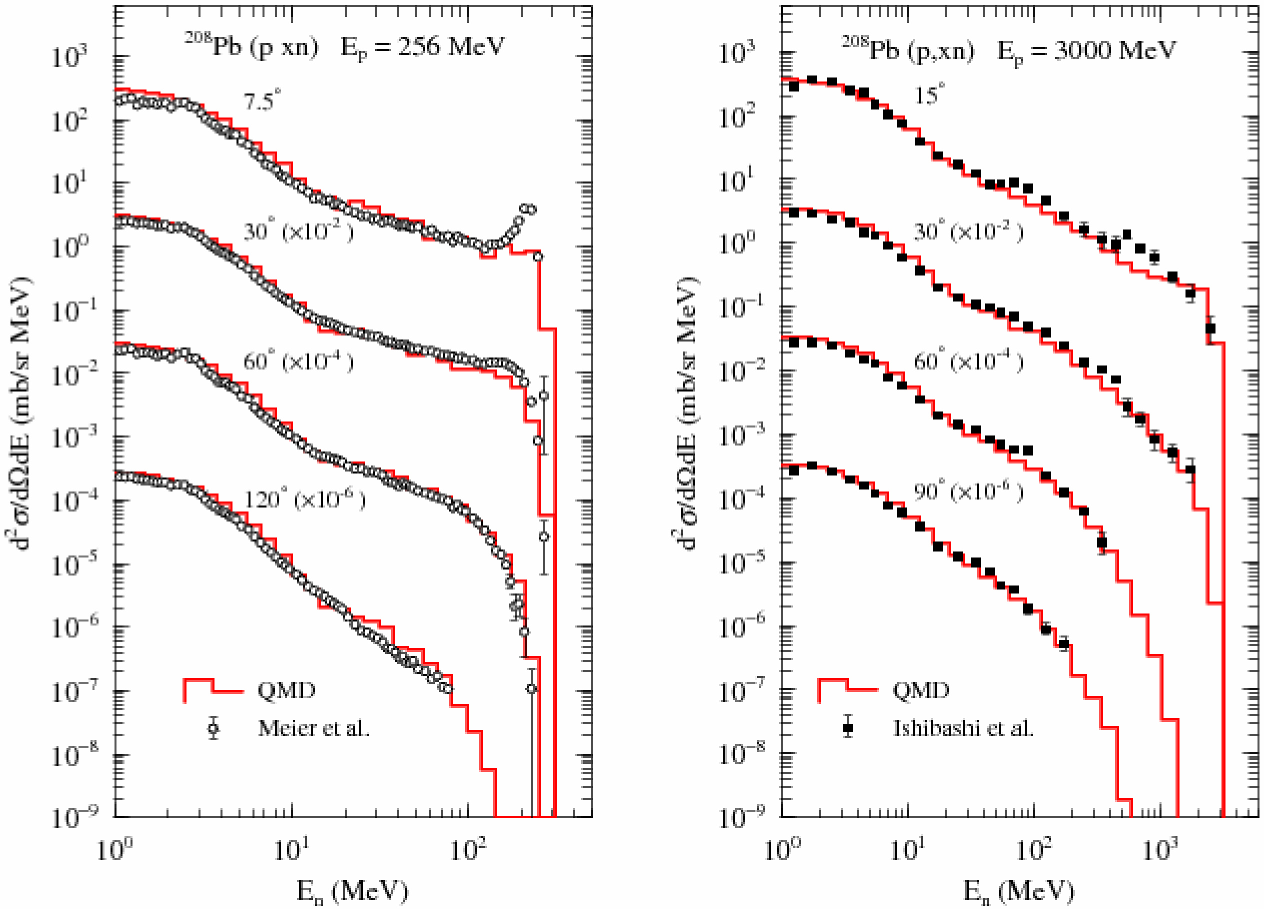




Nucleon Induced Reactions

Neutron energy spectra for the reaction p +^{208}Pb. The incident energy is 256 MeV (left-hand-side) and 3 GeV (right-hand side). The solid histograms are the results of QMD and the open circles and the full boxes with error bars denote the experimental data.

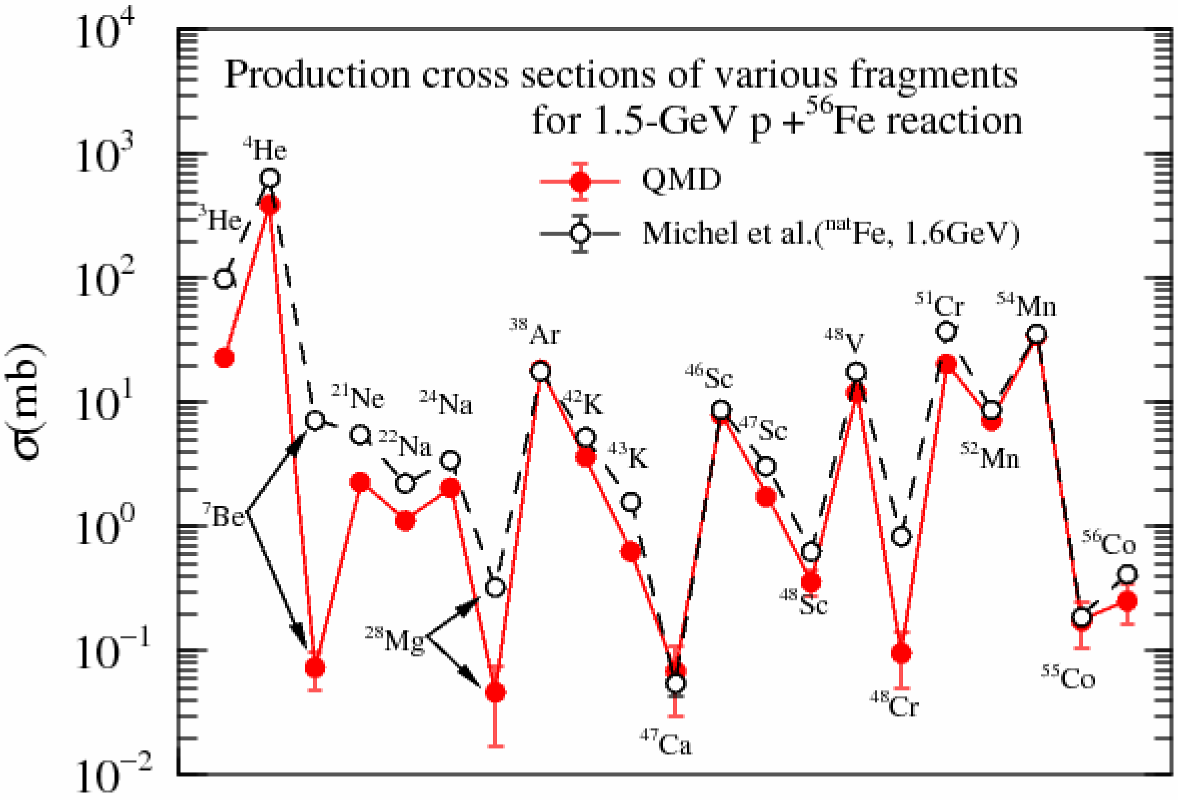
K. Niiita et.al. *Phys. Rev*. **C52** (1995) 2620



Nucleon Induced Reactions

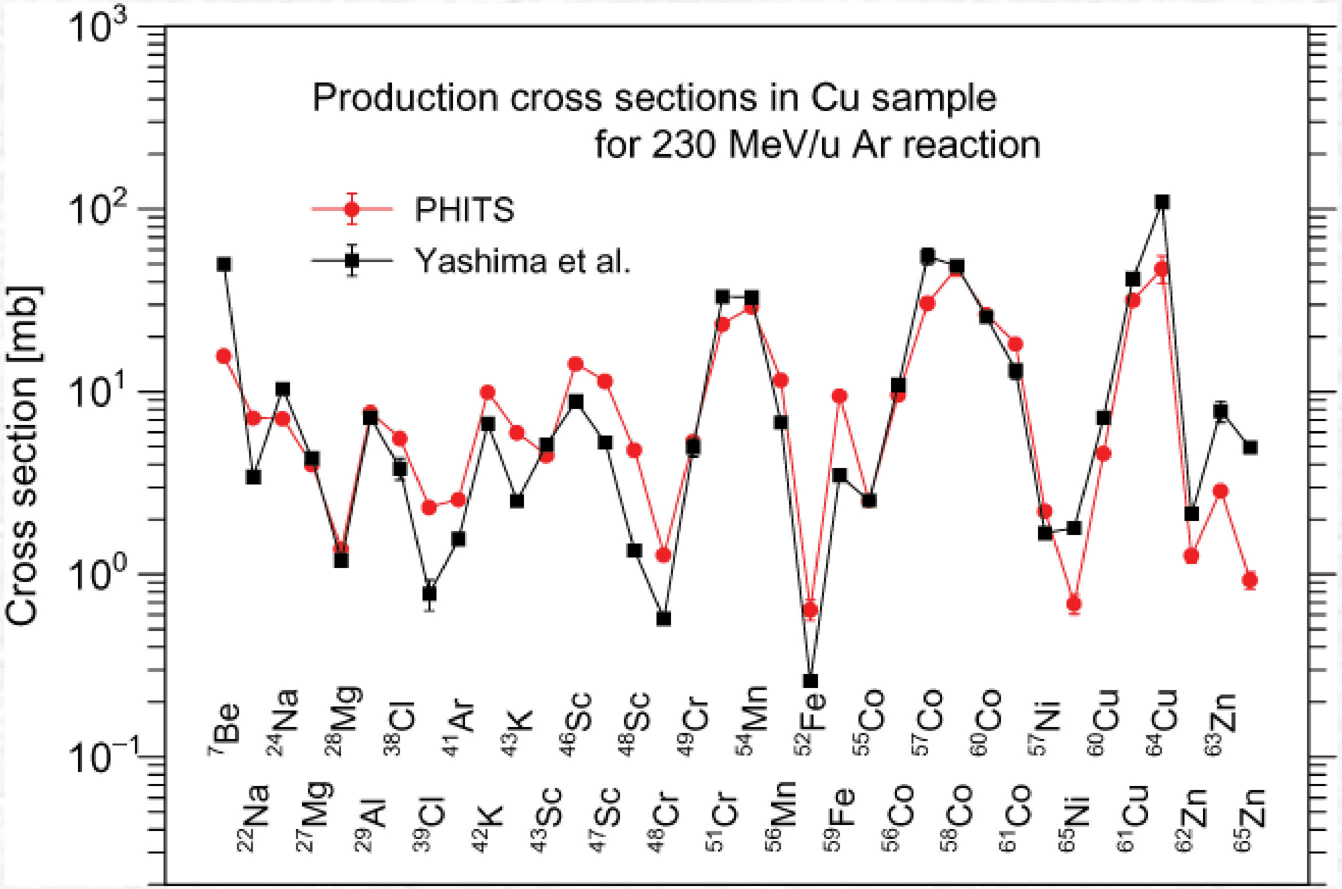
Production cross sections of various fragments for p (1.5 GeV) +^{56}Fe reaction. The full circles connected by a solid line denote the results of QMD, while the open circles connected by a dashed line are obtained experimentally by Michel et al. measured at 1.6 GeV for ^{nat}Fe.

S. Chiba et.al. *Phys. Rev.* **C54** (1996) 285



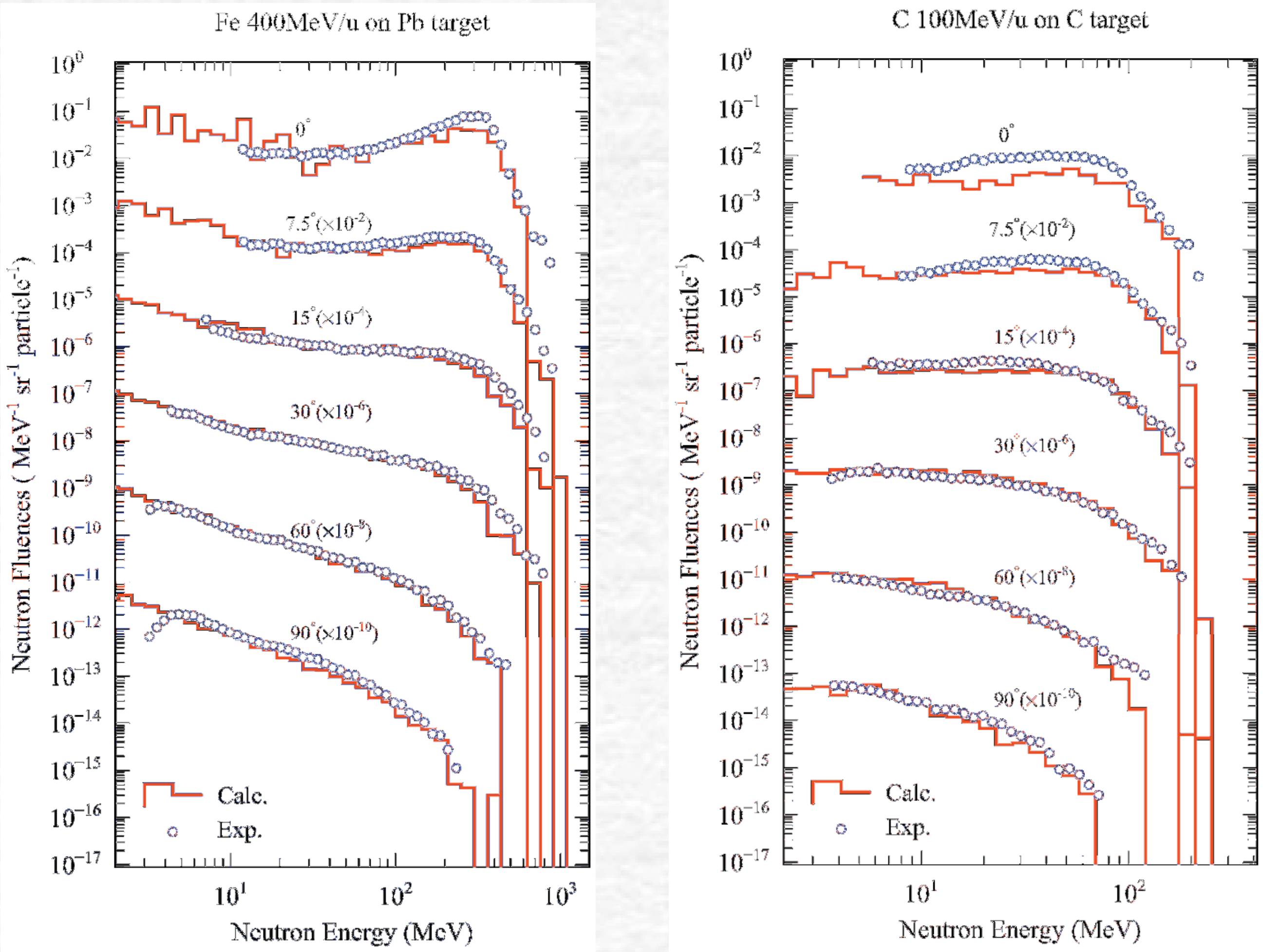
Heavy Ion Induced Reactions

H. Yashima et.al. *Nucl. Instr. Meth.* **B226** (2004) 243



Neutron Spectra from Thick Target

Introducing JQMD in PHITS : H. Iwase et.al. *J. Nucl. Sci.Technol.* **39** (2002) 1142

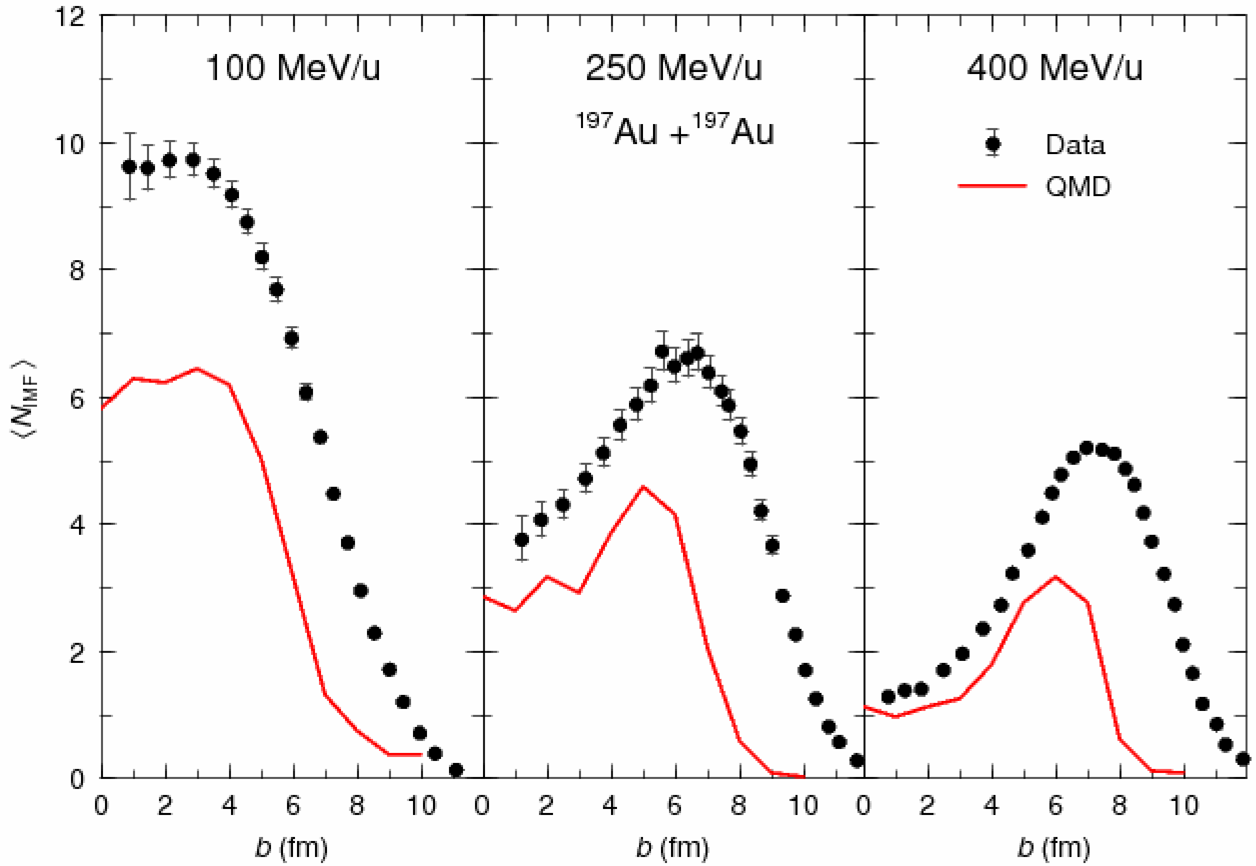


Heavy Ion Reactions

IMF multiplicities for three incident energies (100, 250 and 400 MeV/nucleon) of Au + Au reactions as a function of the impact parameter b. The solid lines denote the results of the QMD, while the solid circles with error bars are the experimental data.

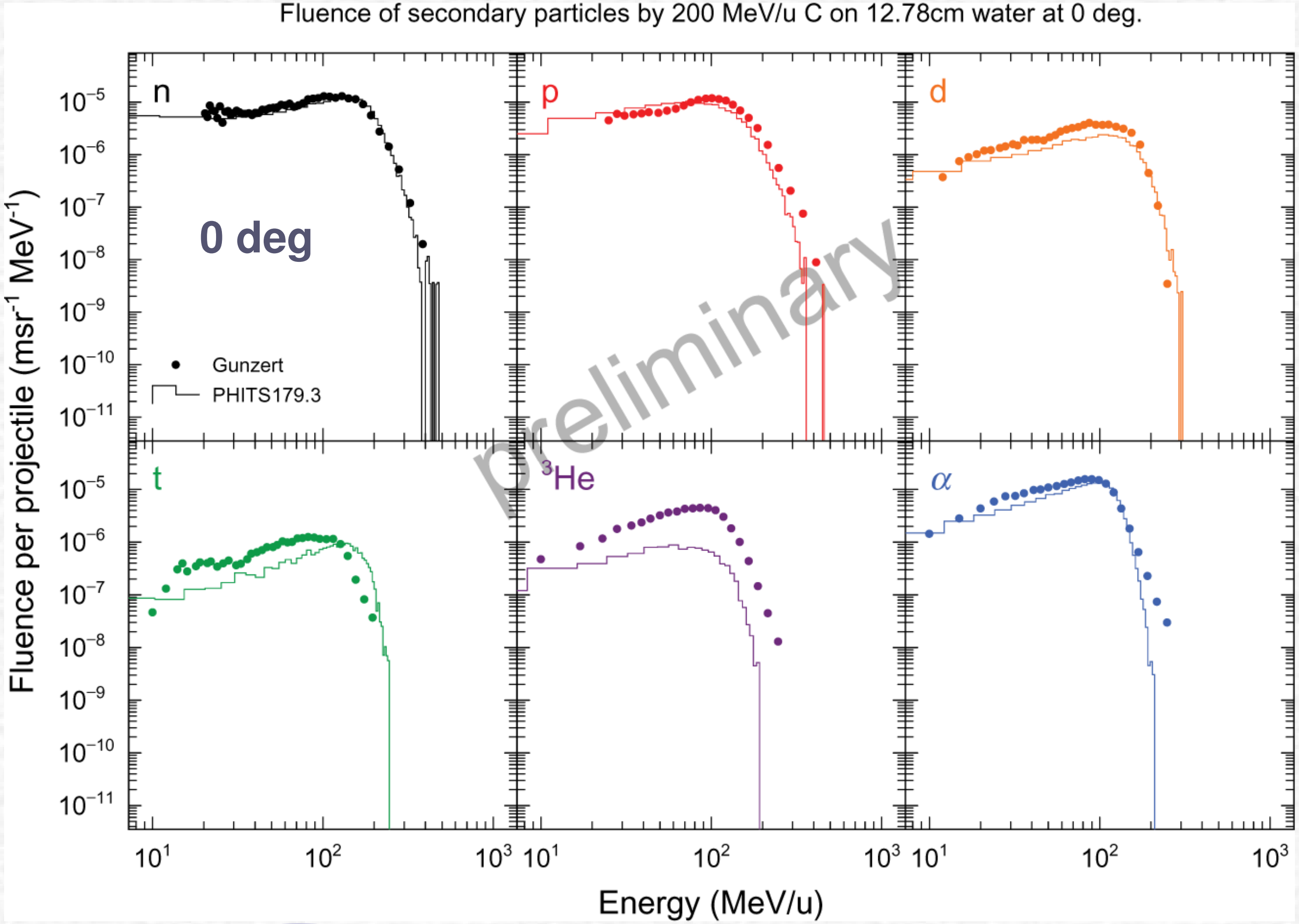
T. Maruyama et.al. *Prog. Theor. Phys.* **98** (1997) 87

IMF 3 ≤ Z ≤ 30

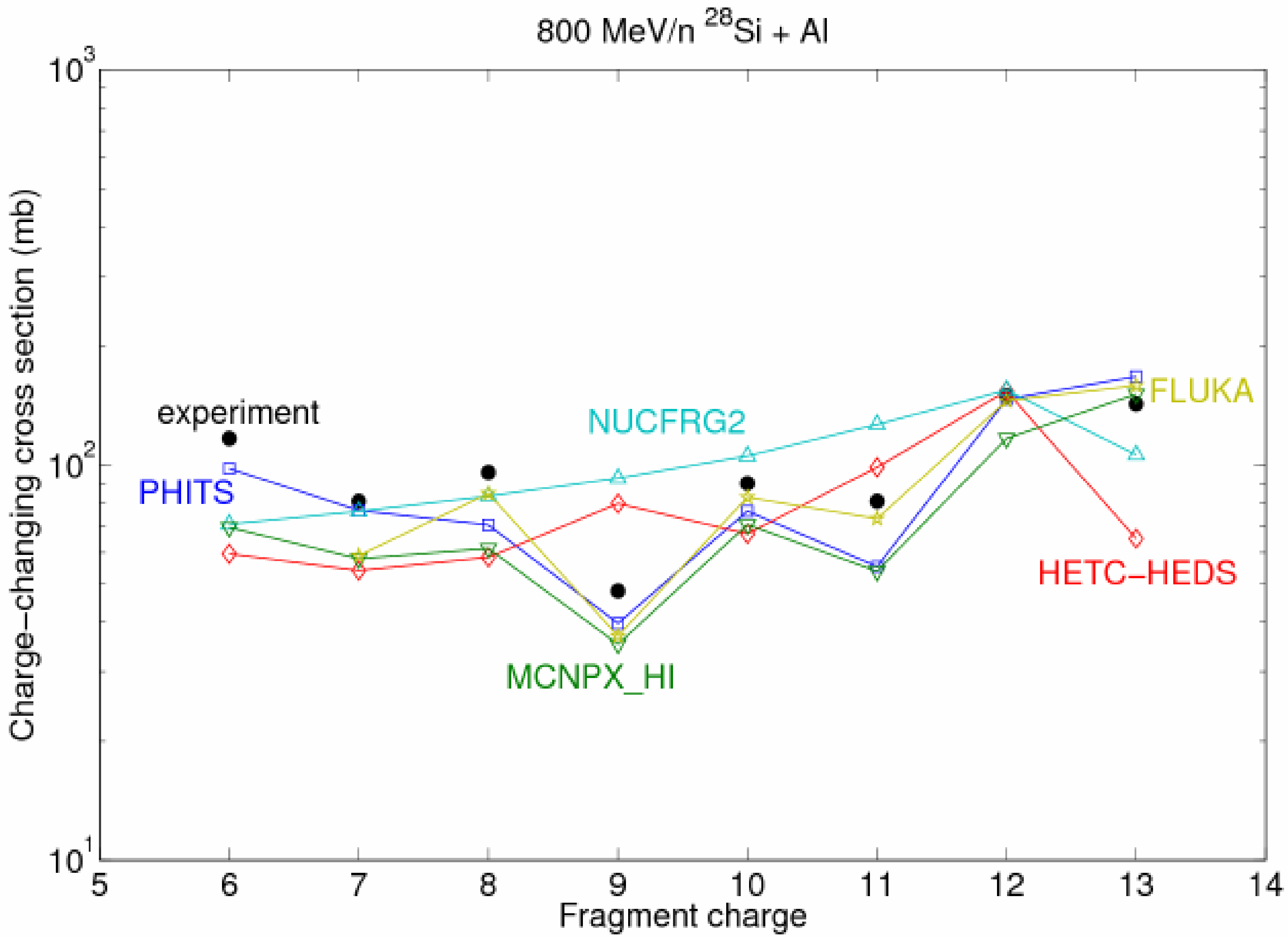


Secondary Particle Production Cross Sections

From 200 MeV/u Carbon beam on 12.78 cm depth Water by K. Gunzert-Marx at GSI



Charge Changing Cross Section



by L. Sihver

Numerical Simulation *for high energy nuclear reactions*

1. Tow-Body Collision (hard interaction)
   - elementary cross sections for hadrons
2. Potential (soft interaction)
   - ground state, residual nucleus, excitation energy, recoil energy

Intra-Nuclear Cascade

Two-Body Collision Term
+
Fixed Target Potential

Nucleon Induced Reactions

Quantum Molecular Dynamics

Two-Body Collision Term
+
Molecular Dynamics

Nucleon Induced Reactions
Heavy Ion Reactions

Limitations and Problems both in JAM and JQMD

1. Tow-Body Collision term

- classical description : low energy limit
  independent sequential hadron-hadron collision
  de Broglie wave length « collision distances
- in-medium effects on elementally cross sections:
  free h-h cross sections are used for high energy,
  in-medium n-n cross sections are used for low energy
  How good ? It is related to the final Pauli blocking factor.
- Pauli blocking factor :
  rigid Fermi sphere is assumed in JAM
  too rigid ?
  estimated from one-body phase space factor in JQMD
  huge fluctuation ?

→ FMD, AMD

Limitations and Problems both in JAM and JQMD

2. Potential term

- ground state : → FMD, AMD

  Momentum distribution : Local Thomas Fermi,
  no shell effect,
  no momentum dependent force

- residual nuclei :
  (N,Z) and excitation energy,
  no information for collective motion nor deformation

  → connection to statistical decay models

Limitations and Problems in JAM

- Fixed target potential :
  no dynamical change of nucleus,
  no cluster emission in the dynamical stage

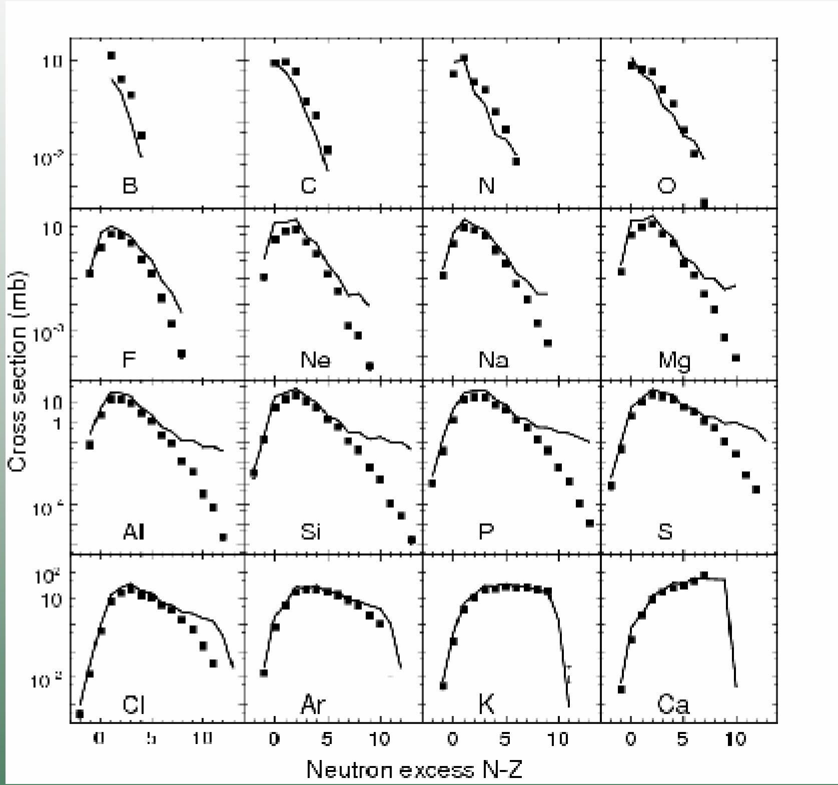
Limitations and Problems in JQMD

- Nucleus : described as a self-binding system
  dynamical change of nucleus,
  cluster emission ??
- ground state is not a energy minimum state
  → spontaneous emission of nucleons
- not fully relativistically covariant
  → unstability of nucleus after boosting
- connection time to statistical model
  → over cooling of the residual nucleus

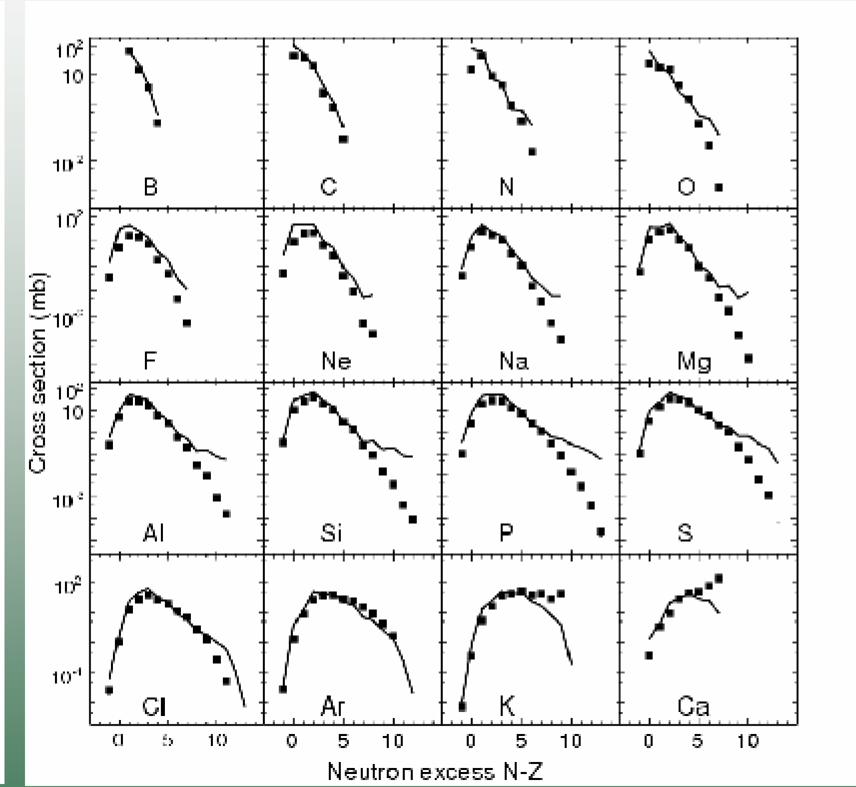
} Solved by new R-JQMD (Relativistic JQMD) by D. Mancusi

$^{48}Ca^{19+}$ at 140 MeV/u

Be Target

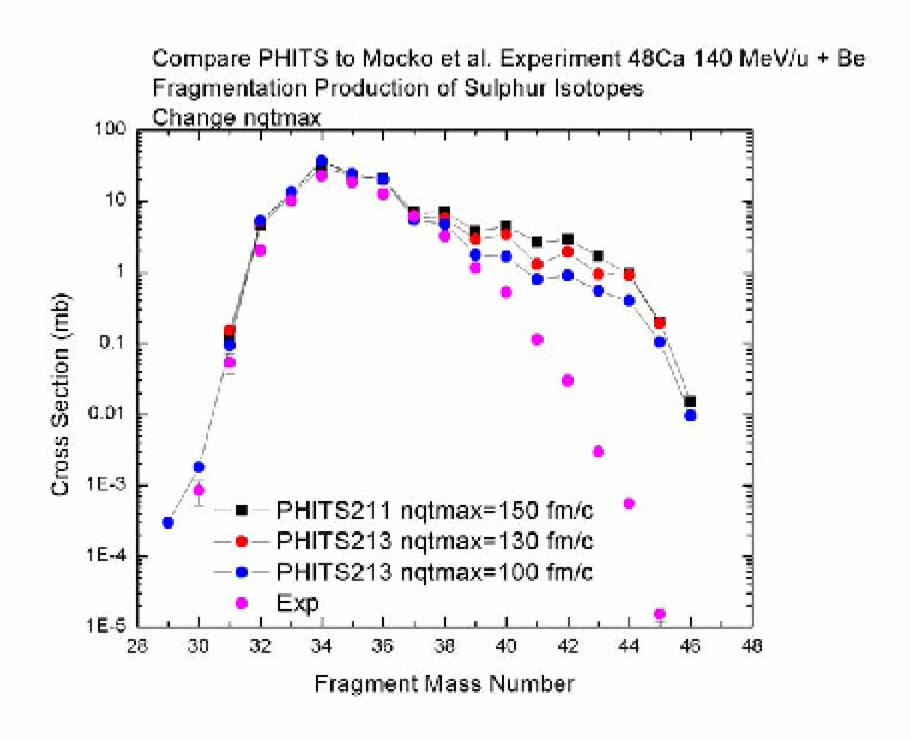


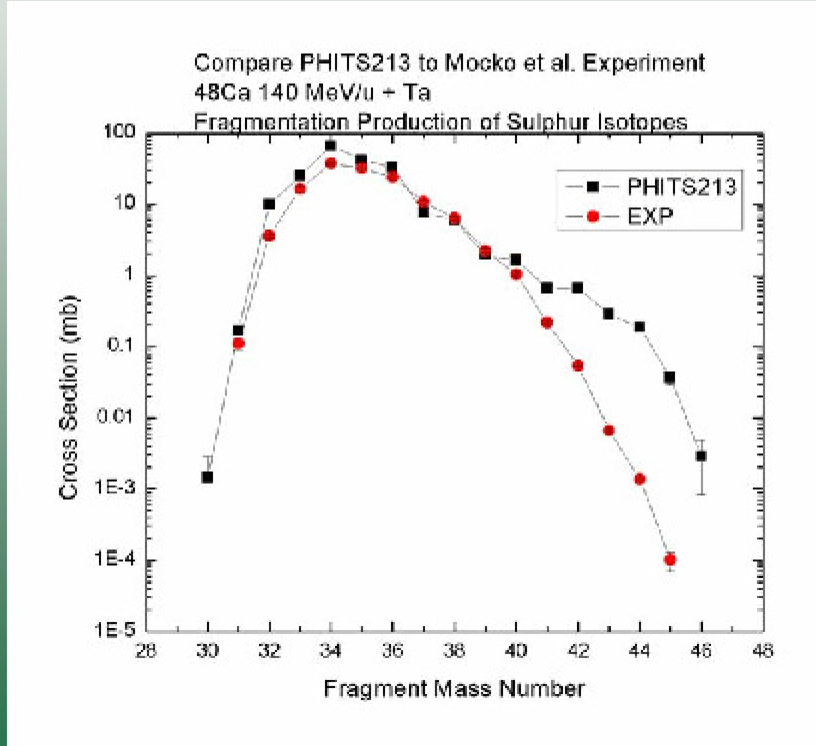
Ta Target



PHITS213 (nqtmax = 100 fm/c)

Exp





U.S. Department of Energy
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Argonne National Laboratory
NSCL Michigan State University
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Strategy *for better description of nuclear reactions*

In PHITS,
Dynamical models (JAM, JQMD) + Statistical Decay model (GEM) can well describe the energetic secondary particles, particularly, neutrons, which are very important for the transport phenomena in material.

However, some cross sections of the fragments are not good.

→ add more sophisticated effective interactions
→ AMD, FMD
→ add new models
    pre-equilibrium model,
    Fermi breakup, percolation, ….

Strategy *for better description of nuclear reactions*

Our strategy for this :
If you need only one-body inclusive quantities,
we use evaluated nuclear data for the fragment cross sections
or some other cross sections.

For an example, for the activation of air and water, we can use
the following cross section data for the yield tally in PHITS.

$^{4}\mathrm{He}(n,x)^{3}\mathrm{H}$	$^{14}\mathrm{N}(n,x)^{3}\mathrm{H}$	$^{14}\mathrm{N}(n,x)^{7}\mathrm{Be}$	$^{14}\mathrm{N}(n,x)^{11}\mathrm{Be}$	$^{14}\mathrm{N}(n,x)^{10}\mathrm{C}$	$^{14}\mathrm{N}(n,x)^{11}\mathrm{C}$
$^{14}\mathrm{N}(n,x)^{14}\mathrm{C}$	$^{14}\mathrm{N}(n,x)^{13}\mathrm{N}$	$^{16}\mathrm{O}(n,x)^{3}\mathrm{H}$	$^{16}\mathrm{O}(n,x)^{7}\mathrm{Be}$	$^{16}\mathrm{O}(n,x)^{11}\mathrm{Be}$	$^{16}\mathrm{O}(n,x)^{10}\mathrm{C}$
$^{16}\mathrm{O}(n,x)^{11}\mathrm{C}$	$^{16}\mathrm{O}(n,x)^{14}\mathrm{C}$	$^{16}\mathrm{O}(n,x)^{15}\mathrm{C}$	$^{16}\mathrm{O}(n,x)^{13}\mathrm{N}$	$^{16}\mathrm{O}(n,x)^{16}\mathrm{N}$	$^{16}\mathrm{O}(n,x)^{14}\mathrm{O}$
$^{16}\mathrm{O}(n,x)^{15}\mathrm{O}$	$^{4}\mathrm{He}(p,x)^{3}\mathrm{H}$	$^{14}\mathrm{N}(p,x)^{7}\mathrm{Be}$	$^{14}\mathrm{N}(p,x)^{11}\mathrm{Be}$	$^{14}\mathrm{N}(p,x)^{10}\mathrm{C}$	$^{14}\mathrm{N}(p,x)^{11}\mathrm{C}$
$^{14}\mathrm{N}(p,x)^{13}\mathrm{N}$	$^{14}\mathrm{N}(p,x)^{14}\mathrm{O}$	$^{16}\mathrm{O}(p,x)^{3}\mathrm{H}$	$^{16}\mathrm{O}(p,x)^{7}\mathrm{Be}$	$^{16}\mathrm{O}(p,x)^{11}\mathrm{Be}$	$^{16}\mathrm{O}(p,x)^{10}\mathrm{C}$
$^{16}\mathrm{O}(p,x)^{11}\mathrm{C}$	$^{16}\mathrm{O}(p,x)^{14}\mathrm{C}$	$^{16}\mathrm{O}(p,x)^{13}\mathrm{N}$	$^{16}\mathrm{O}(p,x)^{14}\mathrm{O}$	$^{16}\mathrm{O}(p,x)^{15}\mathrm{O}$	