Validation of Ion Physics in Geant4 against carbon

Takashi Sasaki
KEK
Outline

• Introduction
  – Geant4 validation

• Protons
  • Tsukasa Aso’s talk

• Carbons
  – Bragg Peak
    • Does distribution in water
    • Satoru Kameoka’s talk at IEEE-NSS
    • To be submitted to PMB
  – Cross section measurement
    • Emulsion
    • Toshiyuki Toshito’s talk at IEEE-NSS
    • To be submitted to NIM

• Voxel graphics
  – gMocren http://geant4.kek.jp/gMocren
Verification and Validation

• Verification
  – The aim is obtaining a right program code for a process
    • To see the code is working as intended
    • Code review by users is good aspect of open source

• Validation
  – To test the given model is right in what precision at what parameter ranges
Validation of Geant4

• For validation purposes, we need to pay an extra attention to compare with measurement and simulation
  – Normalization should be done very carefully
  • In many cases, normalization is done to obtain good agreements between measurement and simulation
Normalization

• Why?
  1. Total number of incident particles are not known
     – We cannot avoid this
  2. Knowledge on geometry is not complete e.g. missing material or wrong dimension
     – Use “good experimental data”
     – Do the experiment by ourselves if necessary
  3. Beam profiles are not well known
     – Again data from “good experiments” is mandate
Simulation of heavy ion therapy system using Geant4

Satoru Kameoka (KEK, JST-CREST)

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High Energy Accelerator Research Organization (KEK)※1, CREST JST※2, Toyama National College of Maritime Technology※3, Ashikaga Institute of Technology※4, National Institute of Radiological Sciences※5, Accelerator Engineering Corporation※6, Gunma University※7, Ishikawa-harima Heavy Industries※8
• Background / Motivation
  – Rising attention to Heavy ion therapy
  – Three-dimensional Monte-Carlo simulation
    - the most reliable and accurate mean for treatment planning in complex geometry
  – Yet to be understood fragmentation reaction of heavy ion beam significantly modifies dose distribution from that expected from ionization of primary particle.

• Objective of this work
  – Develop a practical simulator of a heavy ion beamline of HIMAC based on Geant4, implementing geometries of beamline instruments
  – Validate the capability of ion reaction models of Geant4 to predict expected dose distribution in a clinical target by comparison with irradiation experiments of carbon beam on a water target.
Beamline

- Overhead view of the heavy ion beamline simulated in this work.
- Instruments implemented as Geant4 geometries are visualized.

New beam line of NIRS-HIMAC for R & D
(overhead view)
Water target

- **Experiment**
  - Dose delivered to the target was measured with an ionization chamber with 2 mm-spaced channels in horizontal direction.
  - Depth-dose distribution was obtained by moving the dosimeter along the beam direction.

- **Simulation**
  - Dose-measured region is divided into voxels and energy deposits in each of them were accumulated.
Physical processes in Geant4

- Determine the secondaries produced in the interaction and calculates the momenta of the particles

- **Ions**
  - Electromagnetic interactions
    - Ionization
    - Multiple scattering
  - Inelastic hadronic reaction
    - Shen’s formula for inclusive reaction cross section
    - G4BinaryLightIonReaction or JQMD
  - Radioactive Decay
    - $^5$He, $^5$Li, $^8$Be etc.

- **Secondaries**
  - Electron / positron
    - Ionization, multiple scattering, bremsstrahlung, annihilation
  - Gamma ray
    - Photo-electric effect, compton scattering, pair production
  - Proton / neutron
    - Pre-compound model (-150 MeV)
    - Binary cascade model (-3 GeV)
Ion reaction models

- Treat the process by two stages:
  (1) initial dynamical phase and (2) later statistical phase

- **G4BinaryLightIonReaction**
  (1) Binary Cascade model
  - Cascade of binary collisions between individual nucleons composing projectile and target nuclei
  (2) Pre-compound model
  - Formation of fragment nuclei based on level densities of possible final states and matrix elements deduced from nucleon-nucleon scattering data

- **JQMD** (developed by Niita et al., and interfaced to Geant4 by T. Koi)
  (1) QMD (Quantum Molecular Dynamics)
  - Gaussian wave function for each nucleon
  - Time evolution described by classical Hamiltonian
  (2) SDM (Statistical Decay Model)
  - Calculation of emission probabilities of nucleon and light nuclei based on Fermi gas model
  - Determination of fragment species based on final positional distribution of the nucleons
Event display

- Scatterer
- Dose monitor
- Ridge Filter
- Multileaf Collimator
- Wobbler Magnets
- Collimator
 Depth-dose distribution 
\(^{12}\text{C} 290 \text{ MeV/n}\) 

Simulated dose is normalized to agree with the experimental data of pristine Bragg peak at the surface of the water target, and the same normalization factor is applied to SOBP.

Pristine Bragg peak

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Spread-out Bragg peak

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Normalization factor determined here
Depth-dose distribution
\((^{12}\text{C} \ 400 \text{ MeV/n})\)

Pristine Bragg peak

wo/ Ridge Filter

Spread-out Bragg peak

w/ Ridge Filter

Normalization factor determined here
Simulation of penumbra measurement (1)

Penumbra widening is well reproduced by simulation.
Simulation of penumbra measurement (2)
Summary

• In simulation of an irradiation experiment of 290 MeV/n and 400 MeV/n carbon beam on water target, both of two inelastic ion reaction models, G4BinaryLightIonReaction and JQMD, reproduce pristine (mono-energetic) Bragg peak pretty well.
• As for reproduction of spread-out Bragg peak, there is still room for improvement especially for higher beam energy.
• Lateral beam profile is well reproduced.
Spare slides
Typical processing time in the water target simulation

• Computing environment
  : Compiled by gcc 3.3.3 and executed on Linux 2.6.5 on AMD Opteron 2.4 GHz
• G4BinaryLightIonReaction:
  : 5.8 min / k events
• JQMD
  : 7.0 min / k events

~ 100 hours / CPU for 10% statistics & 2 x 2 mm resolution
Heavy ion therapy at HIMAC

- NIRS – National Institute of Radiological Science, Chiba, Japan
- HIMAC – First heavy ion accelerator facility dedicated to heavy ion therapy in the world
- Over 2,000 cases have been treated on trial basis.
- Broad beam method using wobbler-scatterer system was developed.
General introduction of Geant4

- C++ library for the simulation of the passage of particle through matter
- Designed with object-oriented software technology
- Abundant physics models covering wide energy range down to a few eV
- Powerful capability to describe complex geometry
Broad beam method

\[ B_y = A_y \sin(\omega t) \]
\[ B_x = A_x \sin(\omega t + \pi/2) \]
Physical (dis)advantage of heavy ion beam

- Dose-localizing capability (Bragg peak)
- High biological effect (cell-killing capability)
- Beam fragmentation significantly modifies dose distribution from that expected from ionization of beam particle
Contribution of different Z nuclei to dose
Study on Nuclear Fragmentation by High Speed Emulsion Read-Out System

Toshiyuki Toshito (JST-CREST, KEK)
On behalf of the NIRS-HIMAC P152 collaboration

Nov.1 2006
NSS2006 San Diego, California
NIRS-HIMAC (Chiba in Japan) P152 experiment

Purpose:

➢ To collect data of heavy ion interactions with H, C, N, O, Ca, P, etc in the energy region of ion therapy with the emulsion chamber technology.
➢ Also to collect data of heavy ion interactions which are important in the radiation shielding of space laboratories.

Organization:

12 institutes from HEP, medical and space domains
- Nagoya Univ.
- Toho Univ.
- Aichi Univ. of Education
- Kobe Univ.
- High Energy Accelerator Research Organization (KEK)
- Ritsumeikan Univ.
- Naruto Univ. of Education
- SLAC
- National Institute of Radiological Science (NIRS)
- Gunma Univ., Faculty of Medicine
- Japan Aerospace Exploration Agency (JAXA)
- Univ. of Tokyo

Experiment started in 2003
Heavy ion therapy  Mostly carbon is used.

- Carbon has a tail dose after the Bragg peak.
- The tail dose can be calculated by using semi-empirical models or Monte-Carlo simulation, for example Geant4.

Validation of physics models is necessary.
Reaction data of fundamental process are required.
Fragment reaction in emulsion

$^{12}$C

180 MeV/u

4π tracking detector with 3 dimensional spatial resolution of ~1 µm
excellent multi particle separation
enable to identify all charged secondary particles
capable of kinematical analysis with event-by-event basis
High speed emulsion read-out system

Optical microscope with 3D imaging processor

S. Aoki, et al. NIM B 51(1990)466
T. Nakano, BUTSURI 56,411(2001)

Developed at Nagoya univ. in Japan

For heavy ionizing particles
Positional accuracy: 1 \( \mu \) m, Angular accuracy: 5 mrad
Detection efficiency: \( \sim 100\% \) (\( \tan \theta \leq 0.5 \))
DONUT (Fermi lab. E872): discovery of tau neutrino
: 1 cm\(^2\)/hour

OPERA (CERN to Gransasso): neutrino oscillation,
tau neutrino appearance: 10~100 cm\(^2\)/hour
C-Water data taking on Dec. 2004
A, C: sensitive to M.I.P
B, D: desensitized for charge ID by forced fading in high temperature & high humidity condition
erase latent image
“refreshing” method
NIM A 556 482(2006)
Track and vertex reconstruction after emulsion read-out: NETSCAN

$^{12}\text{C}$ Beam $\sim 10000$ particles
$\sim 4000$ interactions
Pulse heights

Film A: sensitive for M.I.P.

Film B: desensitized

Film D: desensitized
Detection of charge-changing carbon beryllium pulse heights in desensitized film.

Module number

Example

Film B
Film D

Carbon
Beryllium

Pulse heights in desensitized film

Module number
$dz$ is used to select interactions in water.

![Diagram showing the structure of detector modules with layers of polycarbonate and water, along with distances marked as $dz(n)$ and $dz(n+1)$]
C-Water(H$_2$O)
total charge-changing reaction cross sections

\[ \frac{N_{\text{int}}}{N_{\text{beam}}} = e^{-\left(N_{\text{int}}\rho\sigma x\right)/M} \]
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4 $\pi$ tracking detector with 3 dimensional spatial resolution of $\sim 1 \mu \text{m}$

excellent multi-particle separation enable to identify all charged secondary particles

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$\sim$4000 interactions
Pulse heights

Film A: sensitive for M.I.P.

Film D: desensitized
Detection of charge-changing carbon beryllium pulse heights in desensitized film.

Example:
- Film B: ○
- Film D: □

Module number:
- Carbon: C
- Beryllium: Be
$dz$ is used to select interactions in water.

The diagram shows a sequence of layers with the following dimensions:

- **Polycarbonate (A)**: 1050 $\mu$m
- **Water (C)**: 2000 $\mu$m
- **Water (D)**: 4478 $\mu$m

The layers are labeled from A to D, with A on the left and D on the right, representing different materials and their thicknesses.
C-Water($\text{H}_2\text{O}$)

Total charge-changing reaction cross sections

$\frac{N_{\text{int}}}{N_{\text{beam}}} = e^{-\frac{N_{\text{int}} \rho \sigma}{\Lambda}}$
C-Water(H₂O)
partial charge-changing reaction cross sections

A.N.Golovchenko et al.,
PRC 66 014609(2002)

Our results
example

\[ C \rightarrow \text{Li+He+H} \]

C 400MeV/u

220MeV/u

25cm
He

C $\rightarrow$ 3He

C 400MeV/u

150MeV/u

He

He

He

25cm
Summary

- Precise data of fragment reactions are required in the field of heavy ion therapy and radiology.

- New emulsion technology developed for large scale neutrino experiment is applied to the investigation of fragment reactions.

- Charge-changing cross sections of Carbon in Water were obtained in the energy region 200-400MeV/u.

- Data taking in more wide-ranging energy using various target materials and validation of physics models (for example Geant4) with event-by-event basis will be performed in near future.
Charge identification ($3 \leq Z \leq 6$) by refreshing method

- 35 grains/100 μm
- $\sim$ 8 grains/100 μm

$30^\circ C$, R.H. 98%, 3 days

Z = 1
Z = 2
Z = 6

$\delta$ ray $\sim$ 5 tracks/44 μm

Refreshing is used as a method to reduce sensitivity

40°C   38°C
For lower energy region <200MeV/u: more important

Two dedicated exposure to study Low energy interaction

Sep.05 230MeV/u $^{12}$C

Dec.05 100MeV/u $^{12}$C

- Thin target
- For charge identification, emulsion films with much more reduced sensitivity is required because of higher dE/dx in low energy.

More refresh: longer time, higher temperature

New emulsion processing so called gold development is under study!
Normal development

Gold development
Low sensitivity by ~1/30
& Fine grain

290MeV/u $^9$B

290MeV/u $^9$B
Development

• Normal development (Chemical development) 
  Ag⁺ is provided from AgBr crystal.

• Gold development (Physical development) 
  Au is provided from developer

Prof. K.Kuge (Chiba Univ.)
Bending in magnetic field

180MeV/u $^{12}\text{C}$

This technique will be useful for mass identification. $p,d,t$ $^3\text{He},^4\text{He}$ ...
More to study in P152

- More statistics to study interaction in more detail
- Pure Ca,P target
- Target fragment
Treatment for cancer by heavy ion
Treatment for cancer
Heavy ion therapy Facility
HIMAC at NIRS (National Institute of Radiological Sciences)
Chiba/Japan
– Operation since 1994
– About 1,800 patients treated
– Treatment beam: $^{12}$C
In Japan

#Proton beam facilities: 5
#Ion beam facilities: 2

- The Energy Research Center Wakasa Bay (Tsuruga: 200 MeV)
- Hyogo Ion Beam Medical Center (Nishi-Harima: 320 MeV/u)
- NIRS (Chiba: 90 MeV, 400 MeV/u)
- Shizuoka Cancer Center (Mishima: 230 MeV)
- U. of Tsukuba PMRC (Tsukuba: 250 MeV)
- NCC East Hospital (Kashiwa: 235 MeV)
Hadrontherapy in the world

A radiation therapy technique for tumor treatment using hadron beams.

Facilities in operation in the world

Proton beam: 23
Ion beam: 3

Patients treated: > 46,000
Secondary beam line at HIMAC to produce He, Li, Be, B beam having almost same velocity.
Secondary beam from Z=2 to 6 produced by 290MeV/u $^{12}$C

$\beta \sim 0.65$

Available for charge identification up to Z=6

Accepted for publication in NIM A
Charge identification by normal OPERA film

$E_{\text{kin}} = 430 \sim 100 \text{MeV/u}$

Volume pulse height $\propto dE/dx(\beta)$ near MIPs

Detected track

Z=1
Z=2
Z $\geq$ 3

Secondary beam

Volume pulse height

Saturated for multiple charge

44 $\mu$m

Pixel

0.3 $\mu$m $\times$ 0.3 $\mu$m

16 layer
C-Water data taking in P152 Jan.04
R&D for Charge identification in P152
Apr.04 and May.04
Emulsion chamber to study C-Water and C-Lucite interactions

- Water($\text{H}_2\text{O}$) and Lucite($\text{C}_5\text{H}_8\text{O}_2$) hybrid target
- Emulsion film with reduced sensitivity for charge identification to avoid saturation of pulse height
- Reduced sensitivity by 1/5 and 1/10 are combined

Dec.04 exp. 400MeV/u $^{12}\text{C}$

Pulse height

<table>
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<th>1000000</th>
<th>4756</th>
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65 layers

2mm

Lucite(1mm)
Velocity distribution of Hydrogen fragments

Volume pulse height ⇔ dE/dx (LET) ⇔ velocity

Calibrated by proton beam @ KEK PS
Emission angle of secondly particles classified by charge

Emission angle with respect to the beam (tan $\theta$)
Summary and Current status of P152

Apr.03, Jun.03, Sep.03, Apr.04, May.04

R&D for emulsion readout, chamber design and charge identification

Jan.04 and Dec.04

physics result of C-Water and C-Lucite interaction in $>150\text{MeV/u}$

Cross section : consistent with other experiments

Comparison between our data and theoretical model

Validity test of QMD build Geant4 is set going.
C-Water\((H_2O)\) partial charge-changing reaction cross sections
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  - Volume pulse height
  - Secondary beam

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  – DICOM is only supported currently
  – Any other voxel data can be adopted easily

• Free to download
  – http://geant4.kek.jp/gMocren
  – Binary only distributed

• Hardware rendering
  – Under development