PHITS

Particle and Heavy Ion Transport code System

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   - 2.1 Accelerator Design
   - 2.2 Radiation Therapy & Protection
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   - 2.4 Other applications

4. Summary & Future Plans
What is PHITS?

Particle and Heavy Ion Transport code System

Capability

Transport and collision of nearly all particles over wide energy range

in 3D phase space
with magnetic field & gravity

neutron, proton, meson, baryon
electron, photon, heavy ions

10^{-4} \text{ eV to 1 TeV/u}

All-in-one-Package

All contents of PHITS (source files, binary, data libraries, graphic utility etc.) are fully integrated in one package

OECD/NEA Databank, RSICC (USA, Canada) and RIST (Japan)

Applications

Accelerator Design
Radiation Therapy & Protection
Space & Geoscience
Example of PHITS Calculation

Stochastically simulate the motion of each particle using cross sections → Average behavior such as particle flux and mean deposition energy

Motion of 100,000 photons produced from $^{137}$Cs simulated by PHITS
PHITS Developing Team

JAEA
- Programing
- Improvement of the nuclear reaction model

KEK
- Incorporating EGS5

RIST
- Managing the entire project
- Tutorial
- Distribution

TU Wein (Austria)
- Application to space science and biology
- Tutorial in Europe

JAXA
- Application to space science

Kyushu Univ.
- Improvement and verification of nuclear reaction model

RIKEN
- Shared memory parallelization
- Reaction model improvement

CEA (France)
- Implementation and improvement of the INCL model
User Interfaces of PHITS

- **Source code:** Fortran (Intel Fortran 11.1, Gfortran 4.71 or later)
- **Input file:** Free-format text

**You do not have to write Fortran program nor compile PHITS**

- **Geometry**
  - GG format
  - Graphic utility: ANGEL
  - GUI software*
    (SimpleGEO, SuperMC)

- **Tally functions**
  Particle flux, Heat, Particle yield, Ionization density, etc.

- **Output Data**
  Text data, histograms, contour maps

- **Platforms**
  Windows, Mac and Linux (MPI & OpenMP parallelization available)

*Developed in CERN and Chinese Academy of Science applicable to various MC codes
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Physical Processes included in PHITS

- Magnetic Field
- Gravity
- Super mirror (reflection)
- Mechanical devices, T0 chopper

- \( \frac{dE}{dx} \) : SPAR, ATIMA code
  Continuous-slowing-down Approximation (CSDA)

- \( \delta \)-ray generation
- Microdosimetric function
- Track-structure simulation

- Nuclear Data (JENDL-4.0 etc.)
  + Event Generator Mode

- Intra-Nuclear Cascade
  Evaporation

- Quantum Molecular Dynamics
### Map of Models Recommended to Use in PHITS

<table>
<thead>
<tr>
<th>Neutron</th>
<th>Proton, Pion (other hadrons)</th>
<th>Nucleus</th>
<th>Muon</th>
<th>e⁻ / e⁺</th>
<th>Photon</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 TeV</td>
<td></td>
<td>1 TeV/u</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.0 GeV</td>
<td>Intra-nuclear cascade (JAM) + Evaporation (GEM)</td>
<td>JAMQMD + GEM</td>
<td>Virtual Photo-Nuclear JAM/JQMD + GEM 200 MeV</td>
<td>EPDL97 or EGS5</td>
<td>1 TeV</td>
</tr>
<tr>
<td>20 MeV</td>
<td>Intra-nuclear cascade (INCL4.6) + Evaporation (GEM)</td>
<td>Quantum Molecular Dynamics (JQMD) + GEM 10 MeV/u</td>
<td>ATIMA + Original</td>
<td>EGS5</td>
<td></td>
</tr>
<tr>
<td>0.1 meV</td>
<td>Nuclear Data Library (JENDL-4.0) + EGM</td>
<td>1 MeV</td>
<td>Ionization ATIMA</td>
<td>1 keV</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 keV</td>
<td><strong>Track structure 1 meV</strong></td>
<td>1 keV</td>
<td><strong>Only in water</strong></td>
</tr>
</tbody>
</table>

**Physics models of PHITS and their switching energies**

Switching energies can be changed in input file of PHITS
**JAM** (Jet AA Microscopic Transport) Model

- **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/n in CM**

119 kinds of Mesons
170 kinds of Baryons

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New INC models can consider the production of high-energy light fragments

Double differential cross sections of Pb\((p,n)\) and Fe\((p,d)\) reactions calculated using PHITS employing JAM, INCL4.6, or INC-ELF

INCL4.6 is selected as the default model for simulating not only nucleon-induced but also \(d\), \(t\), \(^3\)He and \(\alpha\)-induced nuclear reactions
JQMD (JAERI Quantum Molecular Dynamics) Model

- **JQMD** can simulate the time evolution of nuclear reactions, considering the correlations between *every combination of nucleons* in the frame.
- Dedicated to simulation of nucleus-nucleus (ion-induced) reactions

- Production of residues and secondaries are simulated
- More accurate JQMD-2.0 is available from PHITS Ver.2.76

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**Example Graphs**

- **Cross section (mb)** vs **Charge number**
- **Neutron production double differential cross section (mb/MeV/ster)** vs **Energy (MeV)**

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Simulation Procedure of Nuclear Reaction in PHITS

Intra-Nuclear Cascade
JAM / INCL4.6 / JQMD

Excited Nucleus
SMM

Evaporation
GEM

Fission

Production cross sections of $^{24}$Na and $^{75}$Se from Pb bombarded by C ions

SMM is not activated by default
Cross sections for low energy neutrons strongly depends on nuclear structure

Physics models are inadequate

Isotopic cross section data library is necessary

Neutron reaction cross sections of $^{112}\text{Cd}$ and $^{113}\text{Cd}$ taken from JENDL4.0

http://wwwndc.jaea.go.jp/jendl/j40/J40_J.html
What is event generator mode (EGM)?
Sample all secondary particles from DDX contained in nuclear data library, considering energy & momentum conservation in an event

**Indispensable for detector response and soft-error rate calculation**

How does it work?
EGM ver.1: Sample 1 particle from nuclear data, determine rests by GEM
EGM ver.2: Sample all particles at once from energy & momentum space

T.Ogawa et al., *NIM A*, **763**, 575-590 (2014)
Comprehensive benchmark results are published in an Open-Access paper*

*Benchmarks

All input files used for these benchmarks are included in /phits/sample/benchmark

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J-PARC

Japan Proton Accelerator Research Complex

Materials and Life Science Experimental Facility

Nuclear and Particle Physics Experimental Facility

Nuclear Transmutation

Linac(350m)

3 GeV Synchrotron (25 Hz, 1MW)

50 GeV Synchrotron (0.75 MW)

Neutrino to Kamiokande

Constructed under joint project of JAEA and KEK in Tokai-mura
Shielding Design around Spallation Target

Energy Deposition

Estimation of Heat around target

Geometry around Hg target

Shielding Design around Neutron Beam Line

23 neutron beam lines in material and life science facility

Duct source option

• Source generation program specialized for shielding design of long beam lines
• “Weight” of each source particle is automatically adjusted
• obtain good statistics within reasonable computational time in whole area

Heat distribution calculated by PHITS
Functions for Beam Transport

- Charged particles
  - Angular and energy straggling
  - Dipole and Quadrupole Magnetic field

- Low energy neutrons
  - Dipole, Quadrupole and Sextupole Magnetic field coupled with neutron spin.
  - Pulse (Time dependent) Magnetic field
  - Optical devices; Super mirror
  - Mechanical devices; T0 chopper, ....
  - Gravity

- PHITS can simulate not only trajectories, but also collisions and ionization at the same time.
Design of Other Accelerator Facilities

RIBF at RIKEN by T. Ohnishi

FRIB at MSU by I. Baek

Particle Therapy Facilities in Japan (e.g. HIMAC new building)
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CT Dosimetry System: WAZA-ARI

What is WAZA-ARI?
- Web-based system for calculating patient doses from CT examination
- Organ dose data calculated by PHITS coupled with Japanese voxel phantoms for male & female

What is WAZA-ARI? Experimental study subroutine, ‘usrsors’

Source models Human models

Calculation of CT Dose

CT examination

Human models

Application to Particle Therapy

Secondary dose estimation
K. Takada et al. JRR 59, 91-99 (2018)

REB-weighted dose estimation

Proton

Carbon

Depth in water phantom (g/cm²)
Relative dose
Absorbed dose
REB-weighted dose

Depth in water phantom (g/cm²)
Dose (Gy)
Absorbed dose
REB-weighted dose

drawn by PHITS+SimpleGEO
Application to BNCT

Dose analysis in cellular scale

Treatment planning system: JCDS

Estimation of therapeutic effect
Support Programs for Radiotherapy

**DICOM2PHITS**
Convert DICOM image data to PHITS input format

DICOM Image Data → Voxel phantom in PHITS format

- Image for a slice data
- 3D image for multiple slices

Resolution, range, location of voxels, conversion factor from CT value to material

**PSFC4PHITS**
Phase-Space File (PSF) Converter for PHITS

- Simulate downstream side of various accelerators using dump source files generated from PSF
- PSF are available from IAEA Nuclear Data Services*

*URL https://www-nds.iaea.org/phsp/phsp.htmlx*
What’s tetrahedral geometry?
A kind of 3D polygon geometry composed only by tetrahedrons

What’s the purpose of implementation?
Read complicated geometry such as human body
Read CAD geometry via tetrahedral geometry

How fast is it?

<table>
<thead>
<tr>
<th>Incident particle</th>
<th>Voxel</th>
<th>Tetrahedral</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton 100MeV</td>
<td>1720 sec</td>
<td>362 sec</td>
</tr>
<tr>
<td>Photon 1MeV</td>
<td>561 sec</td>
<td>143 sec</td>
</tr>
</tbody>
</table>

Faster than voxel phantom!

Dose calculation in fine structure such as skin becomes feasible

Calculation of Dose Conversion Coefficients

PHITS Simulation Conditions

- Incident particle: neutron, proton, pion, muon, heavy ions (~Ni)
- Incident energy: 1 MeV/n* up to 100 GeV/n
- Irradiation geometry: ISO, AP, PA, LLAT, RLAT, ROT
- Calculated quantity: dose, Q(L), Q(y) & Q_{NASA}-based dose equivalent

*from 1 meV for neutron

ICRP/ICRU adult reference computational phantoms

ICRP Pub.116
Used for evaluating their reference values

ICRP Pub.123

Applications to Radiation Biology

β from $^{137}$Cs
α from $^{239}$Pu

Electron track-structure simulation

RBE of neutron for DNA damage

Cellular scale doses calculated by PHITS

Applied to the estimate of DNA damage & risk of internal exposure

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MATROSHKA Experiment

MATROSHKA Experiment
- Measure astronaut doses inside and outside ISS
- Lead by G. Reitz of DLR

Calculated dose inside the phantom using PHITS

Aircrew Dose Estimation

PHITS simulation
- Transport of cosmic ray in atmosphere considering solar activity and geomagnetism

_available as online software EXPACS
http://phits.jaea.go.jp/expacs

Currently used in the Japanese aircrew dose estimation for regulatory purpose

Impact of Solar Flare on Earth

WArning System for AVIation Exposure to Solar Energetic Particle

WASAVIES

- Nowcast radiation doses during large solar particle events based on the satellite observation and ground-level neutron monitors
- PHITS was used for analyzing the motion of solar particles in the atmosphere

Web interface (under development)

Validation results

Radiation dose rate map at flight altitude during solar flare on Sep. 2017

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Calculating of Radiation Damage: DPA

What is DPA?
- Average number of displaced atoms per atom of a material
- PHITS-DPA considers not only Coulomb scattering of charged particles but also nuclear interactions.

Accurate prediction of heat, defect, and activation in complex Tokamak fusion device geometry is necessary.

Torus-shaped source to represent Tokamak plasma

Neutron flux distribution in the vicinity of device

Laser-driven ion acceleration technology is under development (acceleration of ions by the electric field of high-intensity laser)

PHITS is applied for beam diagnostics, dose calculation, etc.

Ion species and energy distribution
Experiment and PHITS simulation

Dose per laser shot
Experiment and PHITS simulation
Semiconductor soft error rate evaluation

**Semiconductor soft error?**

- The information stored in semiconductor memory is flipped by incident radiations through the energy deposition process.
- At ground level, errors are induced by reactions of cosmic ray neutrons.

Simulation of secondary particle production by neutrons is necessary.

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**SER analyses with device simulator or multiple sensitive volume model**

- **PHITS**
- **Device simulator**
- **MSV model**

- **Soft error rate [FIT/Mbit]**
- **Critical charge [fC]**

Decontamination effect estimation system

- Software to evaluate decontamination effect based on ambient dose
- PHITS was used to calculate ambient dose in contaminated environment

Provided as spreadsheet

http://nsed.jaea.go.jp/josen/ (←Provided as freeware)
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Typical Features of PHITS

- Capability of transporting nearly all particles
  Over a wide energy range in any materials
- Simple user interface and graphical output tools
- Sophisticated nuclear reaction models and libraries
  INCL4.6, INC-ELF, JQMD, JAM, JENDL-4, EGS5 etc.
- Special functions for various purposes
  - Event generator mode
  - Microdosimetric function
  - Beam transport functions

PHITS has been used by more than 3,000 users in many countries
Future Plans

We are planning to ...

- Improve nuclear reaction model and data library
  - JENDL High-Energy file
- Implement new functions
  - Improvement of track-structure mode
  - Estimation of systematic uncertainties
  - Extension of weight window and D-CHAIN to xyz-mesh
  - Implementation of various dose conversion coefficients
- Improve user support functions
  - GUI

Subscribe to PHITS mailing list for update information

see http://phits.jaea.go.jp/howtoget.html
and Email to phits-office@jaea.go.jp