Monte Carlo Transport Codes for use in the Space Radiation Environment

Tim Goorley

MCNP6 (Monte Carlo N-Particle) Transport Code

For availability (Subject to US ITAR Restrictions) see Reference 1.

MCNP6 [1M], the merger of MCNPX with MCNP5, is a result of more than six years of merger efforts. Extensive documentation of this code, its methods and its verification and validation test suites, can be found on its website, at mcnp6.lanl.gov. MCNP6 Beta 2 contains 16 new features not found in the final release of MCNP5 (version 1.60) nor MCNPX (version 2.7.0). MCNP6 Beta 2 has been distributed since February 2012, and MCNP6 Beta 3 was expected to be released at the end of the 2012 summer.

MCNP6 is able to transport 37 particle types, as well as arbitrary nuclei, through different geometric representations, including unstructured mesh models generated with CAE tools such as Abaqus/CAE and CUBIT.

To address various needs and for some historical reasons, MCNP6 considers several nuclear reaction models, sometimes incorporated in separate modules referred to as "event-generators". The first model of intermediate- and high-energy nuclear reactions used initially in LAHET [2M] was the Bertini INC [3M], followed (by default, but not required) by the Multistage Preequilibrium Model (MPM) [4M], followed by the Dostrovsky et al. evaporation model [5M] as implemented in the code EVAP by Dresner [6M]. If the compound nuclei produced after the INC and MPM stages of reactions are heavy enough to fission, the fission process is simulated either with the semi-phenomenological Atchison fission model, often referred to in the literature as the Rutherford Appleton Laboratory (RAL) fission model (which is where Atchison developed it [7M]), or with the Fong statistical model of fission, as implemented in the ORNL code HETFIS [8M], often referred to in the literature as the ORNL fission model. Bertini INC, MPM, EVAP, RAL, and HETFIS migrated from LAHET to MCNPX, and later to MCNP6. Bertini INC is the default option of MCNP6 for reactions induced by nucleons and pions at energies up to 3.5 GeV, and it is always used to calculate such reactions on the light d, t, ^{3}He and ^{4}He target-nuclei, independently of the model chosen in the MCNP6 input file.

The second model, from a historical point of view, is the ISABEL INC [9M], which migrated to MCNP6 via MCNPX from LAHET. ISABEL is the default option in MCNP6 for reactions induced by d, t, ^{3}He, ^{4}He, and antinucleons at energies up to 1 GeV per nucleon. If specified in the MCNP6 input file, ISABEL can be used to also simulate reactions induced by nucleons, pions, kaons, and heavy-ions at energies below 1 GeV/nucleon. Just like Bertini INC, ISABEL can be used with or without taking into account the preequilibrium reactions as described by MPM, and it can describe the evaporation and fission reactions with EVAP, RAL, and HETFIS.

A newer and recently improved model used by MCNP6 is the Cascade-Exciton Model (CEM) of nuclear reactions as implemented in the event-generator CEM03.03 [10M, 11M]. CEM03.03 is used in MCNP6 as a default choice to calculate photonuclear reactions at energies up to 1.2 GeV and is the only model adopted by MCNP6 to simulate absorption of stopped muons. If selected by input, CEM03.03 can also successfully simulate reactions induced by nucleons and pions at energies up to several GeV. We recommend using it up to about 1 GeV for light targets like C and up to about 5 GeV for heavy targets like U. CEM03.03 uses its own models to describe the preequilibrium, evaporation, and fission reactions. It considers also coalescence of nucleons into complex particles up to ^{4}He and Fermi break-up of excited or unstable nuclei with mass numbers up to A = 12 (see details in Refs. 10M and 11M).

Another new and recently improved model used by MCNP6 is the Intra Nuclear Cascade model developed at Liege (INCL) by Joseph Cugnon in collaboration with colleagues from CEA Saclay, France and GSI, Germany [12M]. The version of INCL implemented in MCNP6 Beta 2 can successfully describe reactions induced by nucleons, pions, and complex particles d, t, ^{3}He, and ^{4}He at energies up to several GeV. INCL always uses the ABLA code developed at GSI [13M, 14M] to describe the evaporation and fission stages of reactions, independently of what MCNP6 users would choose for evaporation/fission models; INCL does not consider preequilibrium reactions. Newer and better versions of INCL and ABLA are planned for incorporating in a future version of MCNP6.

Finally, MCNP6 uses the Los Alamos version of the Quark-Gluon String Model (LAQGSM) as implemented in the event-generator LAQGSM03.03 [11M, 15M]. LAQGSM03.03 is the default option to describe in MCNP6 reactions induced by heavy-ions, by photons at energies above 1.2 GeV, particle-nucleon interactions, as well as reactions induced by projectiles not considered by other models. LAQGSM was developed to describe reactions induced by almost all types of elementary particles and by nuclei at energies up to about 1 TeV/nucleon. LAQGSM uses its own models to describe the preequilibrium, evaporation, and fission reactions; it considers also coalescence of nucleons into complex particles up to ^{4}He and Fermi break-up of excited or unstable nuclei with mass numbers up to A = 12 (these are the same models used by CEM, but adjusted to LAQGSM; see details in Refs. 11M and 15M).

The MCNP6 code represents one of a set of synergistic capabilities developed at Los Alamos that also includes the evaluated nuclear data files (ENDF), and the data processing code NJOY [16M]. The ENDF/B-VII.0 database was released in 2006 [17M], and the latest version of the database was released in December 2011 [18M].

Depending on the nuclear data being used, neutron interaction data is available up to 20, or more recently, 150 MeV. Thermal neutron scattering, S(α,β), data is available for 20 different materials. Proton interaction data is available for 48 isotopes, up to proton energies of 150 MeV. Photoatomic data is available for photon and electron transport up to 100 GeV and 1 GeV, respectively. Photonuclear data, including Nuclear Resonance Fluorescence (NRF), is available for 157 specific isotopes up to 150 MeV, but is not active in calculations by default. Above the respective energy, and for all the hadrons, interactions are based on theoretical models with empirical corrections.

High confidence in the MCNP6 code is based on its performance with the verification and validation test suites, comparisons to its predecessor codes, the regression test suite, its code development process, and the underlying high quality nuclear and atomic databases. MCNP6 also contains the ability to simulate static magnetic fields in air or vacuum, and static electric field capability is under development.

A new feature to MCNP6 is the ability to embed unstructured meshes in a constructive solid geometry (CSG) universe to form a hybrid geometry. Highly complex models can now be created more easily with state-of-the-art CAE tools, such as Abaqus/CAE and CUBIT, and imported into MCNP once an unstructured mesh representation has been created. Both first- and second-order, 3-D finite element types are supported, allowing the user to mix and match the most appropriate element types with the geometry. Second-order elements better approximate curved surfaces so that fewer of these elements are required to represent objects containing these types of surfaces; this provides more accurate volumes and masses while reducing memory requirements. Results are calculated on the finite element mesh and are better suited for data exchange with other finite element codes when a multi-physics analysis is required. Results on the mesh also provide superior state-of-the-art visualization. For highly detailed models, where more than 100,000 cells or elements are needed, performance with the unstructured mesh model beats that with the equivalent CSG model not only in the calculation of results but also with problem setup time; the unstructured mesh input processing supports limited parallel processing through the message passing interface. Since the unstructured mesh is a new feature and has the potential to interface with many existing features, it has not yet been fully integrated with all anticipated features (see details in Ref. 19M).

The current version of MCNP6 is a 40+ year evolution of one of the earliest integrated transport codes, and a number of its embedded features have been incorporated into a number of the other codes described here. One potential difficulty is that, because it is a US-developed code (by Los Alamos National Laboratory), its distribution is restricted due to relevant Export Control regulations. Currently the code is distributed by the Radiation Safety Information Computation Center (RSICC) at Oak Ridge National Laboratory (http://rsicc.ornl.gov/) in optical disc format rather than being available for download as are the other codes described in this article. For FY11 and FY12 it was free to all approved requestors, which included both US and non-US nationals. MCNP is one of the world's leading particle radiation transport codes, with an estimated user base of more than ten thousand users. In fact, in fiscal years 2009 and 2010, RSICC distributed 1,514 and 1,512 copies, respectively, of the MCNP5 & MCNPX package, to users in US government institutions, academia, and private companies worldwide. Between January 2001 and October 2011, there were 11,586 requests for MCNP from RSICC.

MCNP6 user support is provided in several different ways. The MCNP6 reference DVD contains several user manuals, hundreds of specific LANL MCNP publications, and discussions on Monte Carlo theory. A few other resources are provided, such as a database of MCNP input files of medical physics human phantoms, which includes the ICRP 110 phantoms. The mcnp6-forum@lanl.gov has been created to allow users to post questions to users and developers. MCNP6 developers will provide limited feedback to this forum. The MCNP6 development team provides week long classes for MCNP beginners, and separate advanced classes in criticality, variance reduction, and sometimes other specific topics.

Let us note that just like FLUKA and some other transport codes, MCNP6 provides (1) the ability to employ biasing in many different ways, (2) has several completely coherent event generators allowing us to simulate almost all possible types of particle-particle, particle-nucleus, and nucleus-nucleus reactions, (3) provides "history-files" and several types of output files that may help us better understand the simulated results.

MCNP6 and its precursor, MCNPX, have been used in different space applications and in astrophysics. NASA's Robert Singleterry and his coauthors have used MCNPX in the past and continues to use MCNP6 to simulate solar and cosmic ray interactions with orbiting space vehicles and subsequent astronaut dose [20M]. MCNP has also been used to simulate the Martian Orbiter's neutron sensor of the Martian surface, which confirmed the presence of water there, to study neutron density vs. depth on the moon, etc. (see, e.g. [21M] and references therein).

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