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HETC-HEDS RADIATION TRANSPORT CODE DEVELOPMENT AND BENCHMARKING FOR COSMIC RAY SHIELDING APPLICATIONS IN SPACE

T. M. Miller[1], L. W. Townsend[1], and T. Handler[2]
[1]Department of Nuclear Engineering
[2]Department of Physics and Astronomy
The University of Tennessee
Knoxville, TN 37996-2300 USA
tmiller7@utk.edu, ltownsen@utk.edu

T. A. Gabriel
Scientific Investigation & Development
Knoxville, TN 37922 USA

ABSTRACT

In order to facilitate 3-dimensional analyses of space radiation shielding scenarios for future space missions, the Monte Carlo radiation transport code HETC is being extended to include transport of energetic heavy ions, such as are found in the galactic cosmic ray spectrum in space. Recently, the first iteration of an event generator capable of providing nuclear interaction data for use in HETC was developed and incorporated into the code. The event generator predicts the interaction product yields, production angles and energies, using nuclear models and Monte Carlo techniques. Testing and validation of the extended transport code, now called HETC-HEDS (High Energy Transport Code – Human Exploration and Development of Space), has been underway for sometime now. In previous work the status of code modifications, which enable energetic heavy ions and their nuclear reaction products to be transported through thick shielding, was described. This work presents updates to these modifications and gives some new sample results of code validation, benchmarking, and testing against available laboratory beam data for energetic heavy ions interacting in thick targets. These results include comparisons of neutron spectra at various angles along with fluence as a function of charge.

Key Words: Cosmic Rays, Monte Carlo, Charged Particle Transport, Radiation Protection

1 INTRODUCTION

There are several radiation transport codes that transport high energy nucleons, light ions, heavy ions, or some combination of them. At the time this research was started, none transported all of these particles in more than one dimension. Since the beginning of this research similar work has been undertaken in the other transport codes. In order to make a comprehensive tool for space applications that transports all of these particles, with a wide range of energies and in three spatial dimensions, accurate values of the total, elastic scattering, and reaction cross sections, spectral distributions and angular distributions of all emitted particles (nucleons, light ions and heavy ions) from the nuclear interactions of propagating high energy heavy ion (HZE) particles with target nuclei are required, particularly for light and heavy ions. With this database [1], transport codes would be able to transport nearly any radiation field that man or machine might be exposed to in space or otherwise. It will be invaluable for space radiation protection, in low earth orbit or deep space, and it could be used for terrestrial purposes as well, such as accelerator shielding or charged particle radiotherapy. This database is the first high speed comprehensive database suitable for three dimensional radiation transport. Once the comprehensive database was completed, it was incorporated into HETC [2] to create a generalized, three dimensional radiation transport code, HETC-HEDS [3] for space applications.

2 HETC

HETC simulates the projectile interactions with target nuclei by using Monte Carlo techniques to compute the trajectories of the primary particle and the secondary particles produced in nuclear collisions. The particles considered by HETC (protons, neutrons, $\pi^{\pm}$, and $\mu^{\pm}$) may be arbitrarily distributed in angle, energy, and space. Neutrons and/or protons produced below a given cutoff, usually 20 MeV, and photons produced in the interactions or from deexcitation gammas are not transported. Instead, their position, energy, and angular information are stored for transport by codes such as MORSE and EGS, as part of the CALOR package [2], MCNP [4], or MCNPX [5]. The methods used by HETC to describe the physical interactions of the projectile and target are described in references 2 and 6.

3 HETC-HEDS

HETC-HEDS has all of the capabilities of HETC plus an event generator [1] that was previously described for transport of projectiles with mass number greater than 1. One item that is not part of the nucleus-nucleus event generator, but is required for the transport of particles with mass number greater than 1, are range-energy tables. These tables are needed to apply the continuous slowing down approximation to the charged projectiles, and they are calculated by scaling the proton values for the target media. The range-energy table values for protons in a specific target media are calculated using the well-known Bethe-Bloch [7] stopping power formula. Another capability needed in HETC-HEDS, which is not part of the event generator, is the ability to choose the location of the next nuclear collision of projectiles with mass greater than 1. This is done the same way HETC chooses the next nuclear collision site for a neutron or proton by use of the method of fictitious scattering [8].

4 HETC-HEDS SAMPLE RESULTS

In order to better illustrate the capabilities of the newly created generalized three-dimensional radiation transport code HETC-HEDS several calculations have been performed. Each of the HETC-HEDS calculations makes a direct comparison with an experiment whose results have been published in the open literature.

The first comparison between HETC-HEDS and experiment compare fragment production in the forward and near forward directions. The first experiment measured fragments produced by 1050 MeV per nucleon ^{56}Fe on a 3.5 g/cm^2 graphite target [9]. The next two experiments also measure fragments produced by 1050 MeV per nucleon ^{56}Fe, but the targets were 5.0 g/cm^2 and 10.0 g/cm^2 graphite/epoxy composite [9]. These three experiments measured the fragment fluence for ions with charge number 25 through 12. A comparison of these experiments with HETC-HEDS can be seen in Figures 1, 2, and 3.

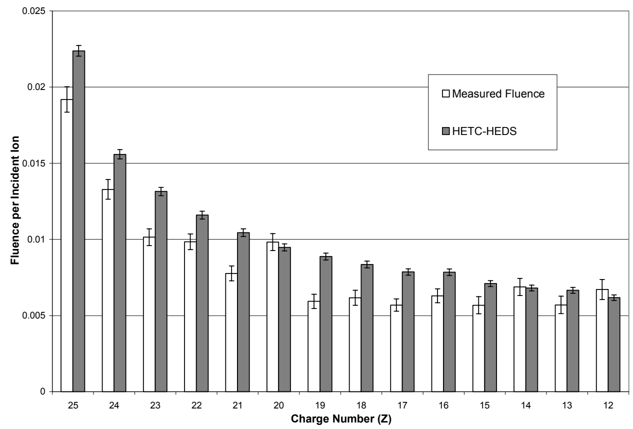

Figure 1: Fragment Fluence Due to 1050 MeV per Nucleon ^{56}Fe on 3.5 g/cm^2 of Graphite

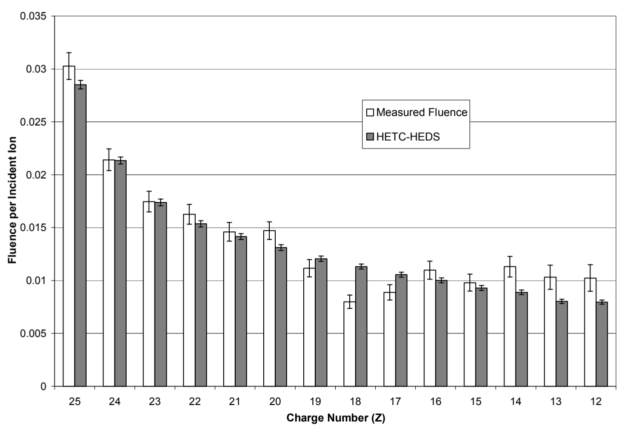

Figure 2: Fragment Fluence Due to 1050 MeV per Nucleon 56Fe on 5 g/cm2 of Graphite and Epoxy

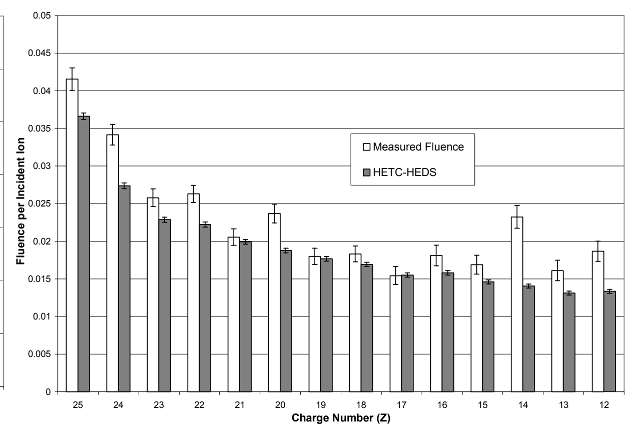

Figure 3: Fragment Fluence Due to 1050 MeV per Nucleon 56Fe on 10 g/cm2 of Graphite and Epoxy

In order to make a comparison with HETC-HEDS that considered all possible fragment charge numbers one more experiment was simulated. The experiment measured fragments produced by 1050 MeV per nucleon ^{56}Fe on 1.94 g/cm^2 of polyethylene [10]. A comparison of this experiment with HETC-HEDS can be seen in Figure 4 and Table I.

Next HETC-HEDS simulated an experiment that measured neutron spectra in nucleus-nucleus collisions. The experiment collided 400 MeV per nucleon carbon ions on a thick carbon target [11]. Neutron spectra were measured at 0, 7.5, and 15 degrees from the beam direction, and a comparison between the experiment and the HETC-HEDS can be seen in Figures 5, 6, and 7. In Figures 5 through 7 the HETC-HEDS results have been normalized to exactly equal the Kurosawa data at one point. The HETC-HEDS data does not extend below 20 MeV because this was the low cutoff energy used in the calculation.

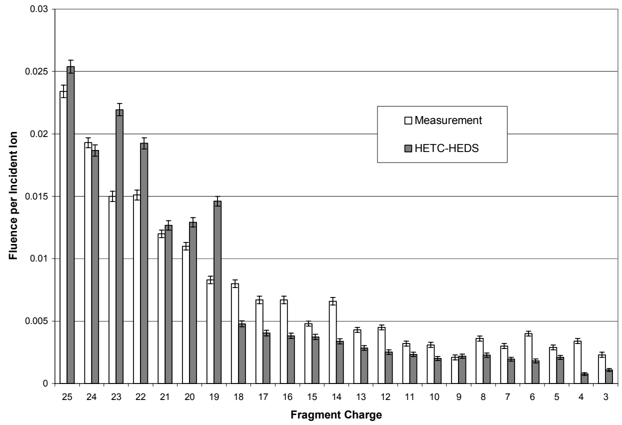

Figure 4: Fragment Fluence Due to 1050 MeV per Nucleon ^{56}Fe on 1.94 g/cm^2 of Polyethylene

Table I: Fragment Fluence Due to 1050 MeV per Nucleon ^{56}Fe on 1.94 g/cm^2 of Polyethylene

Charge	Measured Fluence	Measured Fluence Error	HETC-HEDS Fluence	HETC-HEDS Fluence Error
26	0.7830	0.0005	0.7764	0.0052
2	0.0083	0.0003	0.0918	0.0010
1	0.0160	0.0004	1.5720	0.0049
0	0.0193	0.0004	1.8784	0.0053

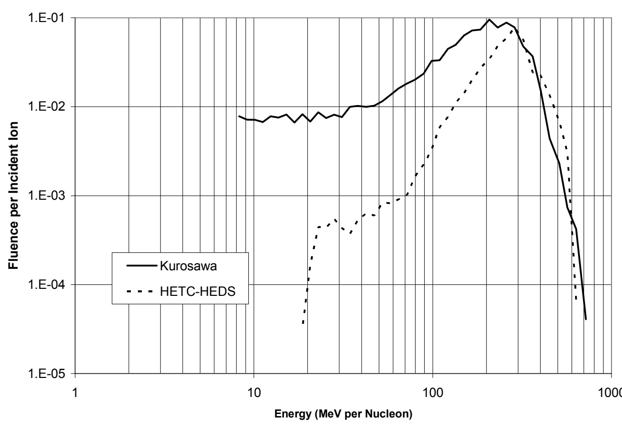

Figure 5: Neutron Fluence Measured at 0-Degrees Due to 400 MeV per Nucleon ^{12}C on 35.4 g/cm^2 of Graphite

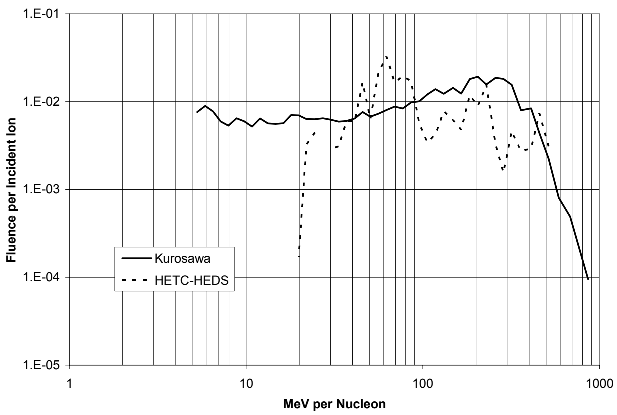

Figure 6: Neutron Fluence Measured at 7.5-Degrees Due to 400 MeV per Nucleon ^{12}C on 35.4 g/cm^2 of Graphite

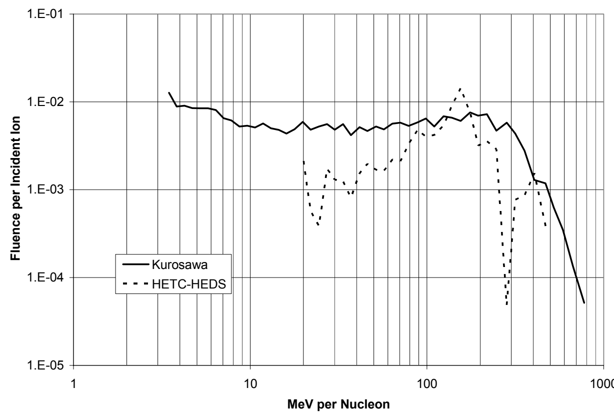

Figure 7: Neutron Fluence Measured at 15-Degrees Due to 400 MeV per Nucleon ^{12}C on 35.4 g/cm^2 of Graphite

5 CONCLUSIONS

Four comparisons were made between HETC-HEDS and experimental measurements of fragment fluence as a function of charge number. The results of these comparisons are in Figures 1 through 4 and Table I. In general HETC-HEDS did a good job of predicting the fragment fluences, especially for charge numbers closer to that of iron. As the charge number decreases the error between HETC-HEDS and the measurements increases. This is due in large part to the fact that NUCFRG2 tends to under predict production cross sections of fragments as the fragment charge number decreases. However, the agreement could be slightly improved by adding a coalescence model in order to form more light ions. Forming light ions by coalescence would also improve the agreement of neutron and proton production by reducing their numbers. It must be pointed out that the comparison of neutron, proton, and light ion production (up to fragment charge of 3 or 4) in these experiments and calculations is not exactly a direct comparison. In the actual experiments only the leading fragments were counted, meaning the heaviest particle that entered a detector as the result of a nucleus-nucleus collision was counted, while the remaining particles are ignored. In the HETC-HEDS calculation all particles that entered the detector were counted. This is not a concern except for protons, neutrons, and other light ions that may also result from a nucleus-nucleus collision along with the leading fragment. Since HETC-HEDS counted all light ions and nucleons entering the detector Figures 4 and Table I are not comparing the same measurement for charge numbers 2, 1, and 0 (and possibly for charge numbers 3 and 4 due to light particle coalescence). However, it is encouraging that HETC-HEDS predicts more neutrons and protons than this experiment measured.

Next HETC-HEDS calculated neutron spectra at three different scattering angles. In all three cases the neutron production was under predicted by 1 to 2 orders of magnitude, therefore, the HETC-HEDS results were normalized to one data point in the measured data. This was done in order to make a better comparison with the shape of the neutron spectra. The disagreement between the magnitudes of the spectra is more inline with what the authors expected to see than the results given in Table I. It was stated earlier that the results in Table I for light ions and neutrons turned out to not be a very informative comparison. This disagreement was expected because it is known that the model to predict yields of particles due to nucleus-nucleus collisions implemented into HETC under predicts light ion yields, and the neutron yields are scaled from the proton yields. That being said the shapes of the neutron spectra calculated by HETC-HEDS compare fairly well with the measured spectra. Again it must be stated that the low energy cutoff for neutrons used in these HETC-HEDS calculations was 20 MeV, therefore, no comparison is made below that energy. At energies above 200 MeV the spectra at all three angles compares well. However, at 7.5 and 15 degrees the spectra calculated by HETC-HEDS cuts off before the measured spectra. This is due to forcing conservation of energy on each collision, which results in HETC-HEDS truncating the possible energy sampling space. This is discussed in more details in the paper discussing the nucleus-nucleus event generator in HETC-HEDS [1]. Below 200 MeV the spectra agree fairly well except in the 0 degree case. The issue mentioned before about truncating the possible energy sampling space affects this region in the spectra very little. What more directly affects this region is isobar production and subsequent pion and nucleon production. This physics is currently not modeled in the nucleus-nucleus event generator, and would lead to the production of more low energy neutrons (i.e. energy less than the projectile kinetic energy). This physics would cause the spectra calculated at 0 degrees to be broader than it is in Figure 5.

6 ACKNOWLEDGMENTS

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