

## EVALUATION OF SPACECRAFT SHIELDING EFFECTIVENESS FOR RADIATION PROTECTION

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### **Abstract:**

The potential for serious health risks from solar particle events (SPE) and galactic cosmic rays (GCR) is a critical issue in the NASA strategic plan for the Human Exploration and Development of Space (HEDS). The excess cost to protect against the GCR and SPE due to current uncertainties in radiation transmission properties and cancer biology could be exceedingly large based on the excess launch costs to shield against uncertainties. The development of advanced shielding concepts is an important risk mitigation area with the potential to significantly reduce risk below conventional mission designs. A key issue in spacecraft material selection is the understanding of nuclear reactions on the transmission properties of materials. High-energy nuclear particles undergo nuclear reactions in passing through materials and tissue altering their composition and producing new radiation types. Spacecraft and planetary habitat designers can utilize radiation transport codes to identify optimal materials for lowering exposures and to optimize spacecraft design to reduce astronaut exposures. To reach these objectives will require providing design engineers with accurate data bases and computationally efficient software for describing the transmission properties of space radiation in materials. Our program will reduce the uncertainty in the transmission properties of space radiation by improving the theoretical description of nuclear reactions and radiation transport, and provide accurate physical descriptions of the track structure of microscopic energy deposition.

### **Introduction**

Estimating the effectiveness of spacecraft shielding on reducing the health effects galactic cosmic rays (GCR) and solar particle events (SPE) is a major issue for HEDS. Spacecraft shielding composed of low Z materials is expected to be advantageous because of reduction of high energy and charge ions (HZE), and target fragments, especially neutrons, in comparison to higher Z materials such as aluminum. Projectile fragmentation reactions in shielding are advantageous because lower charged ions of equal velocity are less biologically damaging than the projectile ion. Materials composed of lower atomic mass atoms are more efficient per unit mass in producing projectile fragmentation. Target fragmentation events are highly dependent on material type. These events are the major nuclear reaction effect for SPE's and are an important contributor to GCR transmission. Quantitative evaluations for material selection must rely on physical descriptions of radiation transmission properties including nuclear reactions. An important factor in the development of nuclear cross section databases is the ability to describe nuclear structure and clustering aspects of specific materials constituents and GCR components. The quantum based QMSFRG model has been shown in previous limited studies to provide this capability. Source terms for nuclear fragments can be included in the state-of-the-art, radiation transport codes, GRNTRN/BRYNTRN and used

for space applications. We are developing theoretical descriptions of nuclear interactions and radiation transport, and fast computational software that will provide accurate predictive capability and an engineering design tool in support of the HEDS enterprises.

An objective of the HEDS Strategic Plan is to understand the effects of space radiation on humans including possible unique effects from heavy ions. The relationship between the transmitted radiation fields at organ sites and biological risk is poorly understood and awaits fundamental understanding in molecular and radiation biology. Determination of the impact of biological counter-measures will be dependent on knowledge of transmitted radiation for specific materials and the microscopic energy deposition events of heavy ions since it is expected that such countermeasures will work on some but not all GCR components. Radiobiology experiments to understand biological risks and potential countermeasures are supported by the Code UL Office of Life and Microgravity Sciences and Applications. Our research program will support these efforts by providing tools to study the combined effects of risk mitigation areas, including relationships between shielding properties and biological counter-measures. We will study the effectiveness of shielding material using conventional risk assessment, and track structure models that quantitatively represent proton and HZE biological response data.

### **Radiation Transport in Materials**

The physics of high-energy heavy ion transport in single or multi-layered materials has been developed at Langley Research Center over the last 25 years by Wilson and co-workers [1]. Several computer codes were developed for application to space or laboratory boundary-value problems. The BRYNTRN code describes the transport of laboratory or space light-ion beams (p,n,d,t,h, and  $\alpha$ ) and the local distribution of heavy target fragments and recoils ( $A > 4$ ). The HZETRN code solves the Boltzmann equation using the straight-ahead approximation for GCR transport in multi-layer materials. The GRNTRN code solves the laboratory heavy ion transport code and is being developed for space application. The HZETRN code contains BRYNTRN as a subroutine and the GRNTRN code is being extended in this manner. Other developments of the model include a multi-group approach for low-energy neutron transport [2] and future extensions of the codes to include meson, muons, and electrons. In Table I we show comparisons of the HZETRN/BRYNTRN code to measurements on-board the space shuttle on STS-81 [3] where several polyethylene spheres were flown with TEPC's inserted. Good agreement for both dose and dose equivalent comparisons are found, however spectral components show larger differences and have indicated areas for improvement in the codes [2,4].

**Table I. Comparison of HZETRN/BRYNTRN to GCR Measurements on STS-81 [3]**

Diameter	Measured Dose	Calculated Dose	Measured Dose Eq.	Calculated Dose Eq.
0.0, g/cm <sup>2</sup>	.147 mGy/day	.135, mGy/day	.479, mSv/day	.521, mSv/day
1.934	.138	.138	.441	.400
4.322	.129	.118	.316	.368
7.903	.128	.113	.371	.322
12.68	.116	.111	.290	.298

## Nuclear Data Bases: The QMSFRG Model

Nuclear interaction cross section data bases are required for the transport of cosmic rays with energies below 10 MeV/amu to energies above tens of GeV/amu, including a large number of projectile and target material combinations. The types of cross sections required for transport involve total yields and secondary energy spectra for one-dimensional transport and double differential cross sections in angle and energy for three-dimensional transport. Neutron and proton cross sections have been studied at some length in the past. Nuclear-reaction modeling is required, especially for both light and heavy ion projectiles, to understand the basic physical processes, and to extrapolate limited experimental data between projectile energies and projectile-target combinations. Our efforts in data base developments have focused largely on quantum multiple scattering theories (QMST), Monte-Carlo approaches to nuclear reactions use an intra-nuclear cascade that imitates the QMST, however neglecting quantum interference effects and nuclear structure effects. In the QMST a the many-body integral-equation for the transition operator for nucleus-nucleus scattering [5] is considered,

$$(1) \quad T = K + K G T$$

where  $K$  is the interaction kernel and  $G$  the Bethe-Salpeter propagator representing two nuclei in intermediate states. The kernel is the sum of all irreducible diagrams for projectile-target constituents. The solution of (1) is made using appropriate high energy approximations for momentum and energy transfers typical of nuclear reactions, development of bound state function models for transitions of interests, and new methods to deal with many particle phase problems for the description of fragmentation channels.

The microscopic QMST theory for the description of nuclear fragmentation, denoted QMSFRG, proceeds by summing the QMST for heavy ion reactions in terms of response functions for an arbitrary number of particle knockouts for the heavy ion abrasion dynamics [5]. The microscopic theory can be shown [5] to reduce to the optical-model formulation of abrasion and the geometric abrasion model. The reaction dynamics for fragmentation processes are unified by the development of a single function, the multiple scattering amplitude, in terms of the momentum vectors of all secondary reaction products. The production cross sections for the fragments are found by considering the phase space for an arbitrary final state where there are  $n$  abraded particles, leaving a projectile pre-fragment with energy denoted  $E_{F^*}$ . Conserving energy in the pre-fragment formation after interactions with the target are complete, the scattering amplitude  $f_{fi}$  and cross sections are related by [5-7]

$$(2) \quad d\sigma = \sum_X \prod_{j=1}^n [d\mathbf{k}_j / (2\pi)^3] \delta(E_i - E_f) dE_{F^*} d^2q |f_{fi}|^2$$

where the  $\mathbf{k}_j$  are the abraded nucleon wave vectors,  $E_i$  and  $E_f$  are the energies in the initial and final states, and  $q$  is the total transverse momentum in the reaction. Equation (2) is summed over the final states of the target nuclei,  $X$ . In the abrasion-ablation model there is a causal assumption that separates the time evolution of ablation processes from the abrasion. It follows that for the emission of  $\nu$  nuclei from the excited pre-fragment with

energies  $E_r$  we have  $E_{F^*} = E_F + \sum_r E_r$  where  $r=0$  is allowed in order to include the possibility that the pre-fragment excitation energy is below the lowest particle-emission channel. The abraded particle momentum distribution is

$$(3) \quad d\sigma/d\mathbf{k} = \sum_n \sum_X \int \prod_{j=2}^n [d\mathbf{k}_j / (2\pi)^3] dE_{F^*} d^2q |f_{fi}|^2$$

where we are integrating over all variables except the momentum of one abraded particle. The excitation spectra of pre-fragment nuclei are obtained from equation (2) as

$$(4) \quad d\sigma / dE_{F^*} = \sum_X \int \prod_{j=1}^n [d\mathbf{k}_j / (2\pi)^3] d^2q |f_{fi}|^2$$

The decay of the pre-fragment nuclei into the final fragment opens the phase space further, and this description is required for predicting the final mass yields as well as momentum distributions of ablated nucleons or light nuclei. Good accuracy for predicting proton and neutron production in heavy ion collision's [6] is found with the model. The development of the scattering amplitude in terms of abrasion response functions has been made using the eikonal approximation. For proton-nucleus and light ion-nucleus collisions, the Watson or Faddeev multiple scattering theories are used directly to perform cluster summations with the eikonal approximation for four-point functions that occur in the expansion. Important interference effects are seen in these calculations (ref. [5] and earlier references cited therein) that are neglected in a Monte-Carlo approach. Many-body response functions are modeled as convolutions of one-body response functions using the shell model. Figure 1 shows results of the model for  $^{16}\text{O}$  fragmentation. Ablation is described by solving the Master equation for de-excitation of the pre-fragments [5,7]. For light nuclei ( $A < 16$ ) experimental decay parameters are used.

### Track Structure and Space Radiation Risk Assessment

Particle energy spectrum for shielding/mission scenarios as determined by transport equations can be used to determine biological risk after a biological response function is defined. Conventional risk assessment uses LET dependent quality factors and risk coefficient's decided on by committee to estimate cancer risk. Track structure models predict [8] that biological response will depend on several aspects of particle tracks including the radial extension and the  $\delta$ -ray energy spectra, and the spatial structure of biological target molecules. Deviations from LET dependence are especially important when considering complicated radiation fields and are supported by experimental data. Track structure models are applied to represent biological response data for protons, neutrons, and heavy ions [8]. These models are then used to evaluate shield material characteristics using radiation transport codes [9]. Important deviations are seen on material properties when using conventional or track structure models. This approach to studying shield effectiveness has been recently recommended by the National Academy of Science's Space Science Board. We are continuing these studies using improvements in the physical description of particle tracks [10,11] and new models [12] of radiobiology experiment's supported under NASA's Radiation Health Program. Figure 2 shows comparisons of the track model [10] to the average specific energy deposited as a function of radial distance from 14 MeV/u Ge ions in 0.5 and 1.0  $\mu\text{m}$  sites. A similar

approach has been developed for nanometer volumes [11]. The model can also be extended to describe micro-electronics damage by heavy ion tracks.

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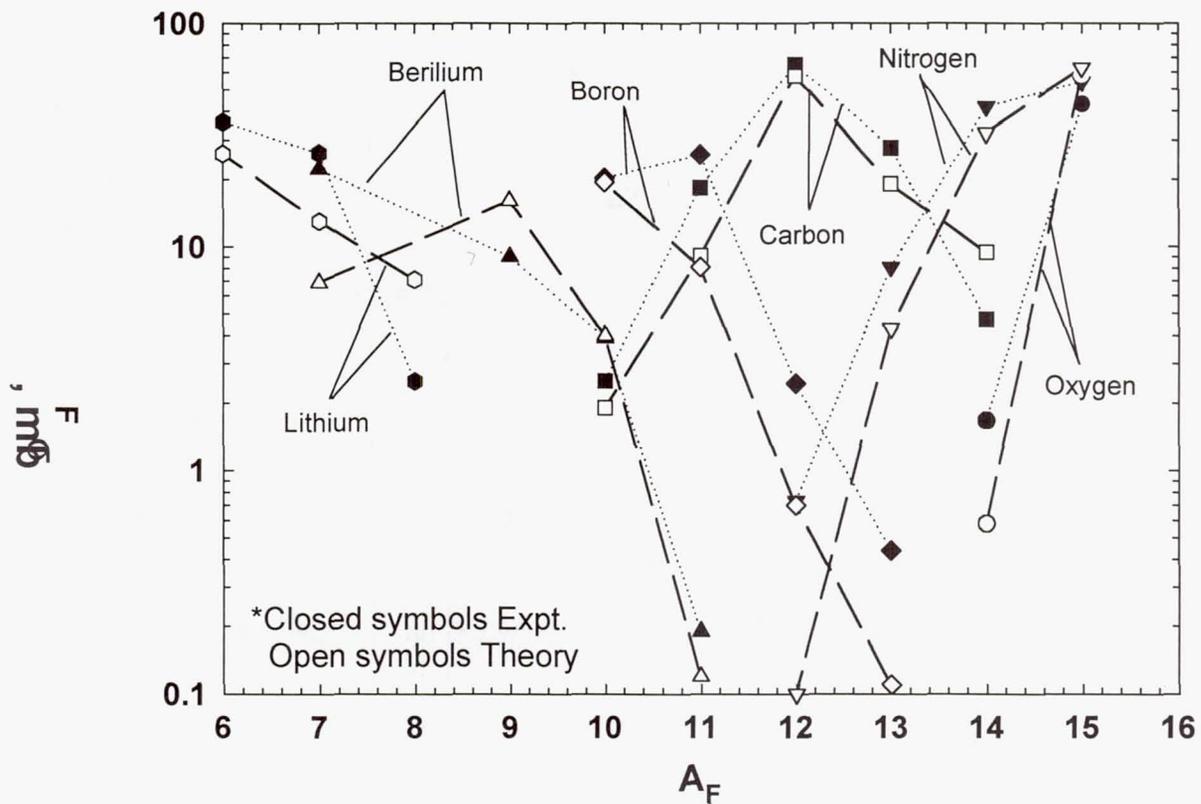


Fig. 1. Comparison of QMSFRG to experiments for 2.1 GeV/u  $^{16}\text{O}$  fragmentation on  $^{12}\text{C}$

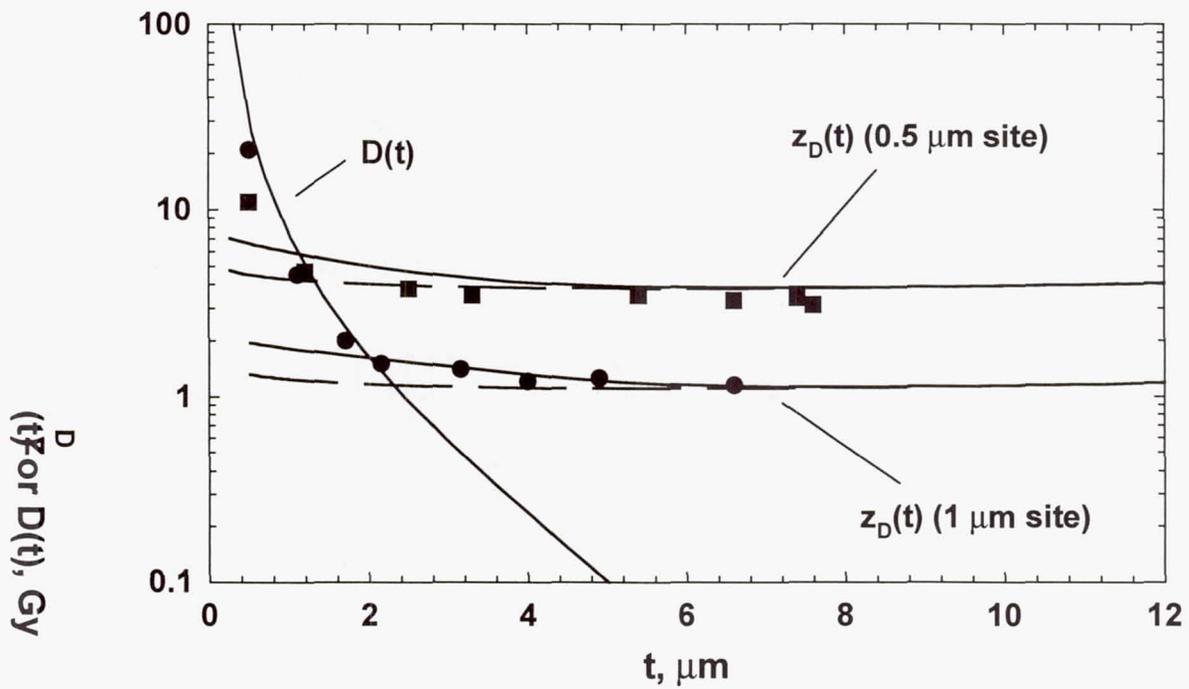


Fig. 2. Comparison of track model to mean specific energy as function of radial distance from ion.