Nonionizing Energy Loss (NIEL) for Protons

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ABSTRACT

The proton induced NIELs for representative spacecraft materials are presented for the energy range between the displacement thresholds of the material to 1000 MeV. All interaction mechanisms (Coulomb and nuclear elastic/inelastic) are fully accounted in the present NIEL calculations.

I. INTRODUCTION

Nonionizing energy loss (NIEL) is a quantity that describes the rate of energy loss due to atomic displacements as a particle traverses a material. The product of the NIEL and the particle fluence (time integrated flux) gives the displacement damage energy deposition per unit mass of material. NIEL plays the same role to the displacement damage energy deposition as the stopping power to the total ionizing dose (TID). The concept of NIEL has been very useful for correlating particle induced displacement damage effects in semiconductor and optical devices. Many studies have successfully demonstrated that the degradation of semiconductor devices or optical sensors in a radiation field can be linearly correlated to the displacement damage energy, and subsequently to the NIEL deposited in the semiconductor devices or optical sensors [1]-[3]. In addition, the NIEL concept was also useful in the study of both Si and GaAs solar cells [4]-[7] and of high temperature superconductors [8], and at predicting the survivability of detectors used at the LHC at CERN. On the other hand, there were a few instances where discrepancies were observed in the application of NIEL, especially in GaAs semiconductor devices [9]. However, NIEL is still a valuable tool, which can be used to scale damages produced by different particles (understanding that there is no obvious reason for an exact NIEL scaling at the microscopic level and that even a significant violation of NIEL scaling can still be consistent with experimental data in some cases [10]) or to simulate the complex space environments in ground experiments.

Despite the widespread adoption of the NIEL approach there are problems which hinder its widespread use. First, the number of cases where extensive data and calculations are available remains limited. For example, proton, deuteron, helium ion, electron, neutron, gamma ray and pion NIEL calculations and experimental data are available only for silicon. The information for other semiconductors is much more limited. Practically no heavy ion ($Z \geq 5$) NIEL data is available even for silicon. This can prevent its application in the space environment, where the NIEL contribution of galactic cosmic ray (GCR) and solar particle event (SPE) heavy ions is unknown. Further, the number and diversity of material and device types for which information will be desired in the future will increase. The limitation in available NIEL data is and will be a serious obstacle to future progress. There is an ongoing effort to solve this situation under the NASA Space Environment Effects program. Particularly, this paper presents the results obtained so far for the proton NIELs for C, Al, Si, P, Ga, Ge, As, In, Cu, Se, Hg, GaAs, and InP. The proton energies covered in this study are from displacement thresholds to 1000 MeV.

When protons traverse a material, they interact with the material through atomic Coulombic interactions, and nuclear elastic/inelastic reactions. At energies below about 10 MeV, Coulombic interactions dominate the production of displaced atoms from their lattice sites. At energies above 30-50 MeV, nuclear reactions are mostly responsible for displacements. Evaluation of the proton NIEL should involve proper treatment of each interaction physics. Expansion of the proton NIEL calculations for the wide energy range and for materials not studied previously was possible using Ziegler, Biersack, and Littmark (ZBL) universal screened potential [11] for the Coulomb interactions and a charged particle Monte Carlo transport code, MCNPX [12], for the nuclear interactions. Brief descriptions of the physics models used are described next, and a couple of the representative results will be followed. Detailed description of the physics and complete results of the study will be presented in the final paper.

II. ATOMIC COULOMB INTERACTIONS

The classical Rutherford scattering formula have been widely used for computing the Coulomb contribution to the proton NIELs. However, the straightforward application of the classical formulation over the entire energy range covered in this study (displacement thresholds to 1000 MeV) is not appropriate for the proper evaluation of NIEL, especially in the low energy region where the screened potential (a reduction of the Coulomb potential because of the electrostatic screening of the nuclear charges by the space charge of the innermost electron shells) is important, and in the high energy region where relativistic treatment of the scattering process is more appropriate. In this study, we successfully used the ZBL formulations and relativistic energy transfer cross sections to properly account for these two effects. Typical results between 1 keV to 1000 MeV are shown in Fig. 1 for silicon. It is obvious that NIEL obtained using the screened potential and the relativistic formulation shows non-negligible deviation from that obtained using the classical Coulomb scattering cross section.

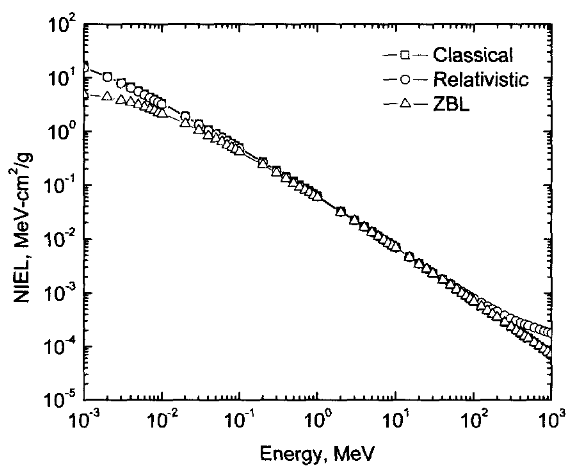

Fig. 1. Proton NIELs for silicon due the Coulomb scattering, computed using three different formalisms.

III. NUCLEAR INTERACTIONS

Recently, Jun [13] described a method to compute the nuclear contribution to the proton NIEL by using a charged particle transport code, MCNPX, based on the thin target approximation. A thin (relative to the CSDA range of incident protons) slab of material of interest with a normalized density of 0.01 atoms/barn-cm was modeled, and a pencil beam of protons was launched onto the slab. Using the damage energy tally, then the history tape written by MCNPX was analyzed to calculate the mean damage energy per source particle, T_{dam}, which is the portion of the energy of the moving atom that is transferred to nuclei. The damage energy cross section, σ_d, is given by: $\sigma_d = T_{dam}/(N_v x)$ where N_v is the atom density and x is the target thickness. Then, NIEL is related to the damage energy cross section: $S_{NIEL} = (N/A)\sigma_d$ where

N is the Avogadro's number and A is the gram atomic weight of the target material. By using MCNPX, we were able to compute the nuclear contributions to the proton NIEL for many materials. Fig. 2 illustrates the results for silicon, which shows the separate contributions of nuclear elastic and inelastic interactions. Further description of relevant nuclear physics will be included in the final paper.

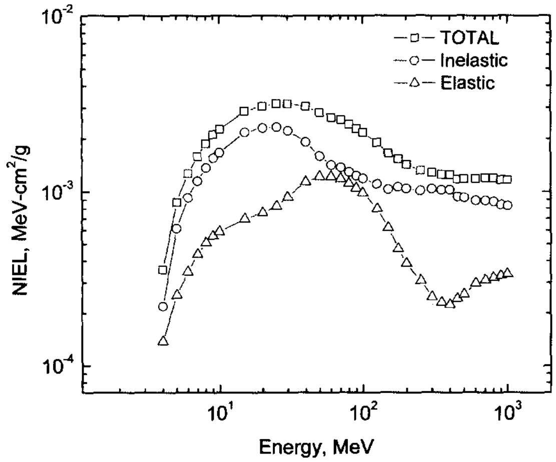

Fig. 2. Proton NIELs for silicon due the nuclear interactions.

IV. RESULTS

Even though we have completed most of the study, we present here only three examples to illustrate how our results are compared to previous study. Figs. 3 to 5 show the proton NIELs for Si, GaAs, and InP, which are being used in many space applications. The results in this study clearly demonstrate the importance of the ZBL screened potential in calculating the proton NIELs, especially in the low energy region. About a factor of 10 reduction is observed at 1 keV NIEL when compared to the values reported by Summers et al.[6]. At higher energies, the NIELs computed in this study agree very well with Summers et al. The results for other materials will be included in the final paper.

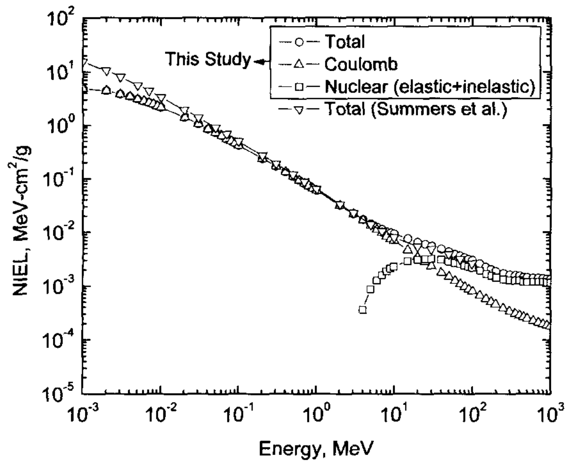

Fig. 3. Proton NIELs for silicon obtained in this study, compared to the Summer's et al. results [6]. For the Coulomb contribution, the ZBL screened Coulomb potential was used for E<50 MeV, and relativistic energy transfer cross section was used for E>/= 50 MeV.

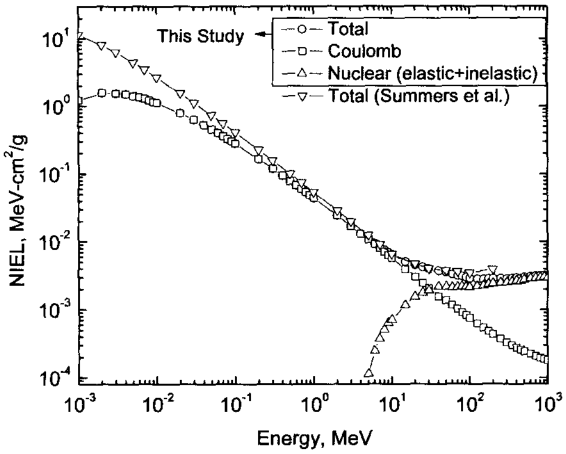

Fig. 4. Proton NIELs for GaAs obtained in this study, compared to the Summer's et al. results [6]. For the Coulomb contribution, the ZBL screened Coulomb potential was used for E<50 MeV, and relativistic energy transfer cross section was used for E>/= 50 MeV.

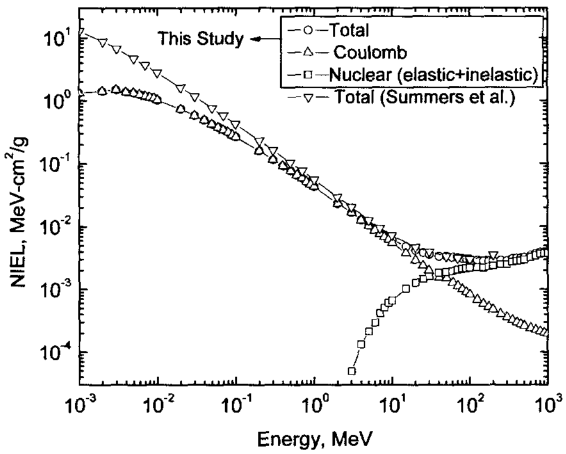

Fig. 5. Proton NIELs for InP obtained in this study, compared to the Summer's et al. results [6]. For the Coulomb contribution, the ZBL screened Coulomb potential was used for E<50 MeV, and relativistic energy transfer cross section was used for E>/= 50 MeV.

V. CONCLUSION

The computation of the proton induced NIELs for many materials of interest to space environment and effect community are being carried out and some of the results are reported in this summary. The proton energies covered are from displacement thresholds to 1000 MeV (although the results from 1 keV to 1000 MeV only are presented here, we will include the results down to the thresholds in the final paper). The ZBL screened potential and relativistic kinematics were used to compute the Coulomb contribution to NIEL. For the nuclear elastic and inelastic interactions, a MCNPX method (thin target approximation) was used. It was shown that in lower energy region, the use of the screened potential is very important to evaluate proper NIELs. At high energies, the results of this study agree very well with previous results, which validates our method to compute the high energy NIELs (relativistic Coulomb and MCNPX nuclear).

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