NIEL Calculations for High Energy Heavy Ions

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ABSTRACT

Calculations of NIEL are reported for heavy ions prominent in the space environment for energies ranging from 200 MeV per nucleon to 2 GeV per nucleon.

INTRODUCTION

Analytical methods have been described for calculating nonionizing energy loss (NIEL) due to Coulombic interactions for many ions and targets at energies ranging from threshold to a GeV. For protons and helium ions at energies above 100 MeV per nucleon, nuclear non-elastic mechanisms can be the dominant contributor to NIEL. For protons and more recently for helium, calculations that include these interactions have been reported [1,2].

At energies in excess of 100 MeV per nucleon, heavy ions can undergo fragmentation interactions where the incident ion is reduced to isotopes with lower charge and mass. Due to the large number of reaction products that emerge from these high-energy heavy ion interactions, at first glance calculating NIEL appears to be rather prohibitive. Consequently the effects of nuclear fragmentation interactions on NIEL have not been reported for heavy ions with atomic number greater than that of helium. Since energetic heavy ions are present in the space environment, the contribution they make to displacement damage in detectors, microelectronics and solar arrays remains an open question. This question is becoming more significant as missions to the moon and Mars are being proposed in NASA's new space initiative. On the other hand, ionization effects of these fragmentation interactions have been extensively studied because of potentially damaging biological and material effects [3,4].

In this paper we first show that the contribution to NIEL for heavy ion fragmentation interactions is small. These results were obtained using experimental data on partial fragmentation cross sections [5,6] combined with our relativistic expression for NIEL [7]. The incident ions considered here include ^{12}C, ^{16}O, ^{40}Ar, and ^{56}Fe. Carbon was selected as a representative target. This means that NIEL for high-energy heavy ions is well approximated by the relativistic formulation. This in turn leads to straight-forward analytic expressions that can be used to obtain fast and reliable estimates of NIEL for high-energy heavy ions in the space environment.

FRAGMENTATION INTERACTIONS

In the abrasion – ablation model [6] attention is focused upon fragmentation of the incident ion. Typically, the ion is reduced to a fragment of lower charge and mass. The partial cross section associated with the production of a particular fragment species can be calculated by first determining the partial cross section for an incident proton. An example of a basic equation used in [5] is

$$\sigma = \sigma_0 f(A) f(E) e^{-P\Delta A} \exp(-R\left|Z - SA + TA^2\right|^{\nu})\Omega\eta\xi \qquad (1)$$

Here σ_0 is a normalizing factor, $f(A)$ and $f(E)$ apply only to heavy targets with $Z > 30$, the factor exp(-$P\Delta A$) accounts for the reduction of cross sections as the difference of product and target mass increases, the second exponential yields the distribution of cross sections for the production of different isotopes of an element with atomic number Z, Ω is related to nuclear structure, η depends on the pairing of protons in the nucleus (e.g. even-even, even–odd), and ξ accounts for enhancement of light evaporation products. Tabulated values of these parameters are provided for a range of projectile-target combinations (see references in [5]).

The cross sections of nucleus-nucleus ($N_1 - N_2$) interactions can be calculated by scaling the proton partial cross sections designated ($N_1 - p$). The scaling relation is

$$\sigma(N_1 - N_2) = \sigma(N_1 - p) \cdot S_c \cdot \varepsilon_n \varepsilon_L \varepsilon_1 \varepsilon_\Delta \qquad (2)$$

N_1 is the ion which is fragmented in a collision with the target N_2 . The factors ε_n,ε_L , ε_1 , and ε_Δ are corrections for neutron deficient products, light products, nucleon stripping, and reactions with large change in mass ΔA. Tabulations are available for the appropriate factors in Eq.(2) as a function of the projectile and the target as well as the energy [5].

The above equations permit the calculation of partial cross sections for most ion target combinations of interest. Tabulations of calculated and experimental partial cross sections have been published for a range of incident ions on carbon targets [5,6]. It is important to note that for an element such as argon with a mass of 40 and a Z of 18 as many as 36 isotopes can result from the fragmentation process - each with its own partial cross section.

The partial cross sections determine the probability of a particular isotope being produced in a fragmentation interaction. In addition to that information we need to assign an energy to the fragment in order to determine NIEL. The most common assumption that has been used in studies of ionization effects produced by fragmentation is that the nucleons in the fragment have the same velocity and momentum as the original projectile. This is the so-called straight-ahead approximation. In the examples shown here we will apply this assumption.

RESULTS

To illustrate fragmentation effects on NIEL we give results for carbon ions incident on a carbon target at energies ranging from 250 MeV per nucleon to 2100 MeV per nucleon in Table 1. NIEL for the Coulombic interactions of these incident ions can be calculated from our previous relativistic form of the Rutherford model [7]. The NIEL associated with the fragments produced by the incident ion can also be calculated from the same model. For carbon there are eleven different isotopic fragments ranging from carbon-11 to lithium-6 and helium-6. In our calculation the values of NIEL for each fragment are weighted according to the associated partial cross section to obtain an average NIEL.

For 3 GeV (250 MeV/n) ^{12}C ions the average NIEL for the 11 fragments was 6.00 x 10^{-3} MeV-cm^2 /g, at 7.2 GeV it was 3.08 x 10^{-3} MeV-cm^2 /g, at 12.6 GeV it was 2.09 x 10^{-3} MeV-cm^2 /g, and at 25.2 GeV it was 1.32 x 10^{-3} MeV-cm^2 /g. After these values have been multiplied by the ratio of the total fragmentation cross section divided by the primary ion cross section the NIEL results are much smaller as shown in Table 1.

The total sum of the partial cross sections ranged from 240 mb to 260 mb. In contrast the primary carbon ions had cross sections that ranged from 187 b to 983 b and associated NIEL values from 2.06 x 10^{-3} MeV-cm^2 /g, to 9.39 x 10^{-3} MeV-cm^2 /g, The data is summarized in Table 1.

The ratio of the partial cross section sum to the primary cross section times the average fragment NIEL yields the contribution of the fragments to the total NIEL. As a consequence of the great difference between the primary cross section and the sum of the partial cross sections the contribution of the fragments to NIEL is very small. For 3.0 GeV carbon ions the contribution of the fragments to NIEL is only 0.0264 percent. For 25.2 GeV the fragment NIEL is 0.1283 percent. Examination of cross sections for a number of different ions show a similar effect and this is expected to be characteristic of all relativistic heavy ion interactions.

TABLE 1. Calculated NIEL for High Energy Carbon Ions On Carbon targets

Energy/Nucleon MeV/n	NIEL (MeV-cm^2 /g) Primary Ion	Fragment/Primary
250	9.394×10^{-3}	1.583×10^{-6}
600	4.832×10^{-3}	1.554×10^{-6}
1050	3.294×10^{-3}	1.558×10^{-6}
2100	2.060×10^{-3}	1.699×10^{-6}

In addition to calculations for carbon atoms incident on carbon we examined the results obtained with oxygen, argon and iron. In all of these cases the energy of the incident ion was at 600 MeV per nucleon. The data for these ions is shown in Table 2. Again the contribution of the fragmentation to the total NIEL is very small.

TABLE 2. Calculated NIEL for High Energy Ions On Carbon Targets at 600 MeV/n

Incident Ion	NIEL (MeV-cm^2 /g) Primary Ion	Fragment/Primary
^{12}C	4.832×10^{-3}	1.554×10^{-6}
^{16}O	9.544×10^{-3}	3.415×10^{-6}
^{40}Ar	6.625×10^{-2}	1.001×10^{-5}
^{56}Fe	1.545×10^{-1}	1.456×10^{-5}

Thus, at these high energies it can be concluded that the heavy ion NIEL is well approximated by the relativistic Coulombic contribution. It has been found that such results can be conveniently expressed as a function of atomic number, Z, as shown in Figure 1. The Figure shows NIEL results in silicon for all heavy ions with Z values ranging from 2 to 34 and for energies ranging from 200 MeV/n to 2 GeV/n. In the space environment, the flux of ions with Z-values greater than 26 (iron) falls off quickly with increasing Z. Thus, Figure 1 fills in what previously has been a large gap in NIEL results for estimating displacement damage effects.

CONCLUSIONS

The above results indicate that an excellent estimate of NIEL associated with high energy heavy ions can be achieved if the fragmentation effect is ignored. Only the relativistic Coulombic interaction need be taken into account. Since analytic models are available for calculating NIEL over the full energy range of interest this greatly simplifies damage estimates for these heavy ions.

Another important implication of the above conclusion is that NIEL spectra can be constructed which include all cosmic ray species of interest. These would play a role similar to the LET spectra originally constructed by Heinrich [8] for studying ionization effects. That would provide another tool for considerably simplifying the assessment of displacement damage produced in a space environment.

In the full-length paper, results analogous to Figure 1 for GaAs will also be presented.

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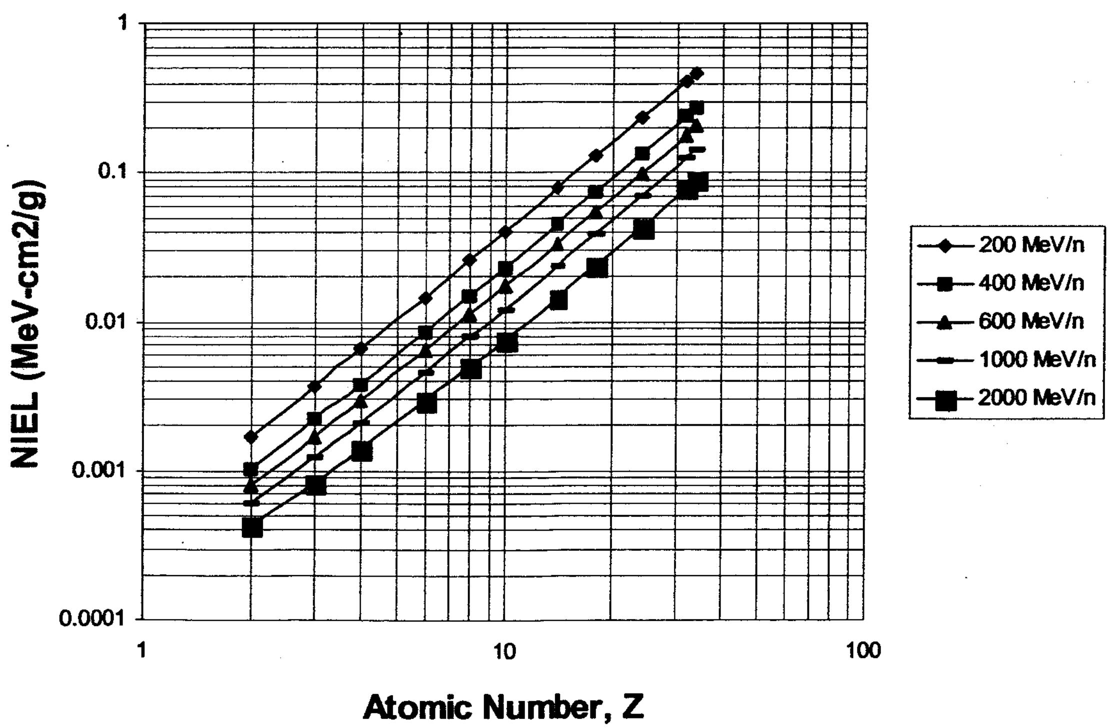

Figure 1. NIEL in silicon for incident ions with atomic numbers ranging from 2 to 34 and energies ranging from 200 to 2000 MeV per nucleon.