



MONTE CARLO TRANSPORT MODEL COMPARISON WITH 1A GeV ACCELERATED IRON EXPERIMENT: HEAVY-ION SHIELDING EVALUATION OF NASA SPACE FLIGHT-CREW FOODSTUFF.

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ABSTRACT

Deep-space manned flight as a reality depends on a viable solution to the radiation problem. Both acute and chronic radiation health threats are known to exist, with solar particle events as an example of the former and galactic cosmic rays (GCR) of the latter. In this experiment Iron ions of 1A GeV are used to simulate GCR and to determine the secondary radiation field created as the GCR-like particles interact with a thick target. A NASA prepared food pantry locker was subjected to the iron beam and the secondary fluence recorded. A modified version of the Monte Carlo heavy ion transport code developed by Zeitlin at LBNL is compared with experimental fluence. The foodstuff is modeled as mixed nuts as defined by the 71st edition of the Chemical Rubber Company (CRC) Handbook of Physics and Chemistry. The results indicate a good agreement between the experimental data and the model. The agreement between model and experiment is determined using a linear fit to ordered pairs of data. The intercept is forced to zero. The slope fit is 0.825 and the R² value is 0.429 over the resolved fluence region. The removal of an outlier, Z=14, gives values of 0.888 and 0.705 for slope and R² respectively. © 2002 COSPAR. Published by Elsevier Science Ltd. All rights reserved.

INTRODUCTION

The problems of high-energy heavy-ion (HZE) transport in shielding and biological samples are important to the field of space radiation protection. The HZE particles in the galactic cosmic ray (GCR) spectra are responsible for a major portion of the dose equivalent with iron ions having the largest contribution (Ginzburg, 1964; Wilson et al., 1991; Curtis and Townsend, 1991). Iron ions are therefore a natural choice for the study of GCR on shielding material. Ground-based experiments with iron beams provide validation for heavy ion transport codes and cross section data for materials of interest. The energy of the iron beam used in this experiment is near the peak of the iron GCR spectrum with an experimental value of 1.05 ± 0.005 GeV/nucleon (Zeitlin et al., 1996a).

The fragmentation of the incident beam is important in the space radiation problem and in the creation of transport models for heavy ions. The emergent secondary field is composed of all elemental ions from the charge of the incident ion down to hydrogen, and neutrons (Curtis and Townsend, 1991). This fragmentation of the projectile can occur in both the shield and a biological sample giving rise to a possibly greater dose equivalent behind shielding and in the body (Curtis and Townsend, 1991; Townsend et al., 1992). A fragment fluence spectrum is measured to characterize the field. This fluence spectrum is used to interpret biological results (Curtis et al., 1992) and form an understanding of nuclear transport of ions in various materials. (Townsend et al., 1992). The principle goal of this experiment is to characterize the charge distribution of nuclear fragments produced by high-energy iron nuclei interacting in a NASA pantry locker containing food from the MIR flight test program and to compare these results with Monte Carlo simulations for a similar target.

EXPERIMENTAL DETAILS

The experiment, known as E-898, was performed at the Alternating Gradient Synchrotron (AGS) of the Brookhaven National Laboratory. The AGS provided a beam of ^{56}Fe with a target-entry energy of 1.05 ± 0.005 GeV/nucleon (Zeitlin *et al.*, 1996a). A silicon detector array was used to collect the data both pre- and post- target on the beam axis with a small solid angle. This array was made up of position sensitive silicon detectors and transmission mount silicon detectors. The detector signal was amplified, converted to digital format, and collected by computer (Zeitlin *et al.*, 1996a&b). The target examined is an example of a food storage locker used in the space program and was supplied for the experiment by the NASA Langley Research Center. The pantry locker is a Lucite box filled with food from the MIR flight test program (Simonsen, 2000). The aerial density of the pantry is 8.1 g/cm^2 and contains food items as described by Simonsen *et al.* (2000).

DATA ANALYSIS

The object of the data analysis is to extract the fragment fluence spectra from the energy loss, ΔE , in the array of silicon detectors and its associated error. The data analysis software Physics Analysis Workstation (PAW) was used in the following analysis (Brun *et al.*, 1989). The energy loss of a particle traversing the silicon detector is proportional to Z^2 by the Bethe-Bloch relationship (Zeitlin *et al.*, 1996b). Thus the energy loss for the produced ion varies as a function of the charge allowing the identification of each observed particle. The fragment fluence ratio is defined as the number of particles of type Z divided by the number of total particles observed.

$$\Delta(Z) = \frac{\text{Number of particles of type } Z}{\text{total number}} \quad (1)$$

With the identification of ions of charge Z the fluence ratio can be calculated. Due to the upstream detectors and other material in the beam line before the target, the incident beam was not exclusively iron. Fragmentation of the beam occurred in upstream elements and must be removed from the calculated fluence (Zeitlin *et al.*, 1996b; Townsend and Wilson, 1998). To accomplish this a no-target data set was collected to determine the fragment fluence spectrum of the pre-target beam. This spectrum was then subtracted from the target spectra.

$$\Delta(Z)_{\text{true}} = \Delta(Z) - \Delta(Z)_{\text{background}} \quad (2)$$

Additionally, incident particles can have interactions in the silicon detectors themselves. These events were removed from the data using PAW. Once all of the above events and background corrections were made each secondary charge peak was plotted. Finally, PAW was used to apply a Gaussian fit to each fragment peak giving the amplitude, width, mean, and associated errors. Using this information it was possible to calculate the total number of events under the Gaussian curve for each fragment and thus the fluence ratio for each secondary fragment (Stephens, 1997).

RESULTS AND MODEL COMPARISON

The fluence ratios of secondary fragments identified by charge for the food pantry are shown in Figure 1. The experimental fluence ratio exhibits a general decrease with nuclear charge from the incident ion to lower Z . The experimental data also exhibit the odd-even effect based on nucleon structure considerations. The error bars indicate the associated rms counting statistics. The data analysis method and experimental setup limit the unique determination of fluence for low Z fragments. In this example the lowest Z fragment resolved is $Z=12$.

The experimental fluence is compared with the Monte Carlo model for CRC-defined mixed nuts over the resolved region of charge (Lide, 1991). The model used for the comparison is a Monte Carlo code created by Zeitlin (1996b). This code uses the NUCFRG2 program to provide inclusive fragmentation cross sections for all of the possible interactions (Wilson *et al.*, 1991; Townsend and Wilson, 1998; Townsend and Wilson, 1986; Townsend *et al.*, 1993). Zeitlin's code uses Monte Carlo methods to transport iron ions through various thicknesses of target materials. This code models the transport in one dimension taking advantage of the unique nature of high-energy, heavy ion interactions where most of the energetic secondaries continue to travel in the incident particle direction of motion (Wilson, 1983). Up to five generations of interactions can be followed in the target with final fluence, generational, and error information

reported. This code was generalized to allow any generic target description by the user for homogenous targets composed of up to fifteen constituent elements (Stephens, 1997).

The predicted and experimental fluence ratios were compared using a plotting method in Figure 2. An ordered pair was created for the fluence ratio of each charge Z with a y -value equal to the predicted fluence and an x -value equal to the experimental fluence. If the model and experiment were in complete agreement the plot of all Z ordered pairs would result in a linear curve with slope of one and intercept equal to zero (Curtis et al., 1992). This represents the line of "best fit". The ordered pairs were plotted and linear regression, forced through the origin, was used to calculate the value of the actual slope. By comparing the "best fit" slope with the regression slope a quantity of "goodness of fit" was calculated. This quantity is the percent difference between the "best fit" slope of unity and the regression slope of the data. It is noted that the predicted fluence ratio does not exhibit the odd-even effect seen in the experimental data. This is thought to be a result of the lack of detailed nuclear structure in the NUCFRG2 model (Wilson et al., 1991; Wilson, 1983; Townsend et al., 1993). The percent error values for the CRC-mixed nut sample is 17.5% for all points and 11.2% excluding the outlier $Z=14$ with R -squared values of 0.4289 and 0.7046 respectively. In general the lack of the odd-even effect in predicted values is shown to contribute to the non-linear behavior in Figure 2 and is indicated by the R^2 values. A plot of the ratio of predicted to experimental fluence ratios as a function of charge Z is plotted in Figure 3. This plot clearly indicate the lack of odd-even effect in the NUCFRG2 cross sections for these heavy charged particles and shows that it generally under predicts cross sections for $12 \leq Z \leq 20$.

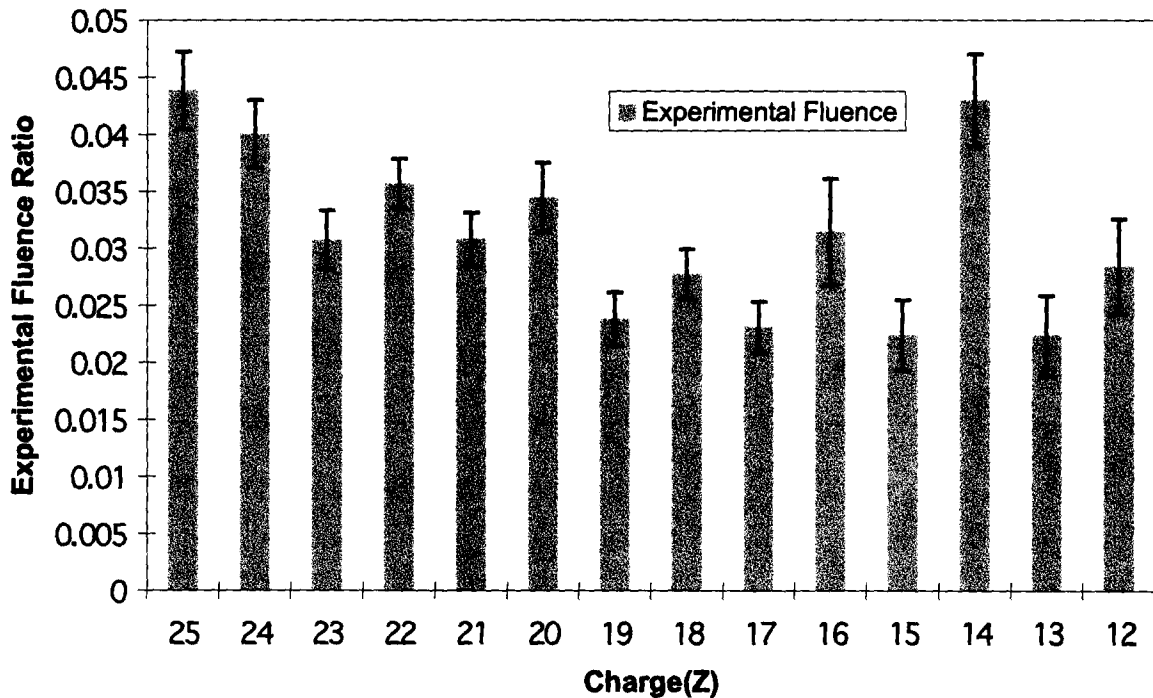


Fig. 1. Experimental Fluence Spectra for Food Locker.

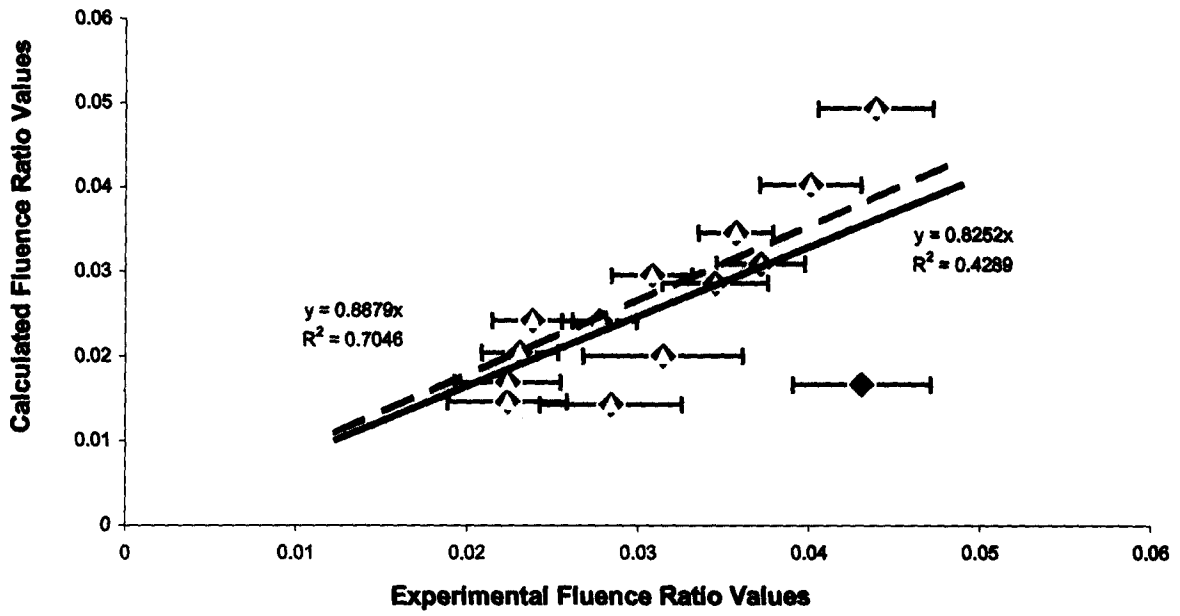


Figure 2. Comparison of Monte Carlo Model (mixed nuts 8.1 g/cm²) to Experimental Data for Food Pantry Sample.

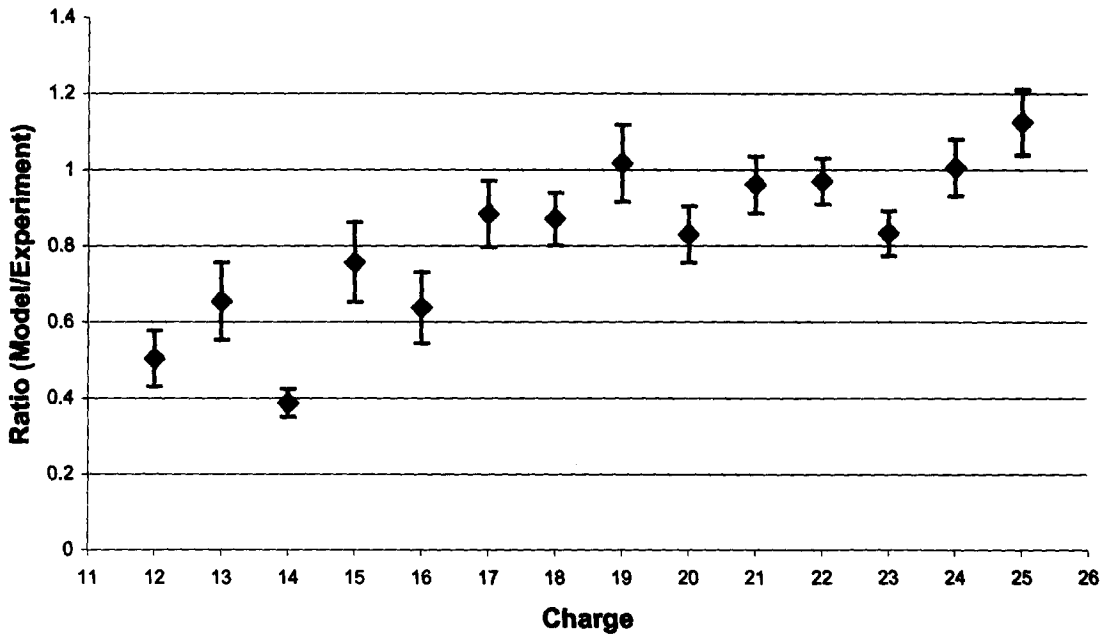


Figure 3. Ratio of Predicted Values to Experimental Values.

CONCLUSION

The experimental fragment fluence data were compared with Monte Carlo beam transport results by plotting the ordered pairs of the predicted and experimental fluence ratio for each charge Z . For complete agreement the expected slope is unity. A linear regression is applied to the data and the resulting slope is compared to unity by means of a percent error. The percent error values for the CRC-mixed nut model is 17.5% for all points and 11.2% excluding the outlier $Z=14$ with R-squared values of 0.4289 and 0.7046 respectively. The agreement between the model and experiment are within the errors attributable to the uncertainties in the presumed fragmentation cross sections.

The odd-even effect seen in the experimental data is missing in predicted values from the Monte Carlo model. This is attributed to the lack of nuclear structure information in the cross section production code used. The plot of predicted to experimental fluence ratios as a function of charge Z indicate the lack of odd-even effect in the calculated cross sections for these heavy charged particles and shows that it under predicts cross sections for ions of charge $12 \leq Z \leq 20$. The lack of nuclear structure in the calculated cross-section production is also indicated in the fluence ratio values for the charge 14 fragments. Conclusions may change when secondary neutron and low- Z fragment production are investigated since light fragments may dominate the biological consequences of the iron fragmentation, as some experiments have suggested.

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