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PREDICTIONS OF LET SPECTRA MEASURED ON LDEF

T. W. Armstrong and B. L. Colborn
Science Applications International Corporation[1]
Route 2, Prospect, TN 38477
Phone: 615/468-2603, Fax: 615/468-2676

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E. V. Benton
Physics Research Laboratory, University of San Francisco[1]
2130 Fulton St., San Francisco, CA 94117-1080
Phone: 415/666-6281, Fax: 415/666/2469

ABSTRACT

The linear energy transfer (LET) spectra measured by plastic (CR-39) detectors in Exp. P0006 on LDEF are much higher at high LET than expected from methods commonly used to predict LET spectra produced by the space ionizing radiation environment. This discrepancy is being investigated by examining modeling approximations used in the predictions, and some interim results are presented.

INTRODUCTION

The P0006 Experiment on LDEF (ref. 1) contained plastic detectors (CR-39) for measuring linear energy transfer (LET) spectra. Analyses of these data reported to date, Benton, et al. (ref. 2), show observed spectra that are quite different than expected from commonly-used LET prediction methods. Since LET spectra are fundamental in predicting a variety of radiation effects of practical importance (e.g., biological damage, electronics upsets) in spacecraft and mission design, it is important to investigate the reason for this discrepancy, and reported here are some interim results of such work.

The problem addressed is illustrated by Fig. 1. Shown here is the measured LET spectrum (ref. 2) in one of the CR-39 sheets located 6.5 g/cm^2 from the space end of the main detector stack in the P0006 experiment. Also shown is a pre-recovery LET prediction made by Derrickson (ref. 3) using the NRL CREME code of Adams (ref. 4), which is commonly used for predicting LET spectra in performing assessments of space radiation effects on microelectronics. Since this pre-recovery prediction was of a scoping nature to obtain a quick estimate, several approximations were involved -- e.g.: (a) the spacecraft and detector shielding is approximated as an aluminum sphere, (b) the calculated LET spectra are for silicon, whereas the CR-39 data have been converted to LET in water, (c) the calculated spectra are for the space environment at the LDEF insertion altitude and not averaged over the LDEF mission, and (d) the calculation neglects the effects of secondary particles created in the detector and spacecraft, including both "projectile fragments" (secondaries from the breakup of incident ions during nuclear collisions) and "target fragments" (residual nuclei and secondary particles from collisions with detector material nuclei). Discussed below are calculations which remove some (but not all) of the approximations in the pre-recovery LET predictions.

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LET PREDICTIONS

Shielding Effects

Since a detailed 3-D mass model of the LDEF spacecraft, experiment tray F2 contents containing the P0006 experiment, and the P0006 detector stack has been developed (ref. 5) for LDEF radiation analyses, the effects of shielding on the LET spectra predictions can be treated accurately. Therefore, the LET spectrum at a point in the center of the CR-39 layer corresponding to the location of the measured spectrum has been calculated using the LDEF 3-D shielding model. Radiation transport calculations were made for shielding in each of 720 solid angle bins around the detector point. A simplified representation of the shielding distribution is shown in Fig. 2. The transport calculations along each shielding direction were made using the Burrell transport code (ref. 6) for incident trapped protons and the CREME code (ref. 4) for galactic protons and heavy ions. The LDEF exposure to trapped protons predicted by Watts, et al. (ref. 7) was used, which takes into account the trapped proton anisotropy as well as altitude and solar cycle variations during the LDEF mission. Incident galactic cosmic ray spectra for the LDEF orbit were calculated using the CREME code. Average galactic spectra over LDEF altitude and solar cycle variations were computed, but the average results are not significantly different from the solar minimum spectra at the LDEF insertion altitude assumed in the pre-recovery predictions, as illustrated in Fig. 3 for protons. The LET spectrum in water is calculated to correspond to the data, as opposed to LET in silicon for the pre-recovery prediction of Fig. 1.

Results from this calculation are compared with measurements in Fig. 4. There is some improvement compared to Fig. 1 when shielding effects are taken into account, but the large difference for the high-LET "tail" ($\geq$ 1500 MeV $\cdot$ cm^2/g) still exists. The difference at low LET ($\leq$300 MeV $\cdot$ cm^2/g) is understandable because of the inherent insensitivity of CR-39 at low LET and because of the particular etching process used. Thus, the CR-39 has very low detection efficiency for trapped protons. This is illustrated in Fig. 5, which is the same as Fig. 4 but indicates the predicted trapped proton and galactic components.

SEP Iron Contribution

From measurements made by the HIIS experiment of Adams, et al. on LDEF, it was found that the large solar energetic particle (SEP) events during Oct. 1989 made a large contribution to the observed iron spectra in the energy range from $\approx$ 200-800 MeV/nucleon (ref. 8). Since iron $\geq$ 350 MeV/n can penetrate the 6.5 g/cm^2 minimum shielding of the CR-39 layer of interest in Exp. P0006, and since the LET calculations above neglect SEP events, we have checked the contribution of SEP iron to the LET.

These calculations were made by modifying the CREME code to incorporate the Fe spectra measured by HIIS on LDEF. LET spectra are compared in Fig. 6 with and without the SEP iron included. These results show that SEP iron makes some contribution at high LET, but not nearly enough to account for the predicted vs. observed discrepancy in Exp. P0006.

Contribution of Heavy Ion Fragmentation

To check the contribution at high LET from secondary particles generated when incident heavy ions breakup into lower-Z ions due to nuclear collisions, the UPROP code of Letaw (ref. 9) was used. This code accounts for the production and subsequent transport of all secondary particles from ion breakup in nuclear collisions. The results of this calculation (made for a spherical aluminum shield) show that, even for the case of rather thick shielding (50 g/cm^2), the secondaries from ion fragmentation do not significantly increase the LET spectrum (Fig. 7).

SUMMARY

The LET calculations described above remove some of the approximations made in initial, pre-recovery predictions, but they do not explain the large difference at high LET between predictions and measured spectra for Exp. P0006. The calculations to date have not taken into account target nuclei fragments and elastic recoils from nuclear collisions produced by trapped protons, which is suspected as being the most likely cause of the large underprediction at high LET.

To account for the effects of nuclear interaction products from trapped proton collisions with the CR-39 constituents, a more detailed radiation transport calculation is required than possible with the codes used for the above predictions. A calculational approach for accurately simulating the CR-39 measurements is under development, but results are not yet available. The approach consists of two steps in the radiation transport: First, the trapped proton flux in the detector is computed using a standard proton transport code (e.g., ref. 6) and the 3-D LDEF spacecraft/detector model. This procedure, which has been used extensively for dose and activation predictions to compare with LDEF data (e.g., ref. 10), takes into account the trapped proton directionality and accurately treats shielding effects. In the second step, the proton flux in the CR-39 layer is used as the source for a 3-D Monte Carlo transport within the dosimeter. A modified version of the HETC code (ref. 11) can be used for the Monte Carlo calculation to take into account the production and transport of nuclear recoils and secondary particles in the detector region.

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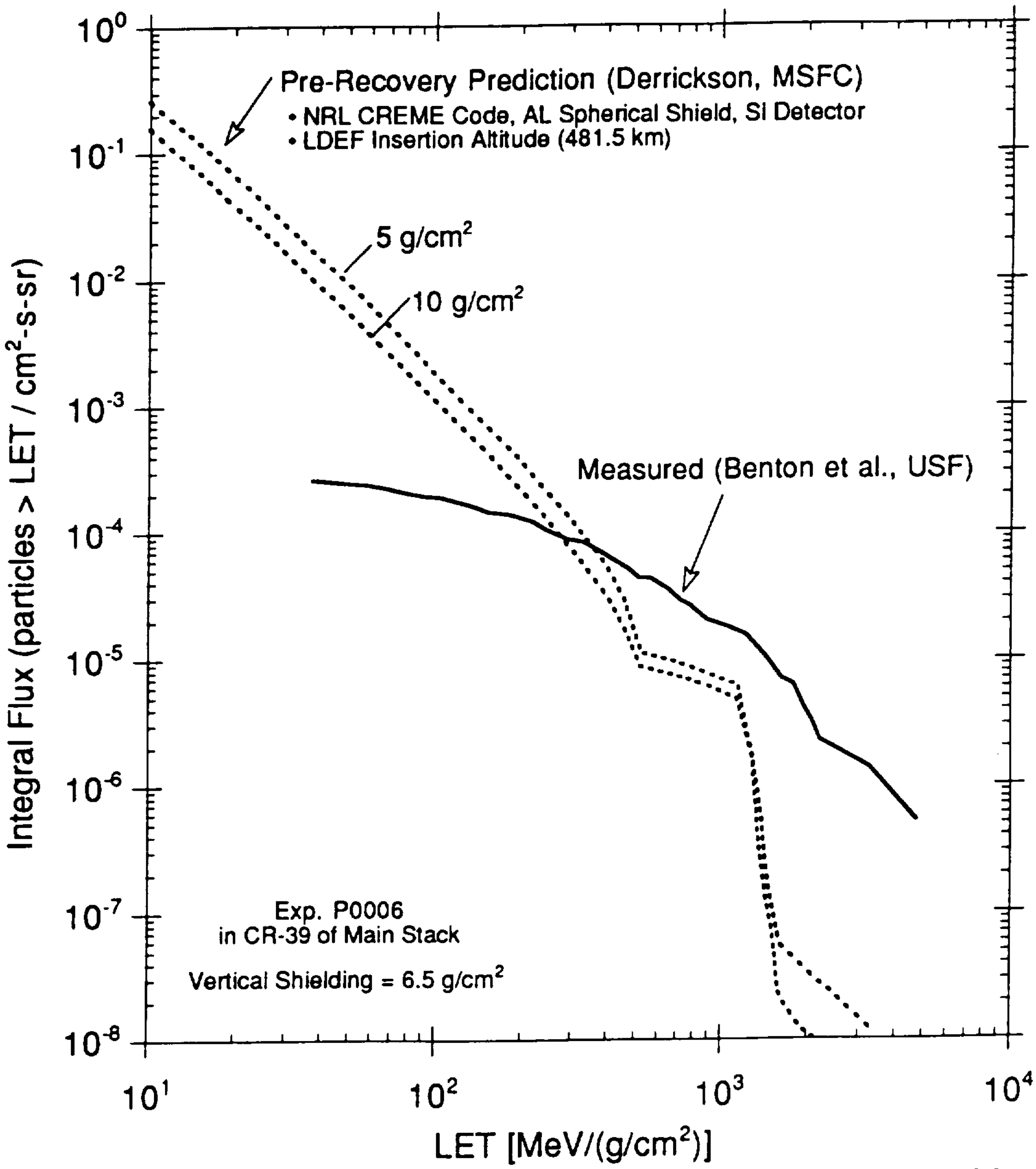

Fig. 1. Comparison of LET spectra measured (ref. 2) by LDEF Exp. P0006 plastic track detector with pre-recovery predictions (ref. 3).

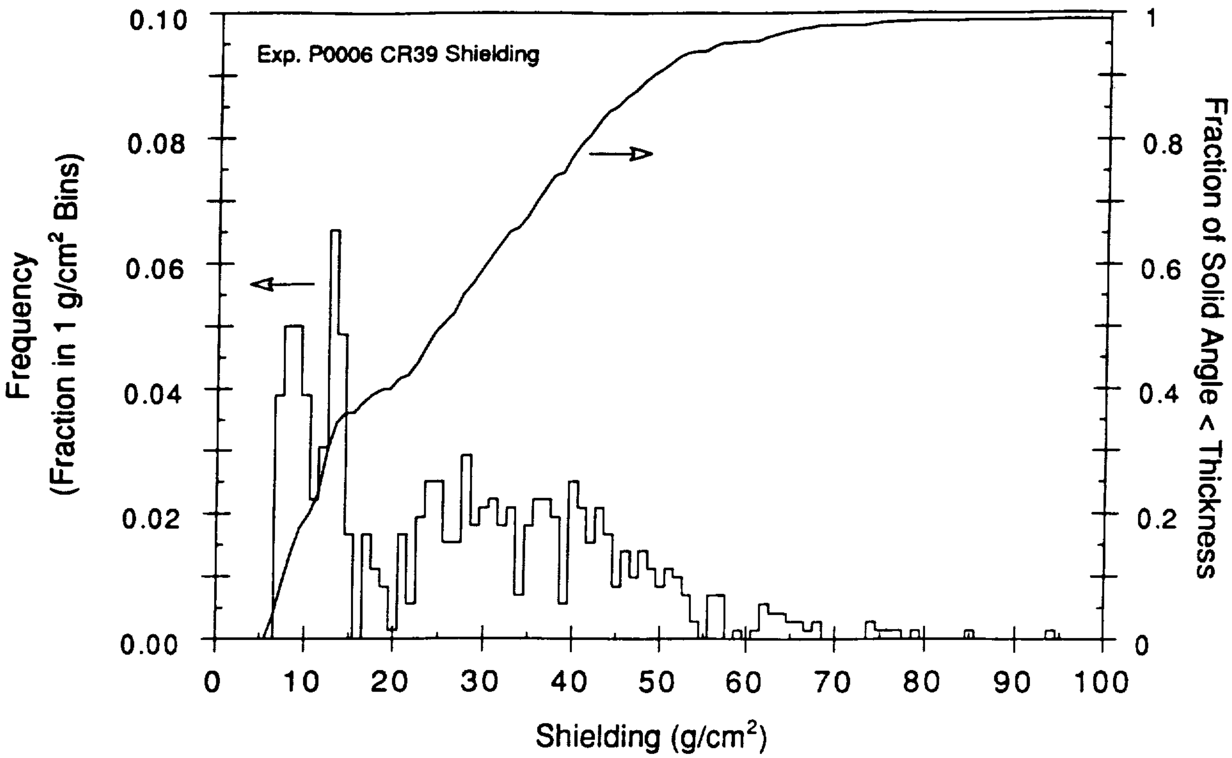

Fig. 2. Shielding distribution for P0006 detector.

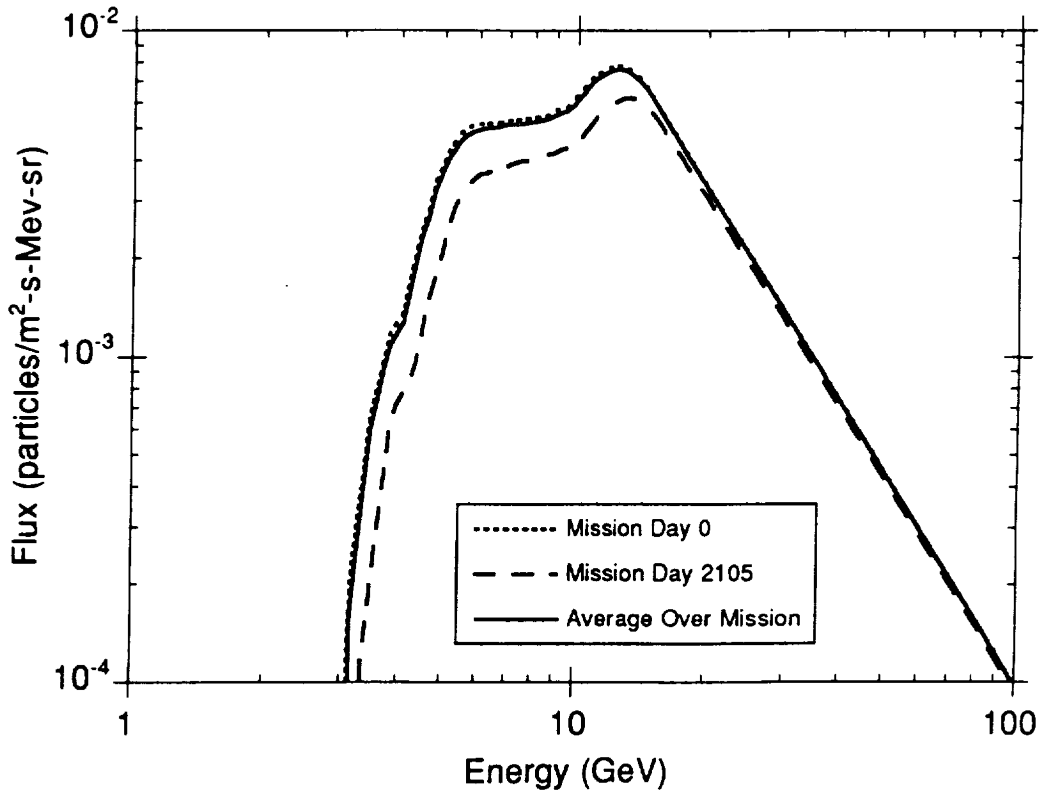

Fig. 3. LDEF exposure to galactic protons.

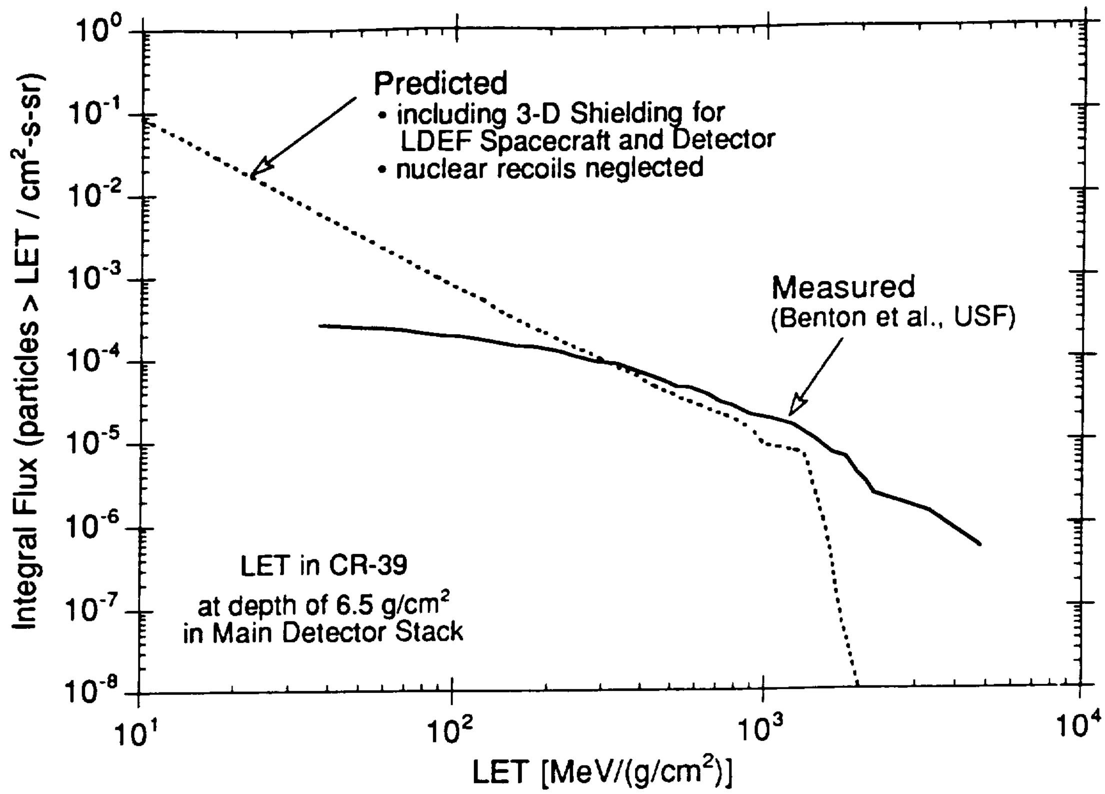

Fig. 4. Predicted LET using 3-D shielding model.

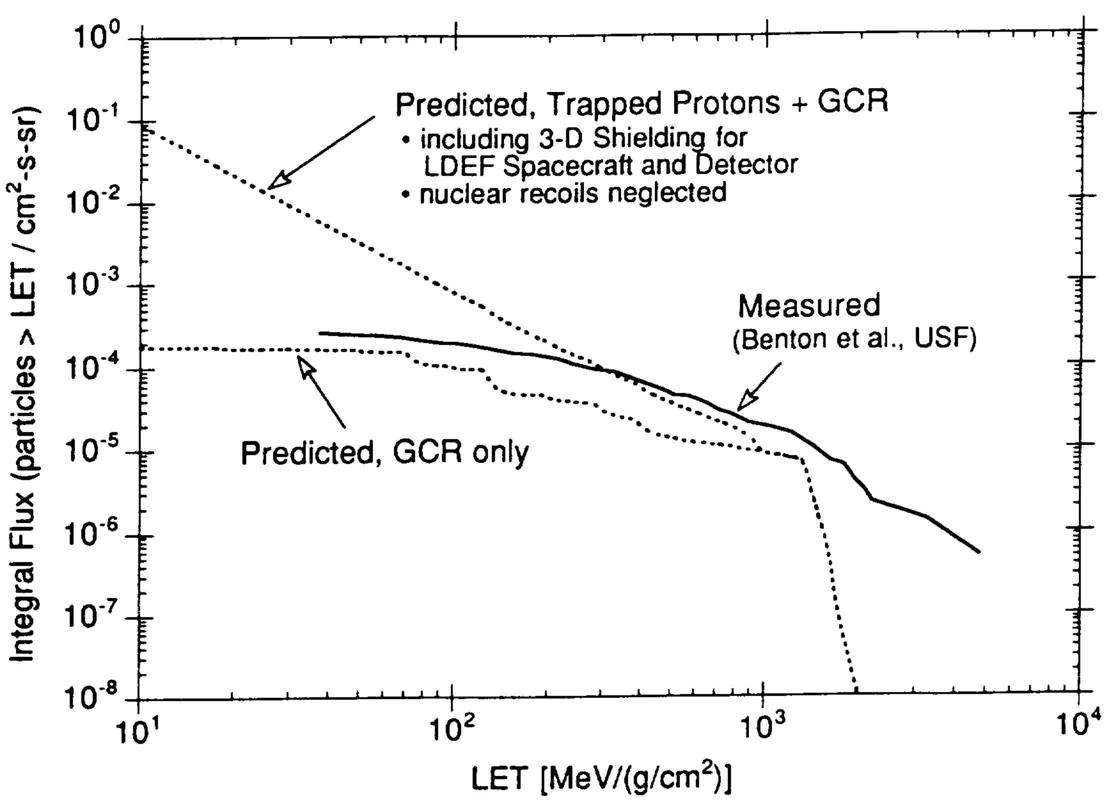

Fig. 5. Contribution of trapped protons to LET.

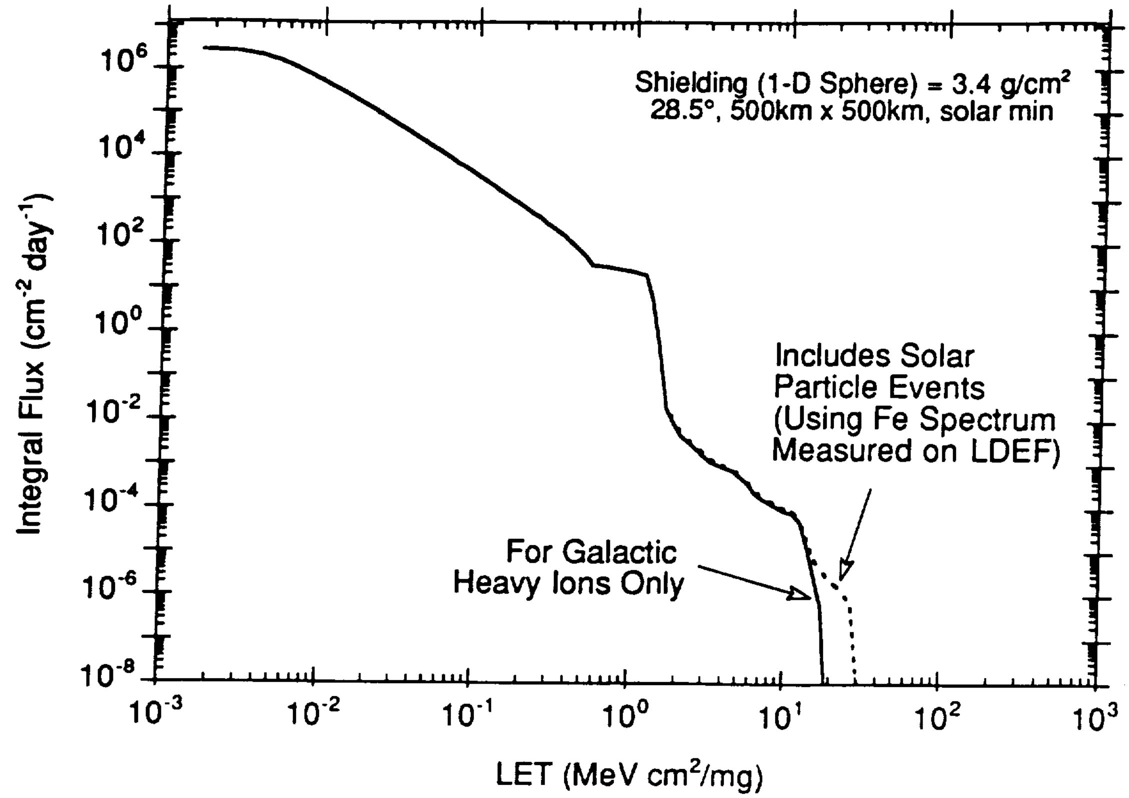

Fig. 6. Influence of SEP iron ions on LET.

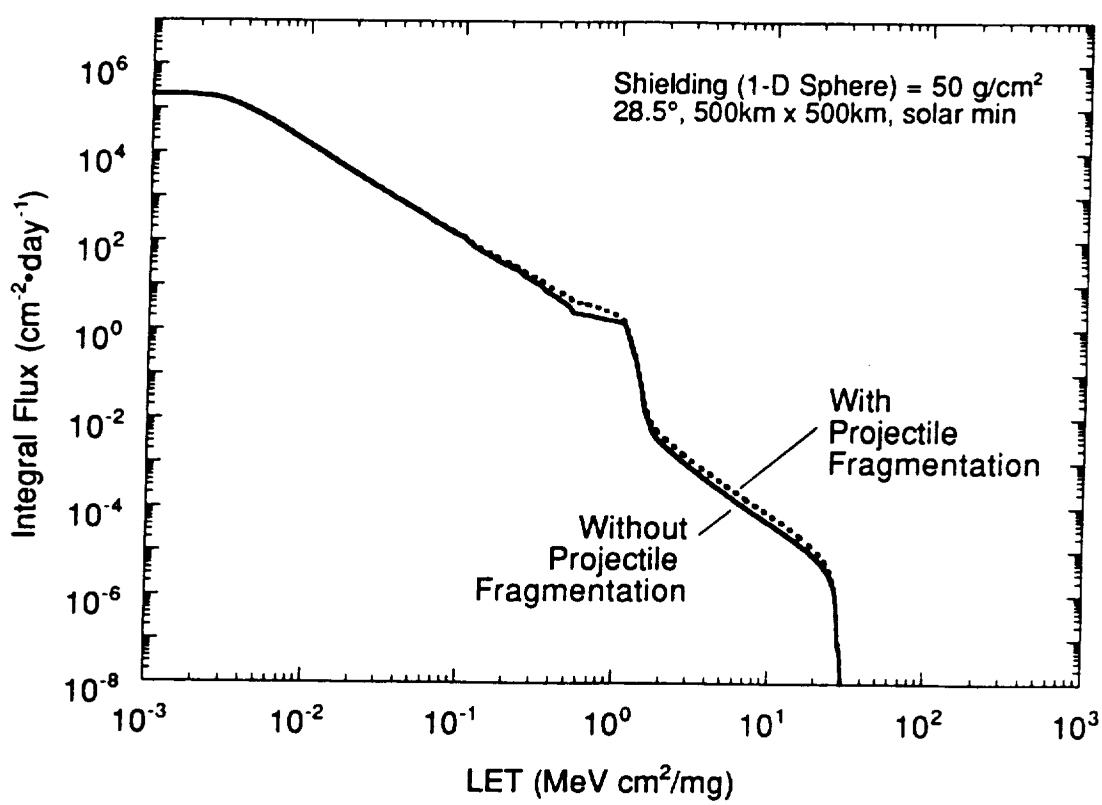

Fig. 7. Influence of ion ("projectile") fragmentation on LET.