Pion-Induced Soft Upsets in 16 Mbit DRAM Chips

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Abstract

Measurements of the soft upset cross section due to energetic charged pions were made in various 16 Mbit memory chips, as a function of incident pion energy and for chips with different cell technologies. Significant differences are seen to exist between cell technologies, up to a factor of 1000 in cross section. Upset cross sections are reported that exhibit proportionality to the reaction cross section for pions on silicon, including the well-known enhancement over proton and neutron cross sections near the delta resonance. Implications of this enhancement for pion-induced upsets due to cosmic ray fluxes are discussed.

I. INTRODUCTION

The study of soft upsets induced by protons and neutrons enjoys an extensive literature, as they have been widely assumed to be primarily responsible for soft upset phenomena at aircraft altitudes and sea level [1–8, e.g.]. The efficacy of protons and neutrons at inducing soft upsets could be attributed to the fact that they are hadrons and thus able to interact with nuclei in the chips via the strong nuclear force, assuming that upset phenomena are caused by nuclear reactions. In contrast, muons, prolific in the cosmic ray spectrum, interact primarily electromagnetically. Charged pions, being hadrons, having a decay lifetime of 26 ns, and having a large reaction cross section relative to other particles at a certain resonant energy, are thus likely candidates for causing soft upsets through the strong force.

Although some attention has been paid to pions [9–12], no data on recent memory devices have been obtained. In fact, pions have been largely discarded as candidates for soft upsets by many authors [13,14], due to either their low flux relative to neutrons and protons, or the assumption that they would only interact electromagnetically. Yet it could be anticipated that pions, if present in sufficient quantities, may be particularly effective at causing upsets. Unlike protons or neutrons, many of which undergo elastic or quasi-elastic collisions with nuclei in the chips and thereby deposit little energy, pions can be completely absorbed by a nucleus, depositing their entire rest mass and kinetic energy to the struck nucleus. Such a reaction results in a highly excited nucleus which deexcites by emitting neutrons and charged particles, including alpha particles [15]. Both the emitted particles and the recoiling nucleus are candidates for causing soft upsets [1,10]. For silicon, this absorption cross section is about 40% of the total reaction cross section, depending on the energy of the pion [16].

Charged pions may arguably be an important contributing factor in soft upsets at aircraft altitudes for two reasons. Firstly, they are present as particles generated in cosmic ray showers in air. By sea level, most charged pions have decayed into muons, and pions have been estimated to comprise only 3% of the hadron flux [17,18]. There are many pions still present at higher altitudes, however. At aircraft altitudes, their intensity relative to nucleons could be one half to one third [19], and estimates extrapolated from sea level measurements using linear cascade theory predict that up to 36% of the particle flux is pions [17], a flux comparable to that of protons or neutrons. Other evidence indicates that these estimates may be too high because pions are comparable in abundance to protons or neutrons only at energies > 100 GeV [20] and comprise less than 10% of the hadron flux at energies < 1 GeV [20,21], the latter energy range containing most of the particles. Secondly, pions are generated in interactions of primary cosmic rays with nuclei in proximity to the chips. As an example, a 730 MeV proton that interacts with a carbon nucleus produces a forward-going charged pion roughly 50% of the time [22]. By symmetry, a neutron of this energy will also produce a pion with this probability. Thus, protons or neutrons interacting with materials in an aircraft shell generate a broad spectrum of energetic pions which have no time to decay before colliding with nuclei in the electronic components of the aircraft. However, since the energetic atmospheric neutrons have an attenuation length of 110 gm/cm^2 [23], only a small fraction of them ($\approx$ 2-5%) will interact with the thin structures of the aircraft (1 inch aluminum $\sim 7\ gm/cm^2$). The effects in bulk silicon of such produced pions have been investigated in Ref. [24] and can be compared to energy deposition measured in bulk silicon devices in flight [25] and in a neutron beam [13].

This paper presents the first measurements of the en-

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ergy dependence of pion-induced single event upsets in 16 Mbit DRAM memory devices. Upset cross sections were measured for three qualitatively different cell technologies, or methods of storing charge.

The evaluation presented in this paper should not be considered definitive as not all variations in major cell technology were tested. Because of the limited testing, the chips are not identified by vendor name, since the results may not be representative of other chips made by that manufacurer. Furthermore, since important details of the 16 Mbit chip circuits have not been published for the chips tested, it is not certain that the cell technology is the most significant component. Within these constraints, however, it is believed that the results presented here indicate that pion-induced soft upset phenomena are strongly dependent on cell technology.

II. EXPERIMENTAL METHODS

16 Mbit DRAM chips were obtained commercially from several manufacturers, including those using high capacitance stacked capacitors, those using trenches with internally stored charge, and those using trenches with externally stored charge. Details of these cell technologies are published by the authors in a separate publication [26].

The testing device used in the experiments was typically operated at a clock speed of 10 MHz, a speed which is slow compared to the nominal chip access time. All tests were run with a pattern called "Complementary R/W Checkerboard," in which first a checkerboard of ones and zeroes are written, and then each bit is read and the complement of its contents written back, resulting in a change of state. This testing procedure alternates reads and writes to the chip, exercising both modes, and further tests all cells in both physical states of storing information bits. All tests were conducted under conditions such that less than one error would be measured due to background radiation. Indeed, no upsets were observed except when beam was incident on the chips. The chip to be irradiated was placed in a testing socket, which in turn was placed in the particle beam. The power connections to the chips were through a voltage source connected directly to the test socket, while the testing device which drove the chips was placed approximately 3 meters from the beamline. The number of soft upsets was recorded for each chip irradiation.

Pions for these measurements were obtained from the EPICS (Energetic Pion Channel Spectrometer) and P^3 (Pion Particle Physics) beam lines of the Los Alamos Meson Physics Facility (LAMPF). LAMPF provides 800 MeV protons incident on a carbon target. The nuclear collisions produce pions (among other reaction products), a fraction of which are momentum-selected and refocussed in any of several beam lines. The EPICS and P^3 beam lines provided both positive and negative parallel beams of pions with energies between 60 and 400 MeV within an uncertainty of 2%. The beam profile at the target was approximately gaussian in shape for both beam lines, with a standard deviation of 6 cm at EPICS and 3 cm at P^3, larger than the sample size. The pion fluence was determined by two methods: The method employed on the EPICS beam line used plastic scintillators, allowing the activation of carbon nuclei in the disks ($C(\pi,X)^{11}C$). The residual ^{11}C radioactivity in the disks was measured by detecting the resultant 511 keV positron annihilation photopeak with a NaI detector and a phototube. Knowledge of the reaction cross section for the production of ^{11}C and the decay lifetime of ^{11}C allows a determination of the pion flux [27]. The method employed at the P^3 beam line was to count directly the number of pions via a scintillation counter similar in size to the chip sample.

III. RESULTS

Soft upset cross sections for the different memory chips express the observed soft fails per particle fluence per memory bit. Thus,

$$\sigma_{SEU}\left[\frac{cm^2}{bit}\right] = \frac{(\text{fails})}{(\text{bits})(\text{fluence}[pions/cm^2])} \qquad (1)$$

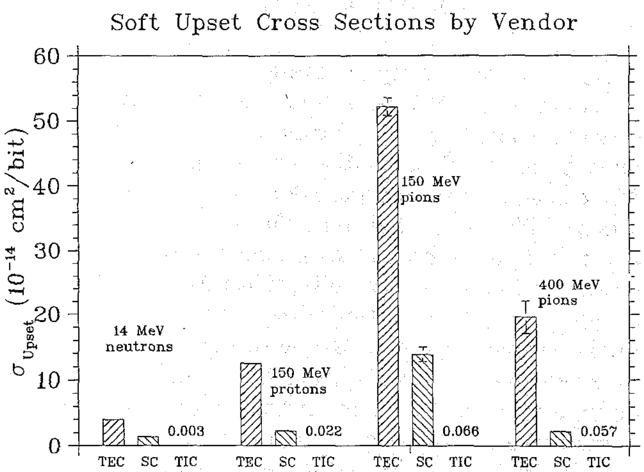

FIG. 1. Soft upset cross sections by vendor and chip architecture are shown on a linear scale to emphasize the differences between cell technology. Data from chips using stacked capacitor design have been denoted as SC; data from the vendor with the trench design and external (internal) charge storage are represented as TEC (TIC). TIC cross section values are included as their histograms are too small to be seen. Pion cross sections are for negative pions only.

Figure 1 shows upset cross sections for negative pions, for 14 MeV neutrons, and for a range of proton energies as a function of cell technology. The neutron and proton data were taken during other experiments [28], using the same samples and cross section methods. Note the dramatic difference between upset cross sections for different cell technologies, up to a factor of 1000 in some cases. The most susceptible technology appears to be TEC, then SC, then TIC, regardless of incident particle or energy. This systematic behavior for each cell technology is well reproduced for all incident particles and energies. In particular, the trench capacitor design with internal charge storage is dramatically less susceptible to soft upsets from any incident particle, including pions. In order to highlight these differences the data of Figure 1 are replotted in Figure 2 as a function of energy, along with additional data from proton-induced soft upset studies [28].

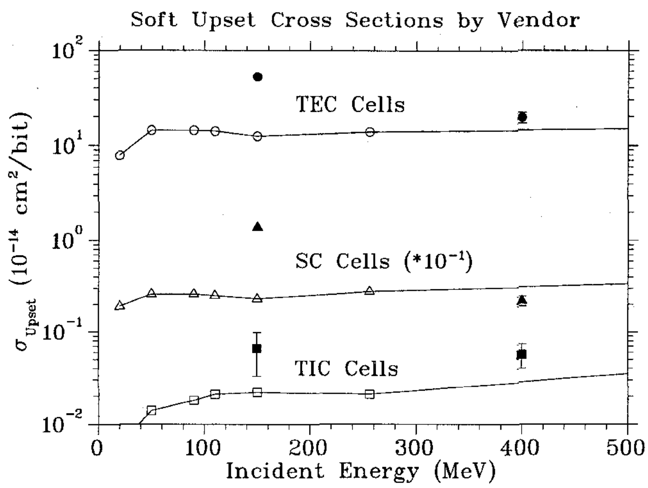

FIG. 2. Soft upset cross sections by chip architecture are plotted as a function of energy. Closed symbols represent the pion data from Figure 1. Open symbols represent proton measurements on the same samples [26]. Data for the SC cells have been multiplied by 0.1 and then plotted. The curve through the proton data is included to guide the eye.

A more technical discussion of the role of cell technology in soft upsets is presented by the authors in [26]. In this paper we emphasize that pions exhibit similar trends in dependence on cell technology as protons and neutrons.

Perhaps the most striking aspect of Figure 1 is the dramatic enhancement of soft upsets for 150 MeV pions relative to neutrons and protons for a given cell technology. The 150 MeV pions are particularly effective at inducing soft upsets, approximately five times more effective than protons of the same energy. Pions of this energy are said to be at resonance, meaning that the pion-nucleon interaction is dominated by the formation of a delta resonance, which is essentially an excited state of a nucleon. Within a nucleus, such as silicon, the delta will interact strongly with other nucleons, resulting in the absorption of the pion. The absorption process conveys a substantial amount of internal excitation energy to the nucleus, including the 140 MeV rest mass of the pion, and the dissipation of this excitation energy proceeds via particle emission. In contrast, protons and neutrons have no such absorption pathway.

In order to study the soft upset enhancement for pions, the pion energy dependence of the upset cross sections for positive and negative pions was studied using a TEC sample. Results are shown in Figure 3. It is readily noted that the pion results are indeed peaked about a beam energy of 150-200 MeV, near the resonance region. Compared to the data is a curve showing the total reaction cross section for pion-silicon reactions. This curve is the result of two model calculations, which agree well with experimental data in the energy regimes under which their approximations are valid [29,30]. As expected for a nucleus with equal numbers of protons and neutrons, such as ^{28}Si, the positive and negative pion cross sections are nearly equal. The shapes of the calculated reaction cross sections and the pion upset cross sections track very closely over a broad energy range, including the pion-nucleon resonance region near 150 MeV. This general agreement in shape gives strong evidence of the reaction mechanism by which upsets are occuring, namely that soft upsets are being caused by nuclear reactions in which the pions are reacting on individual nuclei within the chip. The recoiling nuclei and/or the subsequent deexcitation of these nuclei result in soft upsets. Also shown in Figure 3 are proton-induced upset cross sections [26]. The relative five-fold increase of pion upset cross section is readily apparent.

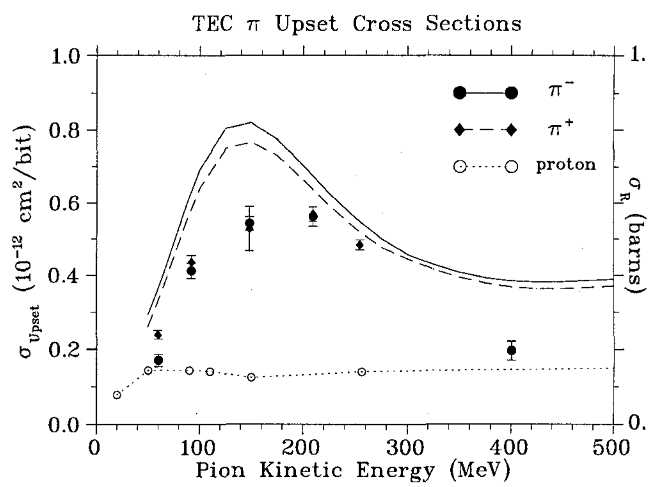

FIG. 3. Soft upset cross sections for $\pi^{\pm}$ and protons are plotted against the left-hand scale. Calculated reaction cross sections for $\pi^{\pm}$ are plotted, with solid and dashed lines, in units of barns, against the right-hand scale. The uncertainties for the pion data are statistical only. Systematic uncertainties are estimated to be $\sim$ 15%.

One could argue that the pion enhancement only reflects the larger reaction cross section (σ_R) for pions on silicon, or that the upset cross section is merely proportional to the reaction cross section for any particle. To this end, we compare the relative upset efficacy of resonant pions and protons to their respective reaction cross sections. The ratio of the pion-to-proton reaction cross sections near 150 MeV is about 2 [31]. The soft upset pion-to-proton cross section ratio is 5, 6, and 3 for TEC, SC, and TIC chips, respectively. (Due to low statistics, the TIC value has a large uncertainty.)

The larger upset rates for pions near resonance, relative to σ_R, indicate that the individual reactions induced by pions create more damage than is produced by the other projectiles. This is consistent with the production of heavily ionizing fragments following pion absorption. The fraction of pion reactions that occur through total absorption is about 40%, remaining nearly constant for pion beam energies from 100 to 500 MeV (see Figure 4) [16].

The fact that pion absorption at resonance appears to result in a higher probability for soft upset phenomena is consistent with a previous set of measurements for 4 kbit samples demonstrating stopped negative pion capture [10]. The data in Ref. [10] clearly show how negative pions can be slowed down to sufficiently low energies so as to be captured by silicon atoms. Subsequent absorption of π^- by the Si nucleus occurs with a nearly 100% probability. No upsets were observed with stopped π^+, since Coulomb repulsion excludes absorption of stopped π^+ as a reaction mechanism. The implication is that pion absorption even without any momentum transfer to the nucleus (e.g. a recoiling struck nucleus) is a significant source of upsets.

The shape of the observed upset cross section is in direct contradiction with an electronic energy loss scenario, one by which the charged projectiles lose energy by collision with electrons in the material, described by the Bethe-Bloch equation, which characterizes energy loss as a function of distance travelled (dE/dx) through a material. In passage through matter dE/dx is largest for low energy particles, with the rate of energy loss falling off as a function of energy. If the pion soft upsets were being caused by this form of energy loss Figure 3 would decrease as a function of incident energy, especially at lower energies. Clearly, then, one concludes that pion-induced soft upsets are driven by nuclear reactions.

Figure 4 shows various cross sections for pion-silicon collisions as a function of incident pion energy. Three different cross sections are shown: reaction cross sections (σ_R), absorption cross sections (σ_{abs}), and quasi-elastic cross sections (σ_{QE}). Note that the reaction and absorption cross sections are largest near 150 MeV. Other higher lying resonances exist between pions and nucleons beyond 400 MeV, which would be present as bumps in the reaction cross section, but they are largely damped out in complex nuclei such as silicon [32]. Note also that the reaction cross section levels out beyond 400 MeV, remaining essentially unchanged out to very high energies. Shown also in Figure 4 is the pion quasi-elastic cross section on silicon. Quasi-elastic scattering occurs when the projectile scatters elastically off a single proton or neutron within the nucleus, instead of being absorbed or interacting with the nucleus as a whole. Quasi-elastic scattering imparts much less energy to the residual nucleus, as the single proton or neutron that is scattered generally is knocked free from the nucleus. One can see that quasi-elastic scattering comprises only a fraction of the reaction cross section and has an energy dependence greatly different from what is observed in the upset cross sections, because the Pauli principle prohibits much of this reaction from occurring at resonance energies. In addition, the measured π^+ absorption cross section is shown [16], comprising about 40% of the reaction cross section. Absorption is the most violent of the possible reaction pathways, leading to maximal deposition of excitation energy. We believe that it is the enhanced pion absorption cross section near resonance that is primarily responsible for the dramatic enhancement of pion-induced soft upsets over proton and neutron data. To emphasize this point, the proton-silicon reaction cross section is plotted using dotted lines. Although these experimental results have no means of discriminating absorption events, stopped pion absorption studies [10] support the hypothesis that absorption near resonance causes soft upsets. New experiments are planned to measure the relevant highly ionizing products from resonant energy pions.

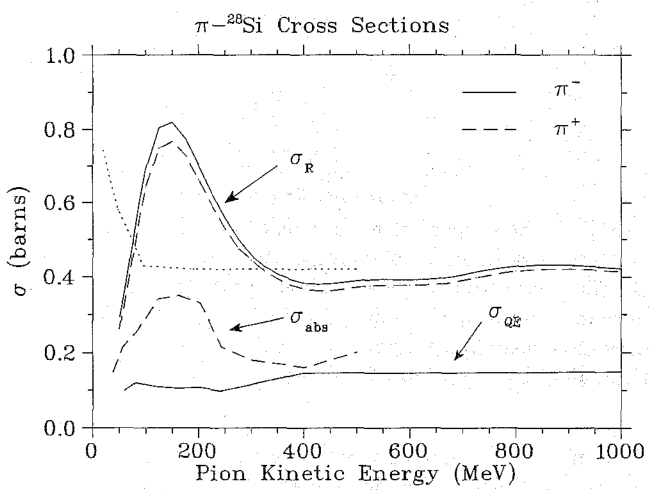

FIG. 4. Cross sections as a function of incident pion energy for $\pi-^{28}$Si reactions. Reaction cross sections (σ_R) are calculated as described in the text. True absorption cross sections for π^+ (σ_{abs}) are data for ^{27}Al [16]. Calculated quasi-elastic cross sections for either pion sign (σ_{QE}) are also shown. In addition, the proton-silicon reaction cross section is drawn as a dotted line [31]. Uncertaintes are $\sim$ 15%.

IV. CONCLUSIONS

Pion-induced soft upsets were studied on a variety of 16 Mbit DRAM chips with various cell technologies for charge storage. Cell technology is observed to affect upset cross sections by up to a factor of 1000, and this dependence on cell technology does not appear to be a function of the type of elementary hadronic projectile.

The energy and pion sign dependence of the soft upset cross section exhibits a shape very similar to the reaction and absorption cross sections for pion-nuclear interactions. This provides strong evidence for a reaction mechanism for soft upsets that involves nuclear reactions within the chips themselves.

Comparisions of pion-induced upsets with proton- and neutron-induced upsets indicate that pions are particularly effective at inducing upsets near the delta resonance in comparison to other particle probes. The differences in effectiveness are significant enough that even at lower relative intensities pions may still be a considerable source of soft upsets. A detailed assessment of the relative pion flux as a function of altitude and chip environment is beyond the scope of this work, but the authors would encourage the publication of such a study. The upset cross section data presented here over a wide energy range, when combined with pion fluxes, provide for the first time a means to definitively assess the role of pions on modern DRAM elements.

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[1] J. F. Ziegler and W. A. Lanford, "Effects of Cosmic Rays on Computer Memories," *Science*, vol. 206, pp. 776-788, 1979.

[2] J. F. Ziegler, *et al.*, "IBM Experiments in Soft Fails in Computer Electronics," *IBM Journal of Research and Development,* vol. 40, pp. 3-18, 1996.

[3] C. A. Gossett, *et al.*, "Single Event Phenomena in Atmospheric Neutron Environments," *IEEE Trans. Nucl. Sci.*, vol. 40, pp. 1845-1852, 1993.

[4] E. L. Petersen, "Approaches to Proton Single-Event Rate Calculations," *IEEE Trans. Nucl. Sci.*, vol. 43, pp. 496-504, 1996.

[5] J. Olsen, *et al.*, "Neutron-Induced Single Event Upsets in Static RAMS Observed at 10 KM Flight Altitude," *IEEE Trans. Nucl. Sci.*, vol. 40, pp. 74-77, 1993.

[6] E. Normand, *et al.*, "Single Event Upset and Charge Collection Measurements Using High Energy Protons and Neutrons," *IEEE Trans. Nucl. Sci.*, vol. 41, pp. 2203-2209, 1994.

[7] A. Taber and E. Normand, "Single Event Upset in Avionics," *IEEE Trans. Nucl. Sci.*, vol. 40, pp. 120-126, 1993.

[8] K. A. LaBel, *et al.*, "Radiation Effect Characterization and Test Methods of Single-Chip and Multi-Chip Stacked 16Mbit DRAMs," *IEEE Trans. Nucl. Sci.*, vol. 43, pp. 2974-2981, 1996.

[9] J. F. Dicello, C. W. McCabe, J. D. Doss, and M. Paciotti, "The Relative Efficiency of Soft-Error Induction in 4K Static RAMS by Muons and Pions," *IEEE Trans. Nucl. Sci.*, vol. NS-30, pp. 4613-4615, 1983.

[10] J. F. Dicello, *et al.*, "Meson Interactions on NMOS and CMOS Static RAMS," *IEEE Trans. Nucl. Sci.*, vol. NS-32, pp. 4201-4205, 1985.

[11] J. F. Dicello, *et al.*, "Microdosimetry: Measured Probabilities for Energy Deposited by Mesons in One-Micron Sites in Silicon," *IEEE Trans. Nucl. Sci.*, vol. NS-33, pp. 1305-1309, 1986.

[12] J. F. Dicello, M. Paciotti, and M. E. Schillaci, "An Estimate of Error Rates in Integrated Circuits at Aircraft Altitudes and at Sea Level," *Nucl. Instrum. and Methods in Phys. Res.*, vol. B40/41, pp. 1295-1299, 1989.

[13] E. Normand, "Single-Event Effects in Avionics," *IEEE Trans. Nucl. Sci.*, vol. 43, pp. 461-474, 1996.

[14] A. J. Sims, *et al.*, "The Single Event Upset Environment for Avionics at High Latitude," *IEEE Trans. Nucl. Sci.*, vol. 41, pp. 2361-2367, 1994.

[15] S. B. Kaufman, B. D. Wilkins, D. J. Henderson, R. E. L. Green, R. G. Korteling, and G. W. Butler, "Emission of ^{3}He and ^{4}He in reactions of 70- and 160-MeV $\pi^{\pm}$ mesons with Ag," *Phys. Rev. C,* vol. 32, p. 1977, 1985.

[16] D. Ashery and J. P. Schiffer, "Pion Absorption in Nuclei," *Ann. Rev. Nucl. Part. Sci.*, vol. 36, pp. 207-252, 1986.

[17] J. F. Ziegler, "Terrestrial Cosmic Rays," *IBM Journal of Research and Development,* vol. 40, pp. 19-39, 1996.

[18] K. O'Brien, "The Natural Radiation Environment," Report No. 720805-P1, United States Department of Energy, 1971, pp. 15-54.

[19] E. U. Condon and H. Odishaw, *Handbook of Physics*, New York, NY, McGraw-Hill, 1967, p. 9-298; A. W. Wolfendale, ed., *Cosmic Rays at Ground Level*, London, Institute of Physics, 1973, p. 72.

[20] C. Z. Garraffo, *et al.*, "Hadronic Scaling and Ratios of Cosmic-Ray Components in the Atmosphere," *Nucl. Phys. B*, vol. 53, p. 419, 1973.

[21] O. C. Allkofer and P. K. Grieder, *Physics Data: Cosmic Rays on Earth*, Fachinformationszentrum Energie, Physik, Mathematik GmbH, Karlsruhe, 1984.

[22] D. R. F. Cochran, *et al.*, "Production of Charged Pions by 730-MeV Protons from Hydrogen and Selected Nuclei," *Phys. Rev. D*, vol. 6, pp. 3085-3116, 1972.

[23] S. Shibata, "Propagation of Solar Neutrons Through the Atmosphere of the Earth," *J. Geophys. Res.*, vol. 99, p. 6651, 1994.

[24] G. R. Srinivasan, *et al.*, "Parameter-Free Predictive Modelling of Single Event Upsets Due to Protons, Neutrons, and Pions in Terrestrial Cosmic Rays," *IEEE Trans. Nucl. Sci.*, vol. 41, p. 2063, 1994.

[25] D. S. Dyer, *et al.*, "Measurements of the SEU Environment in the Upper Atmosphere," *IEEE Trans. Nucl. Sci.*, vol. NS-36, p. 2275, 1989.

[26] J. F. Ziegler, M. E. Nelson, J. D. Shell, R. J. Peterson, C. J. Gelderloos, H. P. Muhlfeld, and C. J. Montrose, "Cosmic Ray Sort Error Rates of 16 Mb Memory Chips,"

IEEE-Journal of Solid State Circuits, in press, 1997.

[27] G. W. Butler, B. J. Dropesky, C. J. Orth, R. E. L. Green, R. G. Korteling, and G. K. Y. Lam, "Cross sections for the $^{12}C(\pi^{\pm},\pi N)^{11}C$ reactions from 30 to 100 MeV," *Phys. Rev. C*, vol. 26, p. 1737, 1982.

[28] J. D. Shell, M. E. Nelson, J. F. Ziegler, R. J. Peterson, and C. J. Gelderloos, "Cosmic Soft Error Rates of 16 Mb dRAMs at Aircraft Altitudes," 1997 HEART/GOMAC Conference, Las Vegas, Nevada, March, 1997.

[29] R. A. Eisenstein and G. A. Miller, Comput. Phys. Commun. vol. 11, p. 95, 1976.

[30] C. M. Chen, D. J. Ernst, and M. B. Johnson, "High-Energy Pion-Nucleus Elastic Scattering," *Phys. Rev. C*, vol. 48, pp. 841-849, 1993.

[31] R. M. DeVries and J. C. Peng, "Nucleus-Nucleus Total Reaction Cross Sections," *Phys. Rev. C*, vol. 22, pp. 1055, 1980.

[32] R. J. Peterson, "Pion-Nucleus Total and Reaction Cross Sections," Few-Body Systems Suppl., vol. 9, pp. 17-28, 1995.