PROTON, NEUTRON AND PION INDUCED SOFT ERRORS IN COMPUTER MEMORY CHIPS

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High energy cosmic rays, mostly protons, cause nuclear reactions in the atmosphere (or in the hulls of spacecraft) producing showers of protons, neutrons and pi mesons with a wide range of energies. At the altitude of maximum intensity near 12km, these strongly interacting particles penetrate aircraft with about 100 particles/cm^2-sec. In turn, these penetrating particles can deposit charge within the volume of semiconductor circuit elements, either directly or by inducing nuclear reactions. One MeV of energy loss in Si will generate 44 fC of charge pairs in the sample. This is comparable to the critical charge which distinguishes between a zero and a one in a memory element, for instance. The device may not be damaged by this event, but may contain one or more bits of wrong information. These events are called Soft Error Upsets or SEU.

Since modern aircraft contain a large number of electronic components and computers, these SEU are a significant hazard to commercial aviation. We and others have deveoped means to measure the cross sections for laboratory beams of protons, neutrons and pions to induce SEU. The cross section is defined as:

$$\sigma_{SEU} = \text{SEU observed/ bits per chip x beam particles/cm}^2.$$

Primary beams of protons and secondary beams of neutrons and pions from a number of accelerator facilities have been used for these studies. The beam is sent through the face of the sample and counted. A driver circuit writes 0's into the sample, and then goes back to read 1's, for instance, to count SEU.

Our work at Colorado has emphasized the use of pi mesons, since they are present in the cosmic rays, but previous studies had not measured their effects. Our results have been published for commercial 16Mb dRAM [1] and 64Mb dRAM [2] samples of modern computer memory elements, made by a range of companies using different technologies. Some conclusions on the implications of these studies are found in [3].

Figure 1 shows the dependence of σ_{SEU} for one 16 Mb dRAM sample upon the pion beam energy. The striking bump near 150 MeV reflects macroscopic effects within the sample of the elementary Delta or 3-3 resonance, the first excited state of the nucleon formed when pions near this energy interact with free nucleons. Note that σ_{SEU} is the same for both pion signs. This might be expected since ^{28}Si has equal numbers of neutrons and protons and we expect charge symmetry. Also shown in Fig. 1 are the computed total reaction cross sections for pions on

^{28}Si, computed with a DWIA code using no free parameters.[4] The free-space pi-N resonance is found in the complex nucleus, and then in the commercial memory unit.

If the average of these cross sections, 0.3 x 10^{-12} cm^2/bit, and the 100 particles/cm^2-sec are considered for a four hour flight, this device in an aircraft would encounter 7 errors. A modern aircraft will contain many such memory chips. More detailed modeling is in fact carried out using numbers such as we are providing for circuit components.

Is the probability of an error the same for all particles? If we could find simple scaling relations among samples irradiated with protons, neutrons and pions, we would need to make fewer measurements. Figures 2 and 3 show scatter plots, with each point marking the cross section for 150 MeV protons and either 150 MeV pi^+ or 14.7 MeV neutrons on exactly the same samples of 16 Mb or 64 Mb dRAMs. Overall, these cross sections are seen to be proportional, with the pion cross sections about four times larger than those for protons of the same energy. Note the great range of cross sections, about a factor of 1000 for devices with the same basic storage capacity. The 16 Mb samples fall into three different zones, related to their internal construction.[1] Two technologies are used for the 64 Mb samples, with less of a difference in their cross sections. Comparisons of high energy neutrons and protons on different memory units also show a close proportionality. [5]

What is the means by which these penetrating particles deposit energy in the Si of the memory chip? It is not by dE/dx, since these are near minimum ionizing and leave only about 2 MeV/gm/cm^2 in passing through the Si. Since the Si is about 10 microns thick, these particles leave only about 10 eV in the device, far below the charge needed to determine its logic state. Instead, some reaction producing more heavily ionizing particles within the volume of the memory chip must be occurring.

We have measured the cross sections for energetic pions to cause reactions yielding alpha particles with energies near 5 MeV using a plastic track detector method. Our sample was aluminum for simplicity. The track detector was sensitive to alpha particle with energies from 0.5 to 6 MeV, with ranges and energy losses that readily deposit charge in the Si of our samples. Cross sections are large, about 500 mb, for these products. We thus learn that the means by which high energy particles cause SEU is by spallation or other reactions creating alpha particles. These processes had been assumed to be important, and we have now verified that assumption.[6] These studies illustrate the use of methods standard in basic nuclear science in applications to problems of great interest to the computer, electronics and aviation industries.

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Figure Captions

Figure 1. Soft upset cross sections for $\pi^{\pm}$ and protons (x) 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. Systematic uncertainties are estimated to be ~15%.

Figure 2. Proton (148 MeV) versus pion cross sections for the TIC, SC and TEC design technology 16 Mb chips. Open squares are 150 MeV π^{-} data, solid circles are 150 MeV π^{+} data and solid triangles are 400 MeV π^{-} data. The straight line indicates equal SEU cross sections for protons and pions.

Figure 3. Proton (148 MeV) versus pion (150 MeV) cross sections for the 64 Mb chips. The dashed line is a fit to the pion data. The solid straight line indicates equal SEU cross sections for proton and pions. The dashed-dotted line separates TIC design chips (below the line) from SC design (above line).