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LIGHT FLASH PHENOMENA INDUCED BY HZE PARTICLES

Co-Principal Investigators

P.J. McNulty

V.P. Pease

March 31, 1980



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1. INTRODUCTION AND SUMMARY

Astronauts and Apollo and Skylab missions have reported observing a variety of visual phenomena when their eyes are closed and adapted to darkness.^{1,2} These phenomena have been collectively labelled as light-flashes. Visual phenomena which are similar in appearance to those observed in space have been demonstrated at the number of accelerator facilities³⁻¹¹ by exposing the eyes of human subjects to beams of various types of radiation. More than one physical mechanism is now known to contribute. In some laboratory experiments³⁻⁷ Cerenkov radiation was found to be the basis for the flashes observed while in other experiments⁸⁻¹¹ Cerenkov radiation could apparently be ruled out.

The principal objective of the effort covered by this grant was to design and conduct experiments that differentiate between Cerenkov radiation and other possible mechanisms for inducing visual phenomena and compare the phenomena obtained in the presence and absence of Cerenkov radiation. Section 2 of this report describes the experiments and the data obtained.

A new mechanism proposed by us to explain the visual phenomena observed by Skylab astronauts as they passed through the South Atlantic Anomaly, namely nuclear interactions in and near the sensitive layer of the retina, is covered in Sec. 3. Brief reviews of the light-flash phenomena in space have been published by us.^{12,13}

It turns out that the light-flash phenomena are only one example of transient phenomena induced in "electrical systems" flown in space. Some of our studies to search for similar transient effects of space radiation on sensors and microcomputer memories are described in Sec. 4.

Safety and No-Cost Extension

The research described in this report involved deliberate exposure of human subjects (the investigators) to heavy ions. A fail-safe beam delivery system had to be designed. The system used is described in Sec. 2. All experiments had to receive the approval of the committees for the Protection of Human Subjects at Lawrence Berkeley Laboratory, Brookhaven National Laboratory and Clarkson College. There were, in addition, reports of evidence at LBL of single - hit track effects in neural tissue of animal subjects which had to be taken into account in granting approval. This necessitated considerable delay in scheduling irradiations. We did finally obtain approval for carbon and neon runs and fell confident now of obtaining approval for argon for this fall. We greatly appreciate the time and effort contributed by the members of the safety committees at all three institutions. The delays required our requesting no-cost extensions well beyond the projected one year duration of this grant. We appreciate that NASA officials took into account the unique features of this experiment and granted these no-cost extensions.

2. LIGHT-FLASH EXPERIMENTS AT THE BEVALAC

One-At-A-Time-Facility

The first step in these experiments was the design and implementation of modifications to the Biomedical beam line that would satisfy the following science requirements.

- i. Beam delivery one particle at a time
- ii. Easy implementation of catch tests
- iii. Random mixing of beams particles incident out speeds above and below the Cerenkov threshold

In addition the beam line had to be fail-safe against accidental overexposure of the human subjects. The beam facility implemented is described in Ref.

14. For the reader's convenience a copy of this publication is included as Appendix A.

Exposure to Carbon Ions

The results of our initial run with carbon ions is described in an article¹⁵ published in Science. A copy of this article is included as Appendix B. We restrict ourselves here to some essential feature of the data.

Two of the three subjects reported observing visual phenomena. The use of catch tests (empty beam pulses) demonstrated high subject reliability during these irradiations. The subjects (V.P. and P.M.) described the phenomena as bright and easily distinguishable from background. A comparison of phenomena induced by Cerenking and non-Cerenking particles (with the subject not knowing which) showed that the "large" and cloud-like phenomena were only observed with Cerenking particles while its point-flash and streak phenomena were observed with both. The reader is referred to Appendix B for details.

A second irradiation with carbon ions was conducted under close to identical conditions a year or so later. Both subjects had experienced

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visual phenomena in the previous irradiation. Neither subject reported observing the type of bright distinct phenomena observed in the first run. The subjects were asked to report any phenomena observed. The data is still being analyzed but it is clear that none of the distinct phenomena of the first run were observed in the second irradiation. This was true for both Cerenking and non-Cerenking particles.

Neon Exposure

An exposure to neon ions was carried out under conditions identical to those described in Appendices A₁ and B. The higher charge of the neon nuclei should have enhanced both the Cerenkov radiation and LET by about $(10/6)^2$. Despite this enhancement none of the bright distinct phenomena of the first carbon run were observed.

Discussion

In summary we have three experimental runs carried out under as close to identical conditions as possible with apparently conflicting results. Proper psychophysical procedures were followed in all three experiments so that the subject did not know if a "beam pulse" contained a Cerenking or non-Cerenking ion or no ion at all. The data from the first run is clear evidence that two subjects were experiencing flash phenomena and that the large bright phenomena appeared only for Cerenking particles.

The changes in the subjects ability to detect heavy ions may be explained in terms of fluctuation in the sensitivity of the human visual systems. Denton and Pirenne^{16,17} have shown that threshold for detecting light pulses may vary by an order of magnitude among normal human subjects and by a factor of 3 for the same subject on different days. This variation is also consistent with the large differences in light-flash rates observed by the same Apollo astronauts at different times in the mission.

3. ROLE OF NUCLEAR INTERACTIONS

Astronauts on Skylab observed point and streak light-flash phenomena as the spacecraft passed through the South Atlantic Anomaly (SAA), NASA scientists described the rates of flash observations as "anomalous" in terms of the known Cerenkov and LET mechanisms and the measured trapped proton fluences in the SAA. We prepared in Ref. 17 that nuclear interactions in and near the sensitive layer of the retina provide a possible mechanism for the light flashes. For the reader's convenience a copy of Ref. 17 is included as Appendix C.

We have explored the use of the Harvard Cyclotron for use in investigating the role of nuclear interactions in the light-flash phenomena. An experiment to measure the spectrum of energy deposited in thin silicon surface-barrier detector of different thicknesses is currently underway. A light-flash experiment involving human subjects is planned. These efforts are not currently supported by external funding.

4. COMPARABLE TRANSIENT PHENOMENA IN ELECTRONIC SYSTEMS

The light-flashes are transient phenomena induced somewhere in the bioelectronics of the human visual system. The question arose as to whether there were similar phenomena induced in man made electronic systems in space. Katz and Rothwell¹⁸ demonstrated that transient in DMSP satellite photographs could be correlated with energetic particles incident on the sensor.

We initiated a preliminary study that suggested digital memories as a location of analogous transients. Electrically stored information could be distorted by changes in the logic state of individual storage events. Such inversions were postulated in bipolar circuit elements by Binder et al.¹⁹

With the help of Air Force support as well as this grant we initiated some tests on LSI circuits that clearly demonstrated memory upsets upon energetic protons.^{20,21} These experiments and their implications for space are described in some detail in Ref. 20 which is included here as Appendix D.

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APPENDIX A

DELIVERY OF SINGLE ACCELERATED PARTICLES

P. J. McNULTY and V. P. PLASE

Columbia College of Technology, Potsdam, New York 13676, U.S.A.

V. P. BOND

Brookhaven National Laboratory, Upton, New York 11973, U.S.A.

W. SCHIMMEREING* and K. G. VOSBURGH†

Princeton Particle Accelerator, Princeton, New Jersey 08540, U.S.A.

K. CRIBBIN, W. FAURETTE and J. HOWARD

Lawrence Berkeley Laboratory, Berkeley, California 94720, U.S.A.

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It is desirable for certain experiments involving accelerators to have the capability of delivering just a single beam particle to the target area. The essential features of such a one-at-a-time facility are discussed. We describe two such facilities which were implemented at high-energy heavy ion accelerators without having to make major structural changes in the existing beam lines or substantially interfering with other accelerator uses.

Two accelerator facilities are described which had the capability of delivering a single beam particle to the target area. This feature is necessary in certain experiments investigating visual phenomena induced by charged particles, other single particle interactions in biology, and other experiments in which the low intensities of cosmic rays need to be simulated. Both facilities were implemented without having to make structural changes in the existing beam lines or substantially interfering with other accelerator uses.

1. Introduction

There are applications of particle accelerators for which it is advantageous to reduce the beam delivered onto a target to just one particle. Examples include testing or calibrating a detector system and investigating the biological effects that result from the passage of a single beam particle through a single cell or structure in an organism. One particular advantage of such a facility at a heavy ion accelerator is the simulation of the passage of cosmic-ray heavy ions.

We became interested in developing a beam facility capable of delivering single particles, during investigations into the visual phenomena induced by the passage of charged particles through the dark-adapted human eye¹⁻⁶). These "light flashes" were first observed in deep space by astronauts on Apollo 11, presumably as a result of the passage of individual heavy cosmic-ray nuclei through the eye³). It was our belief that to properly simulate exposure to the heavy-ion component of the cosmic rays at an accelerator the beam particles

should be delivered to the target at rates comparable to those in space, i.e. one-at-a-time. For example the presence of more than one particle in a pulse may affect the appearance of the visual phenomena observed⁸).

Other effects of cosmic-rays on man and his support systems in space which might be studied at a one-at-a-time facility include: the effects of the passage of heavy ions through photo detection systems¹⁰), electrical circuits¹¹), single nerve cells and various locations in the central nervous system⁹).

Some problems arise when facilities that are designed for stable operation at the highest possible currents are modified for single particle delivery. For example, the beam will probably not be intense enough to provide feedback to the operator through normal instrumentation. However, our experience suggests that these problems can be circumvented or overcome. Section 2 describes the essential features of one-at-a-time facilities; and details of how they were implemented at two heavy-ion accelerators are given in section 3.

2. Essential features

The following features are desirable in any

* Present address: Lawrence Berkeley Laboratory, Berkeley CA 94720.

† Present address: General Electric Research and Development Center Schenectady, New York 12345.

single particle delivery system at a heavy ion accelerator:

- 1) *Beam purity.* The incident particle should have the desired charge, mass and velocity.
- 2) *Reliability.* A pulse should contain one particle and no more. No subsequent pulse should be delivered to the target.
- 3) *Ease of implementation.* Facilities of this type are likely to be used often for short periods in a variety of applications rather than a single long term experiment.
- 4) *Flexibility.* The facility should be capable of delivering different heavy ions over a range of velocities up to and including the threshold for Cerenkov radiation.
- 5) *Fail-safe against accidental over-exposure.* In a fail-safe mode the experimenter can remain at the site of exposure just outside the collimator-defined beam area. This allows him quick access for configuration or alignment changes between pulses. In our experiments the target is a human volunteer (one of the experimenters) who must be protected.
- 6) *Fast response.* When operating in a fail-safe mode the beam line and possibly the entire accelerator will be tied up. Ideally, the experimenter should be able to request a pulse, perhaps by pushing a button and promptly receive one beam pulse consisting of one particle.
- 7) *Small beam spot.* The location where the beam particle enters the target must be accurately known for most applications.

3. Description of two facilities

3.1. PRINCETON PARTICLE ACCELERATOR

Our first single particle delivery facility was set up at the Princeton Particle Accelerator (PPA). The experiment²⁾ involved exposing the dark-adapted eyes of human subjects to individual 530 MeV/amu ¹³N nuclei. A fail-safe stable operation was achieved by running the beam inside the synchrotron at near-maximum intensity and reducing the extracted beam intensity by collimation. A schematic diagram of the facility is shown in fig. 1. Transport and focusing magnets are not shown in the figure. The beam line was the same as that conventionally used for heavy-ion experiments. No structural modifications of the beam line were necessary except the addition of two collimators. The full intensity of the 530 MeV/amu beam was extracted using a resonance tech-

nique¹²⁾. The extracted beam entered a collimator and passed through several focusing and bending magnets and the main synchrotron shield wall before reaching the experimental cave.

The upstream collimator was constructed of brass by matching four brass blocks and combining them together interspersed with 0.25 mm shims. The total thickness of the collimator was 9.4 cm and the opening was 0.25 mm × 0.25 mm. The collimator was mounted on a shaft with provision being made for the adjustment of the collimation axis to correspond with the beam direction. The collimator and shaft assembly were mounted on a vacuum-tight plate with the shaft passing through "O-ring" vacuum seals in the plate, which in turn, formed a side of a rectilinear box in the beam line. The mounting shaft was connected to a linear drive motor. A motor servo system and micrometer-type measurement system allowed the shaft to be moved over several inches, with positioning accuracy of better than 0.25 mm. Thus, the collimator would be positioned accurately in the beam, and removed when desired. The servo control and power unit for the shaft-drive system were packaged in a separate unit and connected to the shaftdrive motor system through a cable and multi-pin connector. The collimator could, therefore, be removed from the beam for alignment purposes and reinserted quickly and accurately for data taking. During experiments with

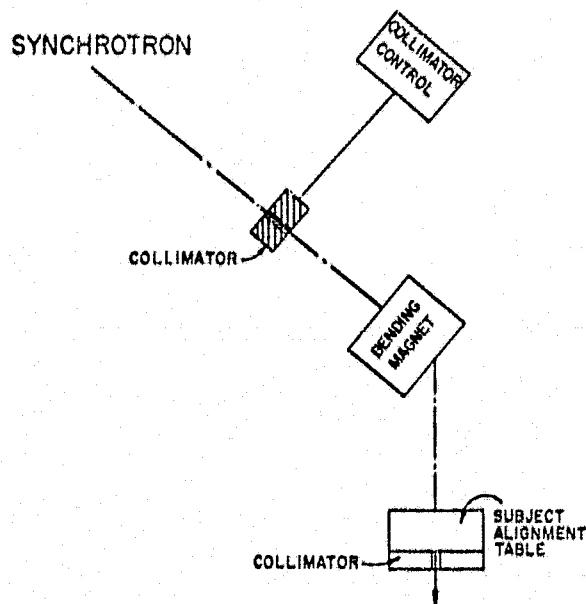


Fig. 1. Schematic drawing of the Princeton Particle Accelerator facility set up to deliver individual nitrogen nuclei

human subjects, movement of the collimator was prevented by disconnecting the servo-control and carrying it into the experimental cave. Because the synchrotron was already operating near maximum intensity, accidental intense pulses were impossible.

Secondary particles generated in the collimator were swept out of the main beam by a bending magnet. The magnet current was set to focus the uncollimated synchrotron beam onto the final collimator on the subject alignment table. The main collimator opening was chosen to be such that when it was inserted in the beam line only occasional particles pass through the final collimator. Because the beam intensity reduction was achieved by collimation, the only way to prevent more than one particle passing through the final collimator and striking the subject's eye was to reduce the intensity so that most pulses are empty. The experimenter waited until a beam pulse results in a particle emerging from the downstream collimator. Because the synchrotron was operating at optimum intensity, reasonably stable beam in-

tensities were attainable and a particle typically arrived at the target within a few acceleration cycles.

3.2. BEVALAC

An improved version of a one-at-a-time facility has recently been developed at the Bevalac at Lawrence Berkeley Laboratory. At the Bevalac, the Hilac acts as a source of heavy ions which are transported to the Bevatron where they are accelerated to relativistic velocities^(11,12). A resonant extraction system is used for delivering beam pulses into a secondary beam line leading to Biomedical Cave II⁽¹³⁾. A diagram of the beam line is given in fig. 2 where again transport and focusing magnets not essential to this discussion are not shown. Again, no structural modification of the existing beam line was necessary. Only the final collimator which defines the exposure area (circle of 2 mm diameter) was added.

In operation the Bevatron and the beam line for Biomedical Cave II are tuned at optimum beam intensities. The number of ions in each pulse is then reduced at the source, i.e., the Hilac. The re-

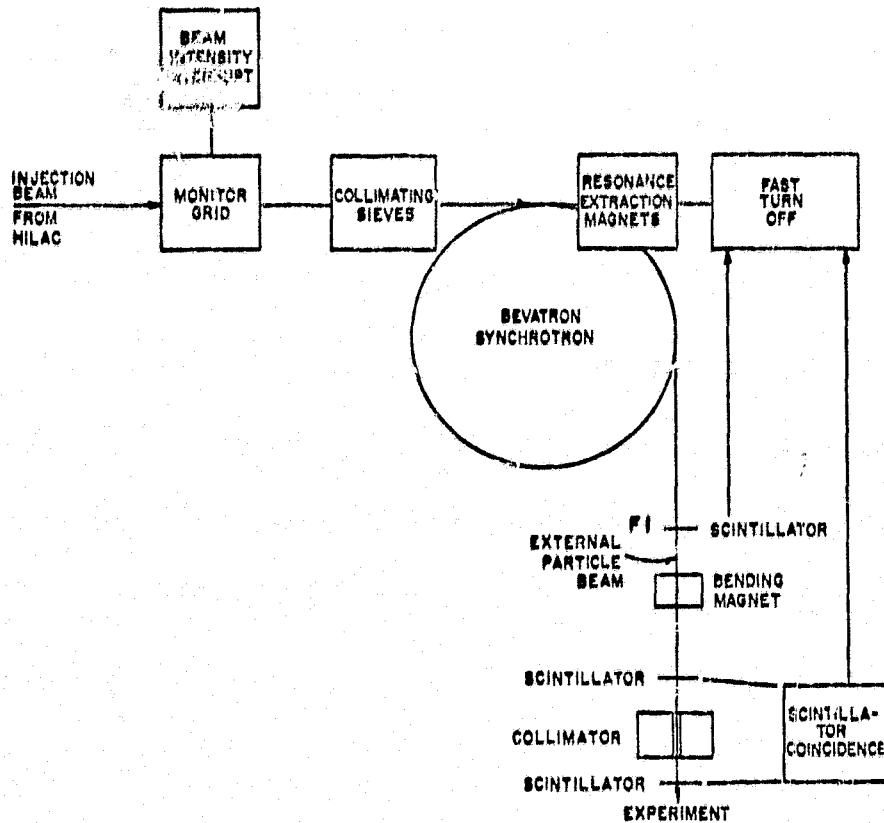


Fig. 2. Schematic of the Bevalac facility as set up for single particle operation in Biomedical Cave II.

sulting intensity of the beam circulating in the synchrotron is too low in the one-at-a-time mode for normal Bevatron tuning procedures to be effective and the beam operators must rely on a scintillation detector in the extracted beam line for monitoring. The beam pulse can be as long as 500–1500 ns. The injection beam is then attenuated by a factor of 10^3 by collimating sieves. Two scintillation detectors in coincidence (one placed upstream and the other just downstream of the collimator in the light flash experiment in front of the subject's eye) detect the first heavy ion to emerge from the collimator opening. The coincidence signal terminates the extraction of the remainder of the beam pulse from the synchrotron and triggers the insertion of the beam plug. The resonance extraction system can be shut down in ≈ 1.5 ns to prevent the delivery of subsequent particles in the pulse. The beam plug cuts off the beam within 3 ns and mechanically prevents the delivery of additional pulses. A continuous range of ion energies can be obtained by inserting the proper absorbing material in the beam line upstream of the bending magnet and modifying the beam optics downstream of the degrader for the new energy. Secondaries generated in this way will be removed from the beam that enters the final collimator as a result of dispersion in the bending magnet. Beam fragments of the same momentum created near the end of the degrader are not removed from the beam and are not necessarily completely rejected by the coincidence signal.

Beam trials have been carried out using 400 and 594 MeV/amu carbon ions without degrading and with degrading by a Pb filter to 467 MeV/amu. The system performed properly in both cases. To test the fast shutdown procedures the beam intensity was set 50 times higher than necessary (or desirable) for one-at-a-time operation. Thirty seven out of thirty nine pulses contained one particle and the remaining two pulses contained only two particles each. At lower intensities no multiple pulses were observed.

Because many experiments involving single particle delivery would involve human subjects or experimenters remaining at or near the beam line during the experiment, the system must be made safe against intense pulses arriving accidentally at the experimental area by the use of redundant beam control systems.

The redundancy was provided by three independent beam detection devices located at differ-

ent places in the acceleration and beam delivery system of the Bevalac. Two of these devices activated an existing circuit for rapid beam turn off. The system, when activated, clamps magnet reference circuits to zero for the perturbation magnet (P1) which drives the beam growth for resonant extraction. A second circuit clamps off the references to the first three bending magnets in the extraction system (M1, M2 and M3) and inserts a beam plug. For normal operation of single particle delivery, the cut off activation signal came from the first coincidence signal from the two photomultiplier-scintillator counters at the subject area. A singles counter (scintillator and photomultiplier) located where the external beam first clears the Bevatron magnet (called F1) is part of the standard beam monitoring for low beam levels ($< 10^5$ – 10^6 particles per pulse). A scaler pulse out, preset in multiples of ten, would also activate the fast cut-off circuit. This cut off level was set just above the count level necessary to give a few coincidences at the subject region.

A grid monitor in the injection channel from the Hilac, upstream of the 10^4 collimator, monitors each injected beam pulse. If the injected pulse exceeds a preset value, the rf is cut off and no particles are accelerated on that Bevatron cycle. This level was set to limit the beam at the F1 area to less than 10^3 particles per pulse independent of the other two cut off devices.

4. Conclusion

What is significant is not that a single particle delivery system exists but rather that many, if not most, accelerator beam lines can be easily and quickly modified for occasional use as a single particle facility. Thus experiments utilizing this type of facility can be accommodated without substantial impact on other accelerator uses.

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APPENDIX B

Visual Phenomena Induced by Relativistic Carbon Ions With and Without Cerenkov Radiation

P. J. McNulty, V. P. Pease, and V. P. Bond

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Visual Phenomena Induced by Relativistic Carbon Ions With and Without Cerenkov Radiation

Abstract. *Exposing the human eye to individual carbon ions ($^{12}\text{C}^+$) moving at relativistic speeds results in visual phenomena that include point flashes, streaks, and larger diffuse flashes. The diffuse flashes have previously been observed by astronauts in space but not in laboratory experiments with particles of high atomic number and energy. They are observed only when the nucleus moves fast enough to generate Cerenkov radiation.*

There have been a number of investigations designed to determine the physical mechanism behind the visual phenomena observed by astronauts when exposed to the radiation environment in space (1-5). Our earlier experiments with muons, pions, and individual nitrogen nuclei (3) showed that Cerenkov radiation generated within the eye can induce visual phenomena similar in description to those reported by astronauts in deep space (1). However, the muon and pion data were obtained in experiments designed to simulate the passage of an ion of high atomic number, Z , and energy, E , with a pulse containing $N = Z^2$ singly charged particles. This raised the question of the extent to which the phenomena observed resembled those induced by the HZE (high Z and E) particles encountered in space (6). Moreover, experiments with neutrons, alpha particles, and nitrogen nuclei (5) showed that star- and streak-like phenomena similar to some of those observed in space can be induced in the absence of Cerenkov radiation, presumably as the result of ionizations and excitations along the trajectory of the incident particle or its secondaries. This raised the possibility that the HZE particles that generated visible pulses of Cerenkov light in the eyes of astronauts on Apollo missions would have been detected anyway because of ionization effects, and that while Cerenkov radiation may have influenced the visual phenomena experienced, it would not have significantly af-

ected the rate at which the flashes were observed.

To directly compare the visual phenomena induced by HZE particles with and without Cerenkov radiation and to determine the effect of Cerenkov radiation on a subject's ability to detect the particles, we initiated a series of exposures of human subjects to HZE particles at the Bevalac accelerator at Lawrence Berkeley Laboratory. The details of the facility devised to deliver HZE particles one at a time are given elsewhere (7). This report describes the results of the preliminary trials, which involved comparing carbon nuclei at speeds above and below the Cerenkov threshold. The nuclei had kinetic energies of 595 MeV per nucleon and a stopping power in water of 94 MeV-cm²/g at the higher speed, and values of 470 MeV per nucleon and 103 MeV-cm²/g at the lower speed. The carbon nuclei do not stop in the eye, nor do they lose a significant amount of energy in traversing it. The patterns of ionizations and excitations along the trajectories are quite similar for the two cases, and a significant increase in a subject's ability to detect the passage of a higher-velocity nucleus through his eye would be attributable to Cerenkov radiation.

After dark-adapting for 40 minutes, the subject aligned himself to the beam line by using a personalized bite plate and fixated on a red light-emitting diode mounted on the far wall of the darkened room. This aligned the head and eye

such that the beam particles entered at an angle of about 60° with the optic axis as defined by fixation. An initial alignment procedure was completed before the experimental sessions. A laser beam was passed through the beam collimator to the subject's head. When the laser spot fell on the proper region of the eye, the bite plate was locked in position. The particle beam pathway was directed away from the lens of the eye. After a foreperiod that was varied randomly from 2 to 4 seconds, a pulse of carbon nuclei or a catch test pulse (one containing no particles) was delivered. The subject signaled readiness by depressing a switch. He signaled detection (a hit) by depressing the same switch. The subject was also in communication with the experimenters in the control room by intercom. After each hit or miss, the subject was asked to confirm his response and describe the visual phenomena for all hits. The cross-sectional area of the beam was determined by a 2-mm-diameter collimator placed in the beam line about 30 cm upstream from the subjects. Particles entering the eye were counted in coincidence by a scintillator downstream from the collimator just before the eye and a scintillator upstream from the collimator.

In procedure 1 the subject did not know whether a pulse would contain one, two, or no nuclei or whether the carbon nuclei were at speeds above or below threshold. Catch tests were randomly distributed among the experimental trials at a rate of approximately 40

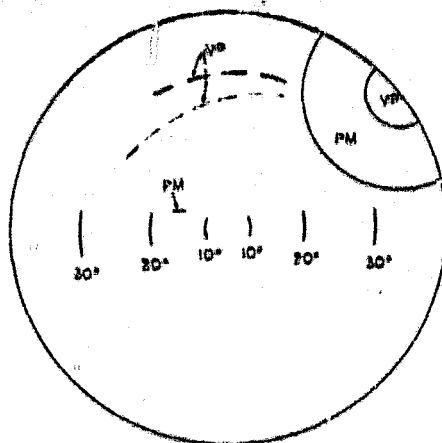


Fig. 1. Schematic drawing of visual sensations described by subjects P.M. and V.P. The scale represents visual angle.

percent. Only one catch test in 81 resulted in a positive response (false alarm) and that visual sensation was described as similar to the phosphenes that subjects observed when dark-adapted in the radiation-free environment.

In procedure 2 the subject did not know whether the carbon ions were incident at speeds above or below threshold. Catch tests were not employed. In procedure 3 the subject knew whether the particles in a particular series would arrive at speeds above or below threshold, but catch tests were included. There were no obvious differences between the data obtained by the three procedures.

Table 1 summarizes the data for the three subjects under the procedures followed. The visual phenomena were often

complex combinations of diffuse flashes and streaks. One subject did not report any observations of particles either above or below the threshold speed for Cerenkov radiation. The ability of the other two subjects to detect carbon ions was considerably greater for speeds above threshold. The detection efficiency for pulses containing one or two particles at speeds below threshold generally agrees with the detection efficiency observed previously for stopping alphas and nitrogen nuclei (5). Diffuse flashes were observed only when the carbon nuclei moved through the eye at speeds above threshold. They consistently appeared in the region of the field of view that corresponded to the location on the retina where the beam particles exited the eye, which would be expected if the visible components of the Cerenkov optical shock wave (which propagates toward the nasal region of the retina) initiated the visual process. The diffuse flashes were similar in appearance to the flashes induced by muons and pions (3). This evidence indicates that the diffuse flashes observed in this experiment were the result of Cerenkov radiation. The more localized phenomena—streaks and pointlike flashes—were observed for particle speeds both above and below the Cerenkov threshold, which demonstrates that Cerenkov radiation is not the sole mechanism for these phenomena.

Figure 1 is a schematic drawing of typical visual sensations described by subjects P.M. and V.P. For both subjects the diffuse flash occurred in the right-hand field of view in the area shown. Both subjects reported that streaks often accompanied the diffuse flashes. When they did, a definite temporal sequence was observed. The diffuse flash appeared first, followed by the streak phenomena. This is the opposite of the physical sequence of events, in which the particle enters the region of the eye where the streaks are observed and exits in the area of the diffuse flash. This sequence takes less than 10×10^{-11} second from entrance to exit. The streaks appeared to be moving from right to left in the visual field. The streak phenomena for subject P.M. were at a location corresponding to beam entrance; for subject V.P. they were not always at such a location. For both subjects a single carbon ion often resulted in the observation of more than one streak. Subject V.P. reported the observation of curved broken streaks of the type shown in Fig. 1.

The length of the long broken trajectories is far greater than could be explained by path lengths in the retina.

Table 1. Summary of procedures and results for three subjects.

Subject	Procedure	Particle speed*	Pulses	Particles	Hits	Diffuse flashes	Streaks or points
V.P.	1	Above	19	35	8	5	6
		Below	19	23	5	0	5
	3	Above	25	33	20	13	14
		Below	22	33	7	0	2
P.M.	1	Above	35	58	14	10	8
		Below	31	44	3	0	3
	2	Above	16	21	7	5	3
		Below	14	18	1	0	1
V.B.	1	Above	38	56	0	0	0
		Below	9	13	0	0	0

*Above or below the Cerenkov threshold.

Table 2. Combined data for subjects P.M. and V.P. for single- versus multiple-particle pulses.

Type of pulse	Particle speed*	Particles	Pulses	Detections	Diffuse flashes	Points and streaks
Single particle	Above	53	53	27	18	18
	Below	55	55	8	0	8
Multiple particle	Above	95	42	23	15	13
	Below	63	31	3	0	3

*Above or below the Cerenkov threshold.

This is consistent with the observations of three subjects exposed to individual nitrogen ions at the Princeton Particle Accelerator (3). Broken streaks have been observed in space and in laboratory experiments (5). It is possible that fragmentation of the carbon nucleus and interactions that lead to the formation of nuclear stars play a role in these effects, but further study is needed.

Table 2 shows the data for subjects P.M. and V.P. and for pulses containing one or more particles. Their ability to detect pulses containing one particle was not significantly different from their ability to detect pulses containing more than one particle—that is, the detection efficiency per particle was far less for multiple-particle pulses. Tobias and co-workers (5) also reported a dependence of the subject's ability to detect HZE particles that did not produce Cerenkov radiation on the number of particles in the pulse. Table 2 shows that the effect holds true for the diffuse flashes, which were shown above to be due to Cerenkov radiation and hence optical phenomena.

In summary, carbon nuclei entering the eye are detected more often at speeds above the Cerenkov threshold than below. This finding lends strong support to the hypothesis that Cerenkov radiation plays a major role in the visual phenomena observed by astronauts in deep space. Large diffuse flashes are observed only at speeds above threshold and occur only at the location in the field of view corresponding to beam exit. They are similar in appearance to the large-area flashes previously observed with muons and pions. These data suggest that an important mechanism for these large flashes and possibly for those observed in space is Cerenkov radiation. Furthermore, the large flashes observed in space can be generated by nuclei with atomic numbers as low as 6 and not only by nuclei of higher atomic number.

P. J. McNULTY
V. P. PEASE

Departments of Physics and Social
Sciences, Clarkson College,
Potsdam, New York 13676

V. P. BOND
Brookhaven National Laboratory,
Upton, New York 11973

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APPENDIX C

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ROLE OF NUCLEAR STARS IN THE LIGHT FLASHES OBSERVED ON SKYLAB 4

P. J. McNULTY^a, R. C. FILZ^b and P. L. ROHWELL^b

^aClarkson College of Technology, Potsdam, N.Y., USA

^bAir Force Geophysics Laboratory (AFSC), Hanscom Air Force Base, Bedford, Mass., USA.

Abstract. The astronauts on Skylab 4 observed bursts of intense visual light-flash activity when their spacecraft passed through the portion of the earth's inner trapped radiation belt known as the South Atlantic Anomaly (SAA). Two experimental sessions were carried out on board Skylab 4 under the auspices of Pinsky *et al.* who compare the flash rates with the measured flux of $Z \geq 1$ particles that would pass through the astronaut's eyes. They concluded that the flash rates, which became as great as 20/min, were anomalously high. We explored a number of alternative explanations for the anomalous flash rate that would be consistent with the accepted SAA flux values and the laboratory data on particle induced visual sensations and found that when one includes the effect of nuclear interactions in and near the retina which result in star formation (the emission of slow protons, neutrons and alpha particles from the nucleus in an evaporation-like process) the apparent anomaly is removed.

I. INTRODUCTION

Astronauts on Skylab 4 have confirmed the observation in earth orbit of flashes of light when their eyes are adapted to darkness for 10 min or more. The unexpected feature was the occasional 5-10-min bursts of intense visual light-flash activity. Dr. Edward Gibson, the science pilot, was able to correlate the occurrence of these bursts with the passage of the spacecraft through the portion of the earth's inner trapped radiation belt known as the South Atlantic Anomaly (SAA).

These reports prompted two separate light-flash observing sessions conducted by Lt.-Col. William Pogue, the pilot, in co-operation with a team of NASA and University of Houston scientists. After careful analysis of Pogue's observations, Pinsky *et al.* [1] concluded that the flash rates in the SAA were considerably higher than would be expected based on the measured flux of singly and multiply charged particles that passed through the astronaut's eyes. The anomalously high flash activity led them to postulate the existence of a previously unobserved inner belt flux of multiply charged nuclei in the SAA.

In what follows we show that when one includes the effects of nuclear interactions in and near the retina and the physiology of the retina one obtains an alternative explanation for the high flash rates that is consistent with the accepted SAA flux values [2] and the limited laboratory data on particle induced visual sensations in human subjects [3-10]. The essential feature of our model is that it includes, first, the induction of visual sensations by nuclear interactions that result in star formation (the emission of slow protons, neutrons and alpha particles from the nucleus in an evaporation-like process) and, secondly, the fact that the dark-adapted retina is known to integrate signals over distances as great as 300 μ m in the retinal layer.

2. POSSIBLE MECHANISMS

There is no generally accepted mechanism for particle induced visual phenomena that is applicable to the Skylab data. Cerenkov radiation, which is expected to be the cause of a major portion of the flashes observed on Apollo flights in deep space [11-14], is not expected to contribute significantly to the Skylab flashes because too few of the incident particles in the SAA would generate Cerenkov light in sufficient intensity to exceed the optical thresholds for detection [15, 16].

There is no quantitative model for the non-Cerenkov flashes. It is not even known whether the concept of threshold which is so useful in modeling the detection of optical and Cerenkov light [8, 10-14] is even valid for non-relativistic particles. In fact there are some data which suggest that particles with LET values above $10 \text{ keV } \mu\text{m}^{-1}$ incident tangentially to the posterior portion of the retina are detected with roughly 40% efficiency at exposure rates of 10 per sec but with less than 5% efficiency at rates of 1 per sec [3].

In their analysis of the Skylab data, Pinsky *et al.* [1] assume that there are two threshold requirements that must be satisfied simultaneously for the detection of a particle: the linear energy transfer (LET) must exceed $37 \text{ keV } \mu\text{m}^{-1}$ and the particle must have a path length through the layer of photoreceptor elements that exceeds $40 \mu\text{m}$. These values were obtained by best fitting the flash rates observed on Apollo flights in deep space and Skylab 4 outside the SAA. The retina was assumed to be uniformly sensitive. In order to obtain the lowest possible values of these parameters, the contribution from Cerenkov radiation was ignored in fitting the non-SAA data. Even with these assumptions they found that not enough of the trapped particles would exceed both requirements simultaneously to explain the SAA flash rates [1].

3. MODEL

The eye is considered in calculations to be a 2-cm diameter sphere with two-thirds of its area covered by a $30\text{-}\mu\text{m}$ thick sensitive layer of retinal photoreceptors. In order to examine the evidence for anomalous flash rates and compare our results with those given in [1], we assume that the retina is uniformly sensitive and that threshold is a valid concept. Because the dark-adapted retina is known to integrate signals over distances as great as $300 \mu\text{m}$ we express threshold in terms of a minimum deposition of energy within a retinal summation unit, consisting of a $300 \mu\text{m}$ diameter region on the sensitive layer. If more than a threshold amount is deposited, the unit is triggered and if at least one such unit is triggered a flash is detected by the astronaut.

The SAA particles can stop in the eye, pass directly through, or produce a nuclear star. Some of the protons (protons and alpha particles) from a star may then pass through the retina. If the star is located sufficiently close to the retina more than one prong may pass through the same retinal summation unit with the total energy deposited exceeding threshold. A particle that exceeds the threshold requirements [1] of $37 \text{ keV } \mu\text{m}^{-1}$ for LET and $40 \mu\text{m}$ for path length would deposit more than 1.5 MeV. An important feature of our model is that particles with LET values below $37 \text{ keV } \mu\text{m}^{-1}$ might, by having path lengths greater than $40 \mu\text{m}$, still deposit more than 1.5 MeV. Such particles would not be counted by the model given in [1] but would be included here. The cross-section for star production is approximated by the geometrical cross-section which leads to 0.025 interactions per cm of proton trajectory.

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The relative contributions of the direct passage of SAA particles through the retinal summation units and nuclear star production depend upon the threshold energy that must be deposited in the summation unit for detection, as is shown in Fig. 1. The dashed curve represents the flashes that result from SAA protons directly and the solid curve represents the contribution from star production. If threshold exceeds 1 MeV the SAA protons themselves cannot produce flashes, in agreement with [1].

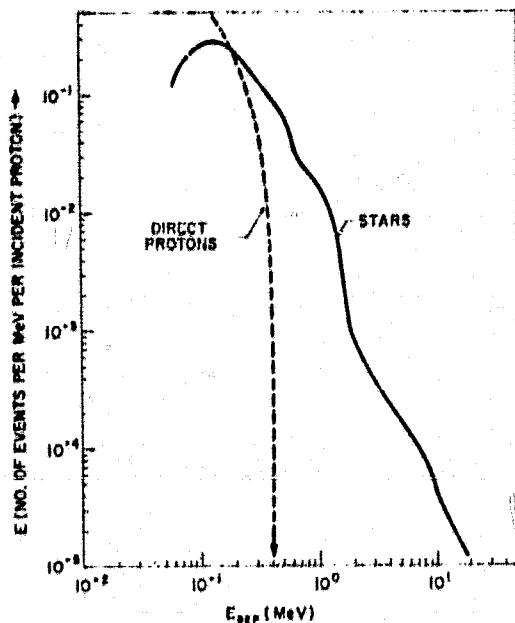


Fig. 1. Relative number of times L a minimum energy E_{dep} is deposited in the sensitive layer of the retina normalized to a 2-cm proton trajectory through the eye. Diameter of retinal summation unit $300\mu\text{m}$.

The flux of SAA protons is isotropic within the plane of the radiation belt and at the orbital altitude of 400 km the trajectory inclination dispersion is $\leq 5^\circ$. Col. Pogue was seated with his visual axis perpendicular to the plane of the particle trajectories. The shielding that had to be penetrated by a SAA particle reaching Pogue's eye depended upon its angle of incidence. The effective shielding thickness for various angles of incidence in the plane of the trapped particles can be summarized. For 85 out of 360 the incident protons must traverse greater than 11 g cm^{-2} of shielding and very few do. For the remaining 275 the particles have path lengths through shielding of between 3.2 and 3.8 g cm^{-2} . To correct for shielding losses, we assumed that only $275/360$ of all protons with kinetic energies above 80 MeV reached Pogue's eye. The SAA spectrum used in our calculations is that given in [2].

A Monte Carlo calculation was performed to follow all possible interactions through the eye and a "pulse height" spectrum of events was generated. The number of protons and alphas emitted by each star and their energy distributions were estimated from Powell *et al.* [17] and the Fermi evaporation model.

4. RESULTS AND DISCUSSION

The model predicts that light-flash activity falls off sharply with increase threshold, as is illustrated in Fig. 2. The dashed curve represents the contribution from SAA protons that pass through the retina. The solid curve represents the rate at which protons from nuclear stars in the ocular media deposit more than the threshold amount of energy in at least one summation unit in the photoreceptor layer. The solid curve in Fig. 2 does not include the contribution from stars that occur outside the sphere defined by the layer of photoreceptors and should, therefore, be considered as underestimating the flash activity. Even so the solid curve in Fig. 2 shows flash activity comparable with Pogue's rates in the SAA for thresholds of the order of a few MeV.

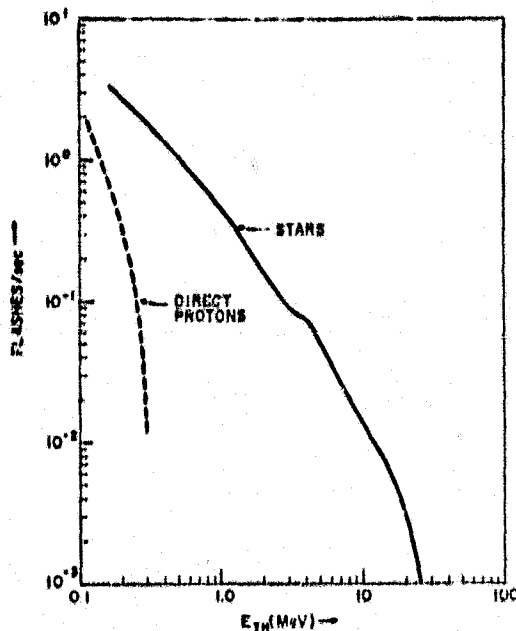


Fig. 2. Flash rates calculated for the SAA as a function of threshold E_{TN} . Diameter of retinal summation unit $300\mu\text{m}$.

A careful comparison of the model with Pogue's observations is not possible in the absence of threshold measurements. At present, it is only possible to estimate reasonable values and, perhaps, establish a lower limit. However, our purposes are satisfied if we can show that Pogue's observations are compatible with the available data without the inner belt flux of multiply charged nuclei postulated in [1]. It was shown earlier that the astronaut observations outside the SAA on Skylab and in deep space on Apollo suggest a threshold value of about 1.5 MeV. The lowest LET at which individual HZE particles have been "seen" in the laboratory is $10\text{ keV } \mu\text{m}^{-1}$ at grazing incidence at the retina. Such particles could travel almost the full $300\mu\text{m}$ through a retinal summation unit and deposit as much as 3 MeV. The solid curve in Fig. 2 predicts rates of 10 flashes per minute for a threshold of about 2 MeV which is in agreement with the above estimates.

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One final observation is that the flashes tend to result from the nuclear stars that lie closest to or within the retina. This is shown explicitly in Fig. 3 where the percentage of flash-producing stars that occur in the retinal sensitive layer is plotted as a function of the threshold energy required to excite a summation unit. The higher that threshold for a retinal summation unit is, the closer the star must be so that enough of the prongs enter the retina within the unit. The sharp rise in the percentage at a threshold of 5.6 MeV apparently reflects the need of multiple prongs to exceed threshold within a unit.

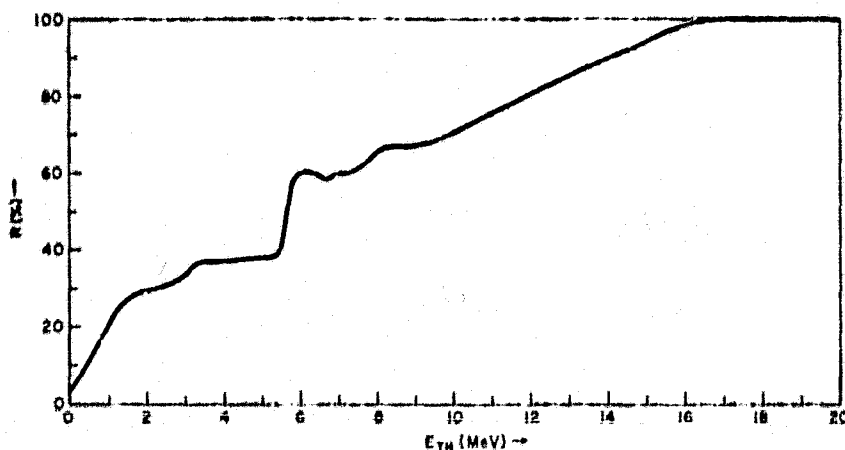


Fig. 3. Percentage R of eye-flash producing stars that occur within the 30- μ m-thick layer of photoreceptors. E_{th} = threshold energy; diameter of retinal summation unit = 300 μ m = range of 4.6 MeV proton.

5. CONCLUSIONS

Further experimentation is required to determine the role that strong nuclear interactions play in particle-induced visual phenomena. The model proposed here is consistent with the known physiology of the retina and the SAA particle flux values that are given in the literature. There is presently no experimental basis for preferring the threshold requirements of [1] to those presented here. Our model has the advantage of removing the anomaly in the high flash rates measured on Skylab 4.

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APPENDIX D

PROTON UPSETS IN LSI MEMORIES IN SPACE

P.J. McNulty*, R.C. Wyatt† and G.E. Farrell§
Clarkson College
Potsdam, N.Y. 13676

and

R.C. Filz† and P.L. Rothwell†
Air Force Geophysics Laboratory
Hanscom AFB, MA 01731

Abstract

Two types of large scale integrated dynamic Random-Access-Memory devices were tested and found to be subject to soft errors when exposed to protons incident at energies between 18 and 130 MeV. These errors are shown to differ significantly from those induced in the same devices by alphas from an ^{241}Am source. There is considerable variation among devices in their sensitivity to proton-induced soft errors, even among devices of the same type. For protons incident at 130 MeV, the soft error cross sections measured in these experiments varied from 10^{-8} - 10^{-6} $\text{cm}^2/\text{proton}$. For individual devices, however, the soft error cross section consistently increased with beam energy from 18 - 130 MeV. Analysis indicates that the soft errors induced by energetic protons result from spallation interactions between the incident protons and the nuclei of the atoms comprising the device. Because energetic protons are the most numerous of both the galactic and solar cosmic rays and form the inner radiation belt, proton-induced soft errors have potentially serious implications, for many electronic systems flown in space.

I. Introduction

The soft error phenomena are becoming an important environmental problem for electronic systems flown in space. Soft errors or bit upsets are anomalous changes in the information stored at certain locations in a semiconductor memory device without observable damage to the device itself. They represent a limitation on systems flown in space. In elec-

* Professor of Physics, Physics Department

† Recent MS Graduate; presently at Pattern Analysis and Recognition Corp., New York

§ Graduate Student, Physics Department

† Research Physicist, Space Physics Division

tronic systems the soft errors must be either avoided by the proper choice of circuit components or corrected through software. Both approaches involve significant design changes and increases in the mass and bulk of the system package.

Our present understanding of the soft errors begins with the simulation studies by Binder et al¹ that gave evidence that the soft errors previously exhibited by bipolar digital components flown in space were the result of the passage of a heavy cosmic ray nucleus with an atomic number above iron ($Z > 26$) through one of the sensitive circuit elements of the device.

The soft error rates observed on satellites have increased significantly since then, presumably as a result of the introduction of large scale integrated (LSI) devices into the electronic systems being flown.^{2,3} The decrease in volume occupied by each element on the LSI chip results in a corresponding decrease in the increment of charge needed to differentiate between the logic states of an element. This has led to an increase in radiation sensitivity for LSI devices that was illustrated recently by May and Woods⁴⁻⁶ who demonstrated soft errors in LSI devices exposed to alphas. Presumably the radiation sensitivity of the devices will increase further as devices are reduced in size (i.e., increase in the number of circuit elements per device) from the LSI regime to that of very large scale integrated (VLSI) circuits. Because of the naturally occurring alpha emitters in almost all materials, including those used to jacket memory devices, there have been a number of recent studies of the environmental implications of alpha-induced soft errors.⁴⁻⁷ Guenzer et al⁸ recently demonstrated neutron-induced soft errors in 16K dynamic random-access-memory (RAM) devices with 16,384 (16K) memory locations.

Since protons are more numerous than any of the heavier cosmic ray nuclei at almost all locations in space, a series of experiments were initiated to determine whether protons contribute to the soft error problem. These experiments are described in some detail in Section III. Physical mechanisms previously proposed to explain anomalous signals observed in Defense Meteorological Satellite Program (DMSP)⁹ and Landsat satellite systems¹⁰ and in the human visual system are described and considered as sources of soft errors in LSI circuits in Section II. Protons would be most likely to deposit a large amount of energy within the microscopic volume of a sensitive circuit element if they either traverse the sensitive element near the end of their range (where the rate of ionization loss is greatest) or undergo a nuclear interaction in or near the element. In Section IV the results of testing with two types of 4K dynamic RAM devices demonstrate the existence of soft errors induced by protons both at high energies and

near the end of their range¹¹. Analysis shows that more than one type of target element on the devices is sensitive to proton interactions.

II. Mechanisms

Any model of the soft error phenomena will almost certainly involve the interactions of energetic charged particles with some sensitive microscopic volume element or elements on the device. These sensitive regions may correspond to the memory cells themselves, the reference capacitance elements, the bit lines, the sense amplifiers, or some other circuit structures on the device. Any mechanism would then involve the creation of electron-hole pairs in or about the sensitive structure. Similar microdosimetric considerations played a role in earlier studies of another cosmic ray induced transient phenomena, the light flashes experienced by astronauts as a result of exposure of the human visual system to the cosmic rays. (The term light flashes denotes a variety of visual phenomena experienced by Apollo and Skylab astronauts with their eyes closed and adapted to darkness.^{12,13}) Laboratory simulations using human subjects exposed to accelerator beams¹⁴⁻²² and theoretical studies^{23,27} indicate that at least three different physical mechanisms contribute and, depending on the type of visual experience or the region of space, any of the three might dominate. All three are potential mechanisms for soft errors in electronic memory systems.

The first mechanism is ionization loss along the trajectory of the primary cosmic ray nucleus. The rate at which the particle deposits energy along its trajectory is known as the linear energy transfer (LET), and some experimenters found evidence of a threshold LET for visual phenomena.^{17,25} This implied that the probability that a visual sensation would be experienced depended upon the amount of energy deposited (or the number of ionizations created) within a retinal summation unit, a microscopic volume on the retina less than 300 μm in diameter and 30 μm thick.²⁷ These retinal summation units typically integrate signals over a thousand or more photoreceptor elements. The similarity to the standard soft error model¹⁻⁸ is striking. Figure 1 shows schematically a heavy cosmic ray nucleus traversing one of the microscopic circuit elements on an LSI device. The conventional model for soft errors requires the deposition of a threshold amount of energy in or about the depletion region of such an element.¹⁻⁷

The second mechanism by which an energetic charged particle can deposit the same amount of energy within either a retinal summation unit^{24,26,27} or a memory element^{11,28,29} is by means of a nuclear interaction between the primary particle and a nucleus of the medium. Figure 2 shows a

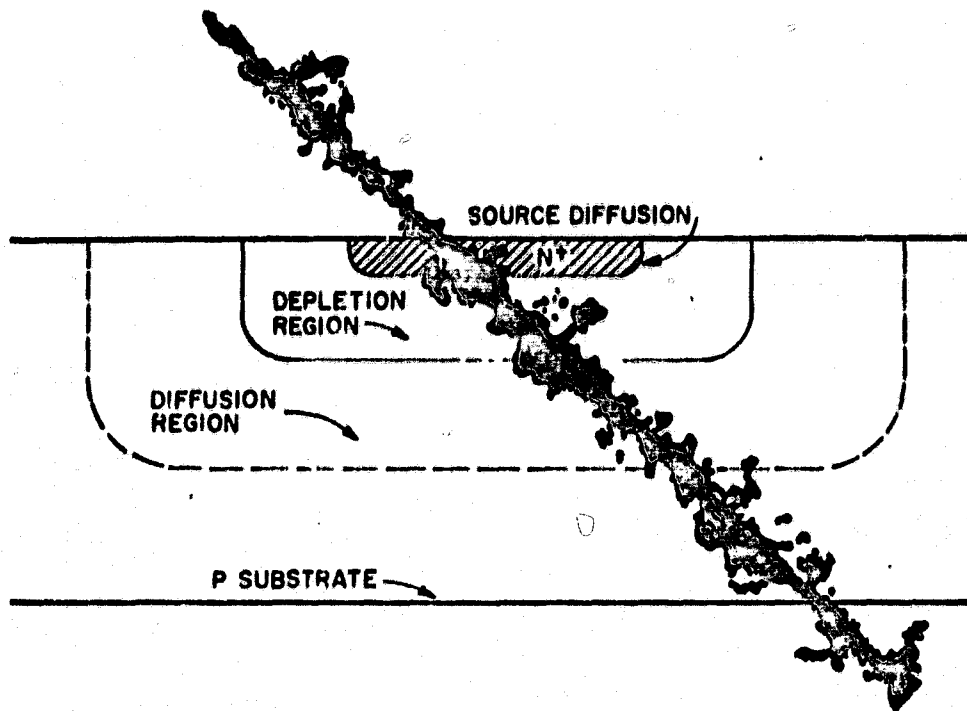


Fig. 1 Schematic representation of a high LET particle traversing an LSI circuit element.

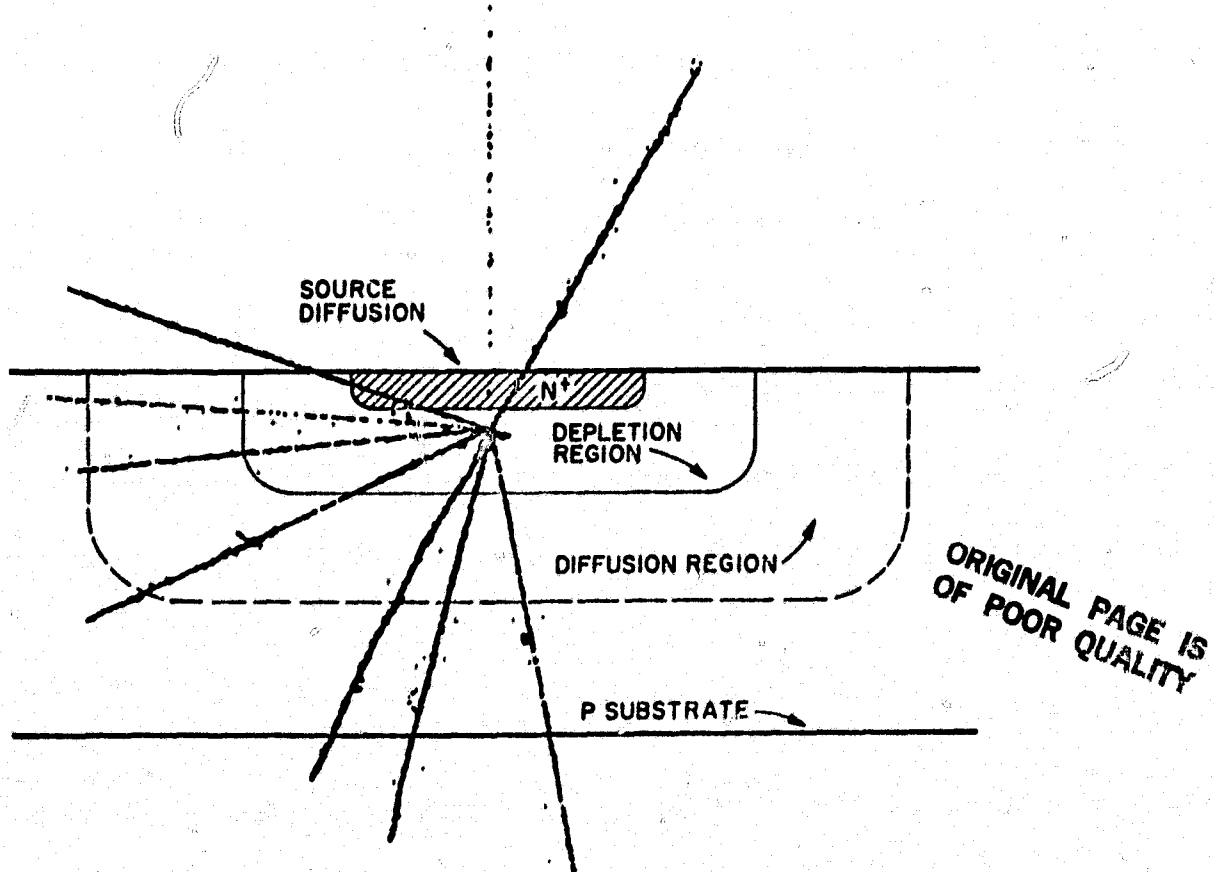


Fig. 2 Schematic representation of a cosmic-ray interaction.

schematic representation of a cosmic-ray-induced nuclear interaction in a circuit element. The total energy deposited in the sensitive volume about the depletion region is the sum of the energies deposited by each of the secondary charged particles emerging from the event (mostly protons and alphas) and the recoiling nucleus. The relative contribution of the recoiling nucleus increases as the dimensions of the sensitive volume decrease. The trajectory of the primary particle is shown incident normal to the device, and the track is represented as that of a near minimum ionizing particle to emphasize the fact that nuclear interactions provide a mechanism by which low as well as high LET particles may induce soft errors.

Proton-induced nuclear stars provide a mechanism to allow low LET trapped protons to induce the unexpectedly high light-flash rates observed when Skylab entered the region of the inner radiation belt known as the South Atlantic Anomaly.¹³ Moreover, they provide a reasonable explanation for the imperfections or blips in satellite photographs that were found to be correlated with the energetic proton flux incident on the DMSP spacecraft.⁹ A major goal of the research described in this paper was to determine whether nuclear interactions contribute to soft errors in LSI devices.

A third possible loss mechanism is Cerenkov radiation. This mechanism requires an appropriate amount of transparent material in front of the sensitive region. While this condition is satisfied for the light flashes experienced by astronauts¹² it does not apply to LSI devices. Cerenkov radiation should, therefore, be a poor source of soft errors in LSI circuits.

III. Methods

The LSI devices studied were 4K dynamic RAMs, Intel's C2107B and National Semiconductor's MM-5280. The higher energy proton exposures were carried out at the Harvard Cyclotron. The configuration used for these exposures is shown schematically in Fig. 3. The 158 MeV beam from the cyclotron passed through 0.318 in. of brass, emerging at an energy of 130 MeV. The beam energy at the test device was controlled by inserting lucite degraders into the beam upstream of the chip. Exposures were carried out at beam energies, at the test device, of 18, 32, 51, 91, and 130 MeV. The beam energy was relatively well defined at the higher energies (± 2 MeV at 130 MeV) but quite spread out at 18 MeV (± 9 MeV). All proton irradiations to date were carried out at normal incidence. The device being irradiated was connected by about 3 ft of flat ribbon cable to a memory board of an 8080 CPU based Imsai Microcomputer. The device remained an integral part of the system's memory during

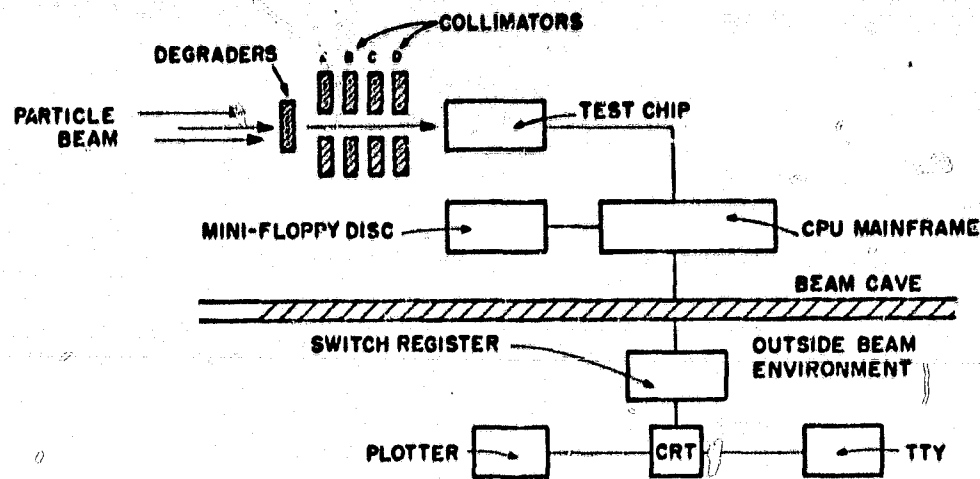


Fig. 3 Experimental configuration.

irradiation. The microcomputer was connected by means of a switch register to a terminal, a printer, and a digital plotter located outside the radiation area. The operator was free to reset, reinitialize, and transfer control among the terminal, printer, and plotter without entering the beam cave. The memory was searched for soft errors either upon manual command, or automatically after preset intervals.

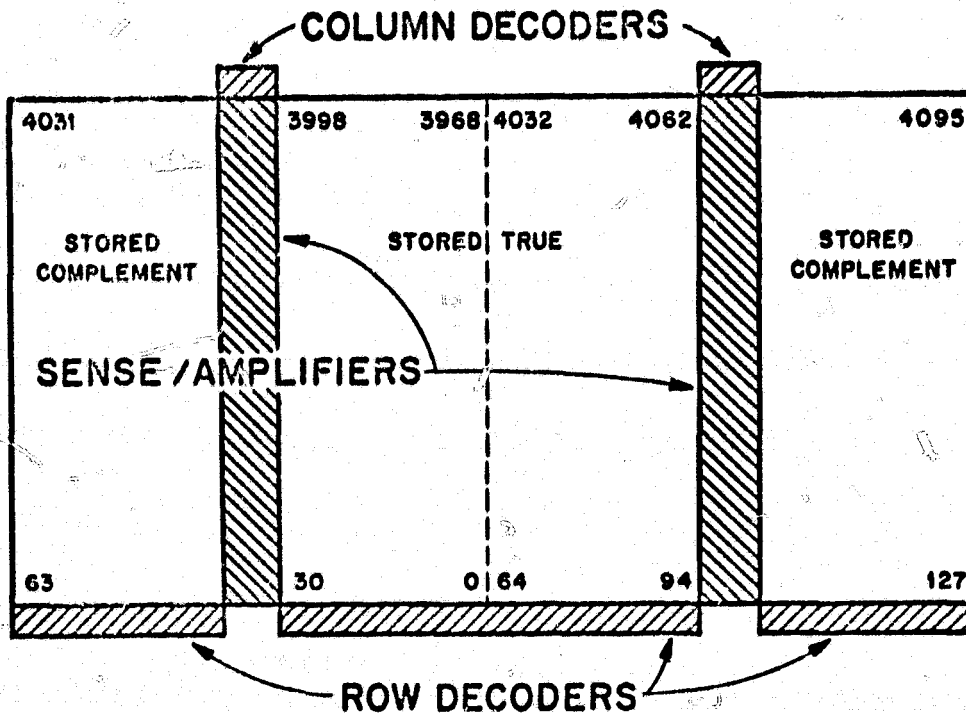
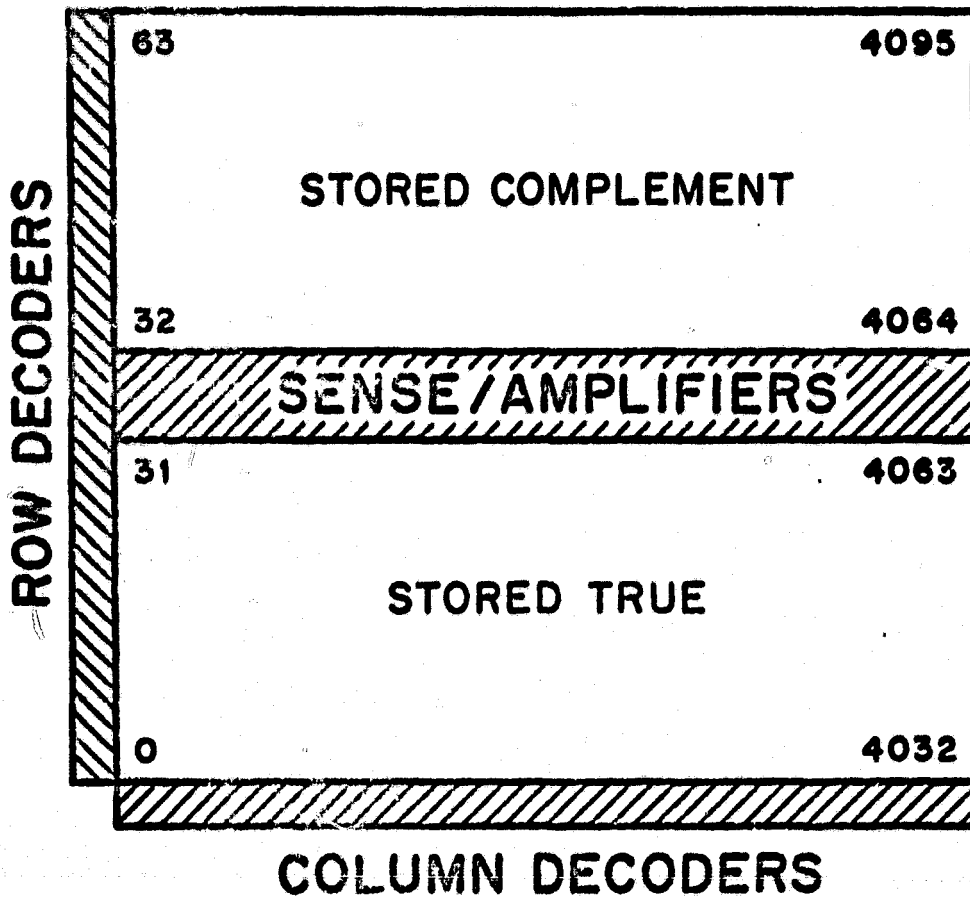
No soft errors were found in over 70 hr of running the search program with the accelerator beam off. Nor were any errors observed when the device was placed in the beam cave but not directly in the beam. For the data described in this paper, the device was initialized at the beginning of each run with a checkerboard pattern of alternating ones and zeroes along each row and column.

In addition to the high energy protons that were available at the Harvard Cyclotron, exposures were made to proton beams at incident energies of 0.93, 1.3, and 1.8 MeV using the RARAF Van de Graaff Facility at Brookhaven National Laboratory. These exposures were carried out to determine whether protons could induce soft errors without nuclear interactions. These beams had LET values in silicon of 42, 35, and 28 KeV/ μ m compared to 1 - 5 KeV/ μ m for the cyclotron beams. If ionization loss was a significant mechanism at the cyclotron energies (18-130 MeV), then the same devices should be even more sensitive to the low energy protons. The Van de Graaff proton beams typically had a full-width-half-maximum (FWHM) spread in energies of only a few percent but included a 5-20% contamination of lower energy protons.

For comparison irradiations of these devices also were carried out with 4.3 MeV ^3He nuclei at the RARAF Van de Graaff. The ^3He beam contained a contamination of approximately 20% protons. Exposures also were carried out to alphas from an ^{241}Am source.

At intervals during the irradiation, a device exhibiting changes was tested for hard errors (i.e., damage to the memory at one or more locations). The test consisted of reading and writing new data at each address in a sequence of four or five steps that changed the information at each location at least twice. All the data presented in this report involved devices that were, as yet, free of observable hard errors. The occurrence of a hard error was usually coincident with a sudden increase in the error rate.

The layout of the Intel C2107B and the National Semiconductor MM5280 devices are shown schematically in Figures 4a and 4b, respectively. In the Intel device the sense amplifiers divide memory into two regions while the National Semiconductor device is divided into four regions by two



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Fig. 4 Physical layout of the a) Intel C2107B and b) National Semiconductor MM5280 devices used for proton irradiations.

series of sense amplifiers. The corresponding regions where data is stored true or in complement form are shown. For the Intel device the sequential memory locations occupy adjacent locations along columns in memory starting with the 0th location in the lower left corner and ending at the 4095th location in the upper right. The memory locations are laid out in the National Semiconductor device in a somewhat more complicated manner. The 0th location is at the center bottom of the memory array, as shown, and the addresses are sequenced horizontally (see Fig. 4b in a repetitive pattern of the form 0, 1, 3, 2, 4, 5, 7, 6. This pattern also determines the sequence of rows also and the memory locations 3068 through 4095 would occupy the second column from the top in Fig. 4b.

IV. Results

The most striking feature of the proton-induced soft errors is the correlation between the type of error and its address in memory. Such correlations were evident in all the devices of both types tested. Typical soft-error patterns following exposure to 20, 32, 91, and 130 MeV protons are shown in Figs. 5a - 5d for an Intel C2107B device. The corresponding patterns for 32, 91 and 130 MeV proton exposures of a National Semiconductor MM5280 device are shown in Figs. 6a - 6c, respectively. Both figures are bit maps on which each error's position represents its address in memory; the two-dimensional space of the figures is divided into 4096 memory addresses distributed in 64 columns of 64 locations each. The map starts with the 0th address in the lower left hand corner. Memory locations 0 - 63 occupy the left edge of each figure, 64 - 127 the next column of locations, and so on, until locations 4032 through 4095 at the extreme right of the display.

The individual memory locations are not shown in the figure except where a soft error has occurred. Errors which correspond to changes in logic state from one to zero are represented as slanted crosses and zero to one transitions as solid circles.

The address space used for the error maps of Figs. 5 and 6 corresponds to the physical sequence of the memory locations on the Intel device (as shown in Fig. 4a) and not the sequence on the National Semiconductor devices. In both maps the soft errors corresponding to zero to one changes (solid circles) and those from one-to-zero (slanted crosses) segregate into distinctly separate regions of memory. These regions are the same for devices of the same type and are delineated in the figures by solid lines. For the Intel devices but not for the National Semiconductor devices, these regions are also the regions of true and complement storage. For both

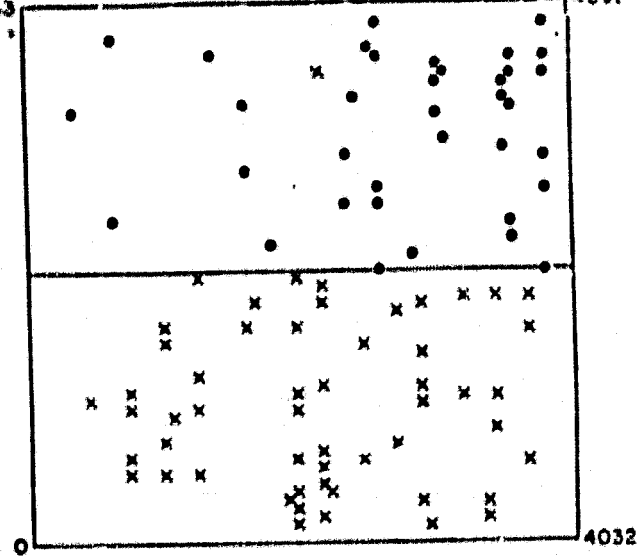
device types, these regions of zero-to-one and one-to-zero errors reflect the architecture of the device in that they correspond to the regions of ones and zeros that are typically obtained when the system is first energized, the so-called turn-on patterns.

The Intel devices tested typically had turn-on patterns consisting of zeros in the upper half of memory and ones in the lower, and the National Semiconductor devices had alternating regions of eight rows each of all ones and all zeros. Turn-on patterns for the Intel and National Semiconductor devices are shown schematically in Figs. 5e and 6d, respectively. By repeated power-ups of the main frame of the micro-computer, it was often possible to transform the original National Semiconductor turn-on patterns to one nearly its complement.

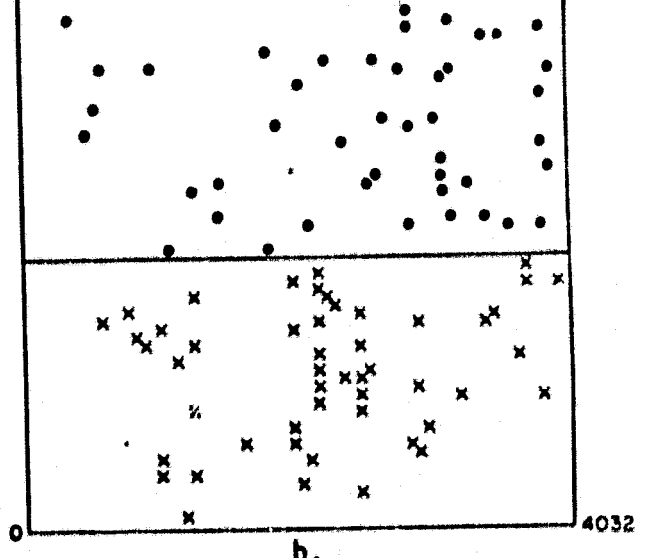
The soft-error patterns in the error maps shown in Figs. 5 and 6 vary appreciably with beam energy. Soft errors in which zero logic states changed to ones were particularly sensitive to the incident particle energy. The ratio of zero-to-one and one-to-zero type upsets is plotted vs incident proton energy in Fig. 7 for individual Intel and National Semiconductor devices. While the ratio increased with beam energy for all the devices tested, there was considerable variation among devices, even those from the same manufacturer. The data shown in Fig. 7 are from measurements on single devices and should be interpreted as a qualitative representation of the trend to be expected from other devices of the same type.

At low proton energies ($<2\text{MeV}$) all the soft errors were one-to-zero. The sharp rise in the relative number of zero-to-one errors with beam energy reflects differences in either the physical mechanisms of energy deposition or the circuit elements sensitive to upsets. The fact that these differences are dependent on beam energy implies that different energy deposition thresholds are involved.

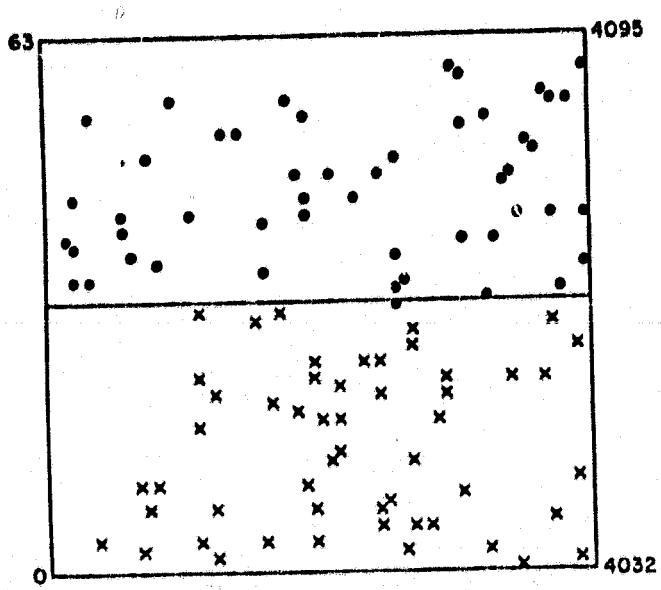
Typical error maps obtained by exposing an Intel C2107B device to $4.3\text{ MeV } ^3\text{He}$ particles at the RARAF Van de Graaff is shown in Fig. 8a, and a similar plot for a National Semiconductor device exposed to ^4He nuclei (alphas) from an ^{241}Am source is shown in Fig 8b. Again, the memories were initialized with a checkerboard pattern of ones and zeros. Clear differences between the helium and proton data are evident when Figs. 8a and 8b are compared with Figs. 5 and 6. First, only one zero-to-one type errors occurred in the Intel device exposed to ^3He and none occurred in the National Semiconductor device exposed to alphas. Besides the absence of zero-to-one soft errors, the helium data of Figs. 8a and 8b exhibit considerably more structure than is



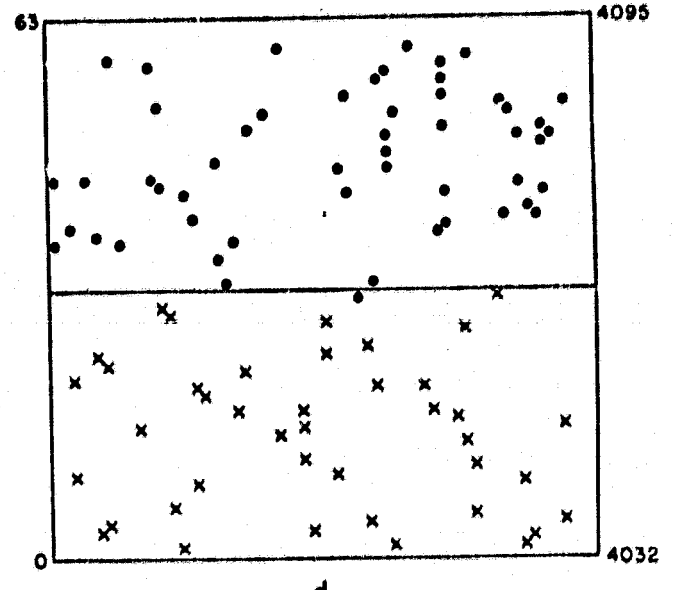
a.



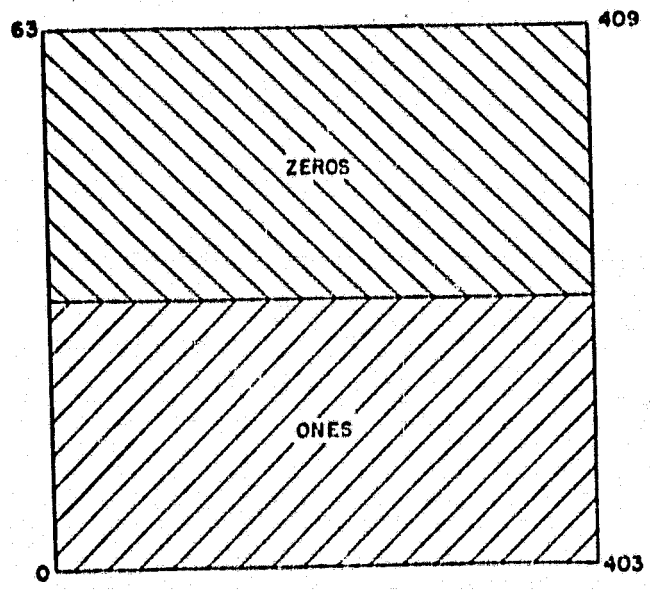
b.



c.



d.



e.

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Fig. 5 Error maps at a) 20 MeV, b) 51 MeV, c) 91 MeV, and d) 130 MeV for Intel C2107B device following exposure to protons; e) Typical turn-on pattern for Intel C2107B devices.

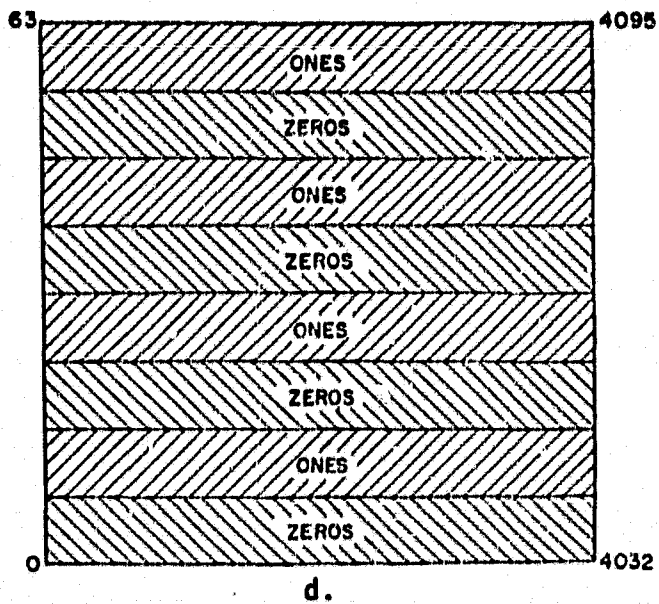
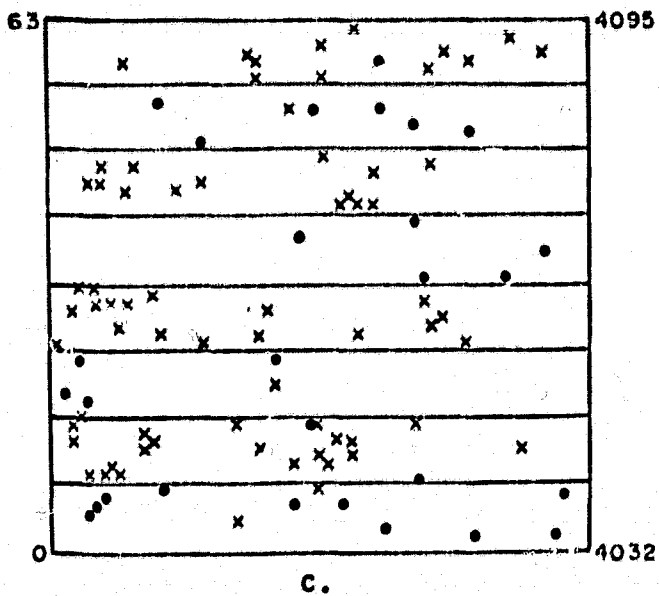
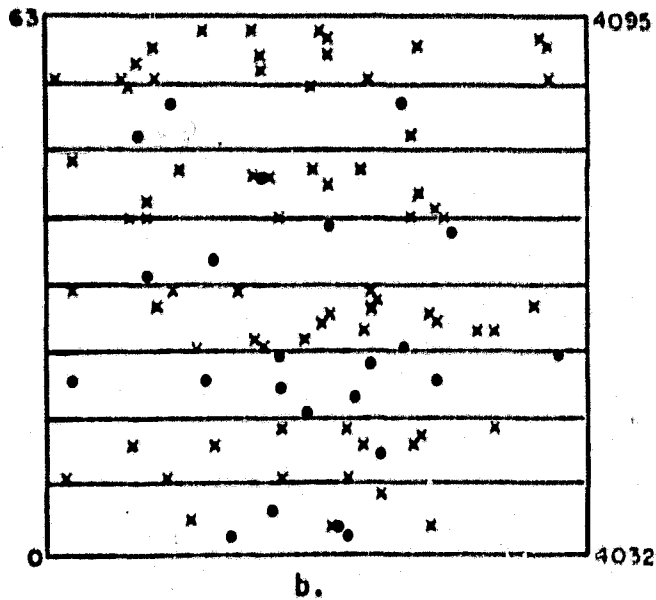
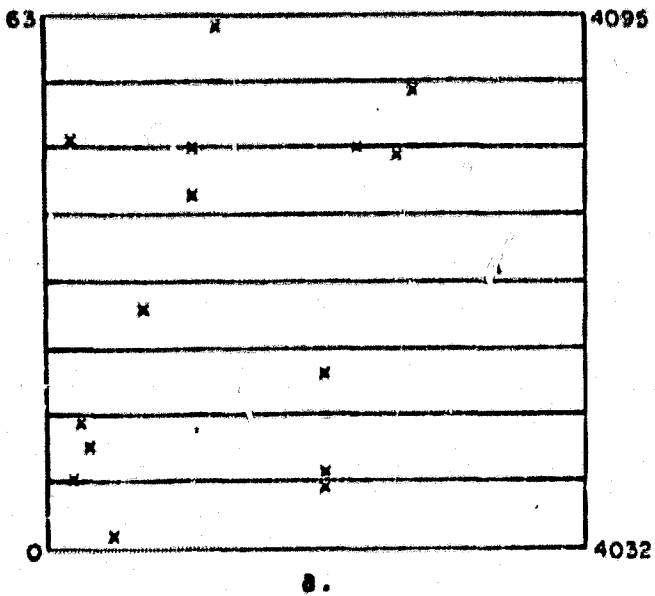


Fig. 6 Error maps for National Semiconductor device MM-5280 when exposed to protons at a) 32 MeV, b) 91 MeV, c) 130 MeV, d) Typical trun-on pattern for the National Semiconductor devices.

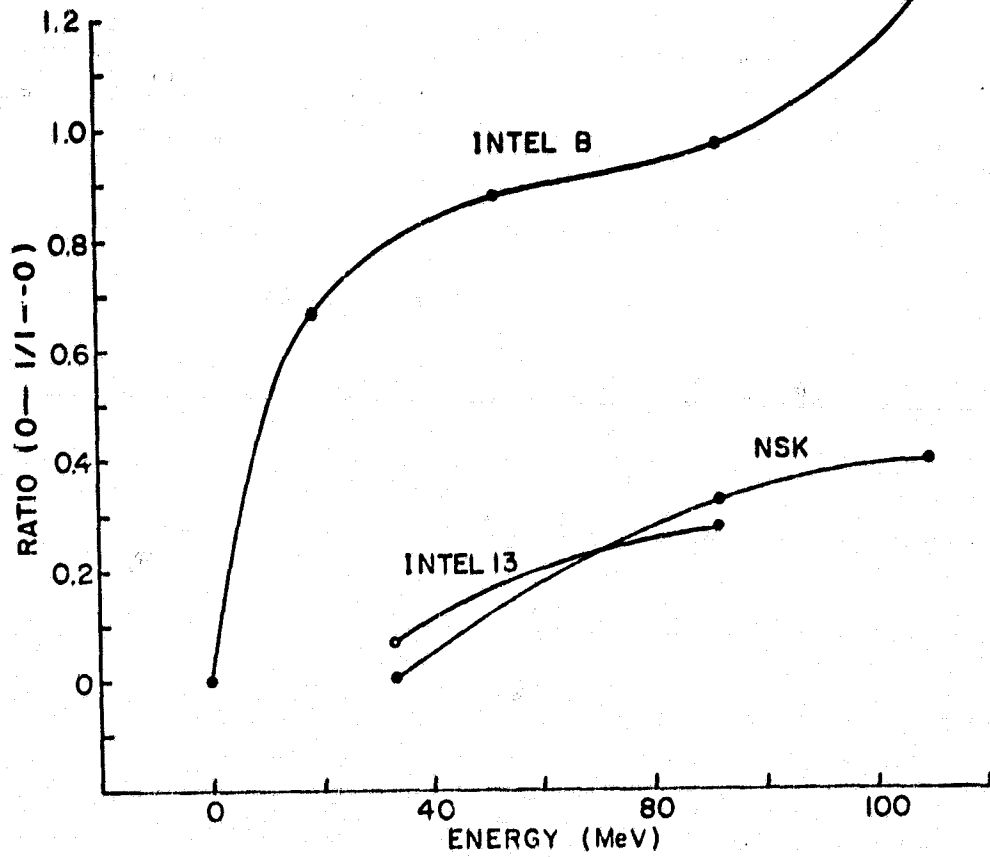


Fig. 7 Ratio of zero to one to one to zero transitions vs beam energy.

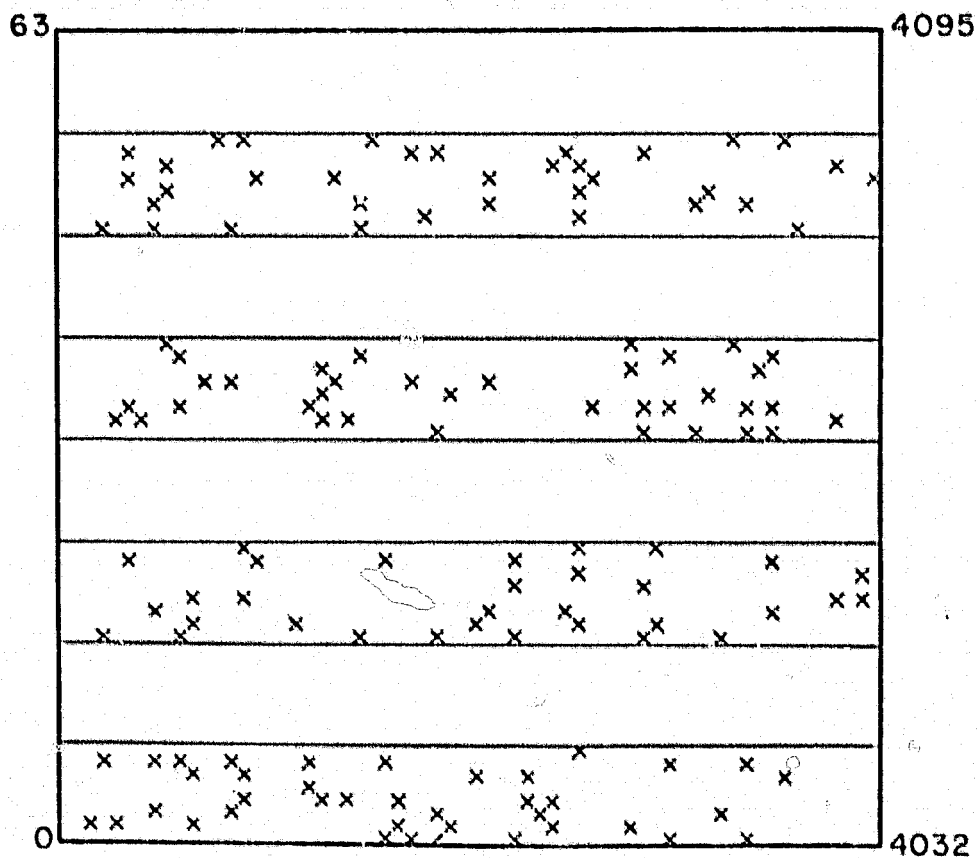
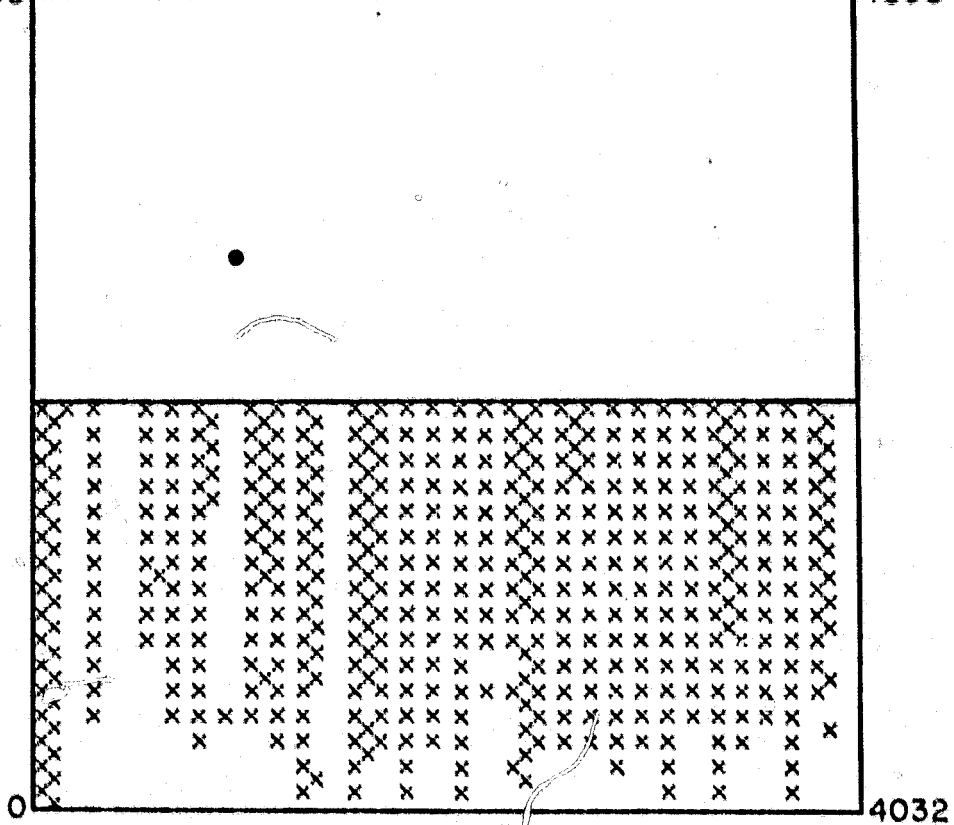


Fig. 8 (a) Error map for Intel device C2107B exposed to 4.3 MeV ^3He . (b) Error map for National Semiconductor device MM-5280 exposed to alphas from an ^{241}Am source.

evident in Figs. 5 and 6 for protons. The errors in Figs. 8a and 8b occur almost exclusively in certain columns. Moreover, in the Intel devices these columns appeared to fill from the center line in Fig. 8a downward.

The soft error patterns of Figs. 8a and 8b appear to be in agreement with the earlier studies of May and Woods⁴⁻⁶ and Yaney et al⁷ who concluded that alpha-induced soft errors are not due to interactions in the memory cells themselves; they found that the bit lines and sense amplifiers were likely targets. The column structure exhibited in Figs. 8a and 8b is much less evident in the 130 MeV proton data in Figs. 5a and 5b, and the columns in Fig. 4a definitely did not fill from the center line down.

The structure evident in the error maps and the variation of the patterns with beam energy are not understood but appear inconsistent with models assuming that the memory elements are themselves the only sensitive targets. In that case the errors would be randomly distributed on an error map, as in fact they are for errors induced by stopping heavy ions³.

Soft Error Cross Sections

The soft error cross sections were obtained by dividing the number of first soft errors by the proton fluence. The soft error cross sections measured in this study are plotted in Fig. 9 vs beam energy for the Intel and National Semiconductor devices. Data points obtained at different energies on the same devices are connected by lines. Considerable variation among devices by the same manufacturer is evident, but for the same device there seems to be a clear increase in the soft error cross section with energy. This increase occurs despite the fact that the LET and the total inelastic cross sections are decreasing with increasing energy over this interval. The explanation, presumably, lies in the fact that the average energy released in the interaction (and that transferred to the recoiling nucleus) increase with beam energy, and the cross section for events which result in large local depositions of energy probably increase with beam energy over the range 18-130 MeV.³⁰

In the series of irradiations discussed here, the memory was reinitialized each time a soft error was discovered, and the records for a number of device exposures were examined to determine whether the sensitivity of the devices varied with exposure. No evidence for significant changes in the soft error cross section for first soft errors as a function of dose were found.¹¹

The devices were found to be less sensitive to the low

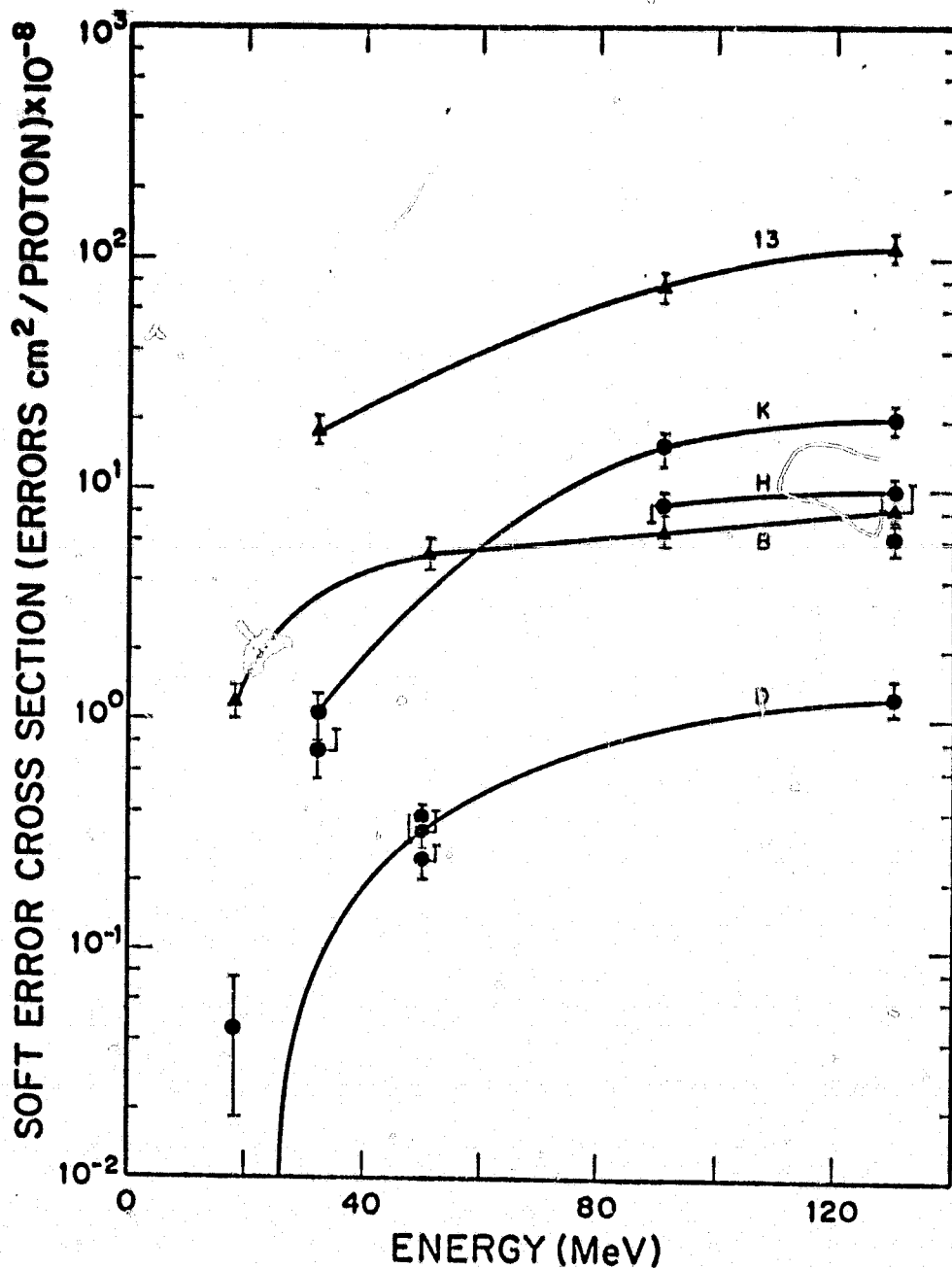


Fig. 9 Soft error cross section vs beam energy. (Lines connect data points obtained for the same devices; circles and triangles represent National Semiconductor and Intel devices, respectively.)

energy protons despite their much higher LET values (28-42 KeV/ μ m vs 1-5 KeV/ μ m for the cyclotron beams). Table 1 gives the proton errors observed in a number of different devices exposed to 0.93, 1.3 and 1.8 MeV protons. For most of the devices the soft error cross section was zero. The non zero cross sections in Table 1 are not necessarily evidence that the device is sensitive to individual low energy protons. Individual elements on the device would experience enough proton traversals to absorb 4 MeV or more within a refresh cycle at rates that were greater than the observed error rates. However, in the data given in Table 1, there is no evidence of dose-rate dependence of the type to be expected multiple hits were required for a soft error.

Different circuit elements may become sensitive to soft errors at the higher proton energies as a result of the higher local energy deposition through interactions. This would be consistent with the changes in the type of errors evident in Figs. 5 - 7.

V. Error Rates in Spacecraft Systems

The soft error cross sections plotted in Fig. 9 range from 10^{-8} to 10^{-6} errors $\text{cm}^2/\text{proton}$ at the higher proton energies. If, in the absence of measured values, the soft error cross section is assumed to be constant at energies above 130 MeV, then the soft-error rates to be expected in space can be estimated. A spacecraft system with 10^5 bits of memory distributed in 25 memory devices of the type tested in this study, flying in a region of deep space characterized by an energetic proton flux of 2 protons $\text{cm}^{-2}\text{sec}^{-1}$, would exhibit proton-induced soft errors of from 0.04 to 4 errors per day. This is comparable to the rates currently being reported.² The high proton fluence in space compensates somewhat for the relatively low proton cross sections. In the radiation belts or during solar flares, the proton-induced nuclear interactions would, of course, be greatly increased, resulting in correspondingly higher soft error rates.

VI. Conclusion

Energetic protons have been shown to induce logic upsets in two types of 4K dynamic RAM. These devices must, therefore, be soft error sensitive to the entire charge spectrum of the cosmic rays. The cross sections measured for protons are at least four orders of magnitude lower than those measured by Blanford et al.² and Kolasinski et al.³¹ for 180 MeV stopping argon and krypton ions incident on similar devices. In the latter case the measured cross sections were comparable to the cross-sectional areas occupied by the sensitive regions of all the memory cells on the device, and those data apparently are consistent with the hypothesis that a

heavy ion must deposit 8-20 MeV or more within the sensitive volume associated with a memory cell in order to change the logic state of that element.

The lower soft error cross section protons may still be a significant source of upsets in memory systems flown in space because the lower cross section is compensated by the fact that protons are considerably more abundant in space than are heavy ions capable of depositing 3 MeV or more in ionization loss along a few microns of trajectory. The proton contribution to the radiation-induced soft errors to be expected for specific devices flown in space can be determined experimentally using protons available at accelerator facilities.

The range of proton soft error cross sections measured in this experiment (see Fig 9) are clearly smaller than the physical dimensions of any LSI circuit element. The exact dimensions of the element that might be sensitive to soft errors are not known because of proprietary restrictions, and their determination was beyond the scope of this work.

The soft errors induced by protons with incident energies between 18 and 130 MeV exhibit clear differences from those induced by alphas⁴⁻⁷ as shown by comparing Figs. 5 and 6 with Fig. 8. The structure evident in the error maps and the differences between zero to one and one to zero type errors distinguish proton-induced soft errors from those reported recently for stopping argon ions.^{3,31} At low energies the differences from alpha-induced upsets is less pronounced. This is consistent with the findings of Guenzer et al⁸ who report agreement between upsets obtained with 6-14 MeV neutrons and rough predictions based on "n, alpha" and "n, alpha n" cross sections. (During the preparation of this manuscript we have learned that Guenzer et al. have observed proton-induced soft errors at cross sections of approximately 10^{-8}cm^2 . Their data will be included in the published version of Ref. 8.) The alpha-induced soft errors and, presumably a significant fraction of the lower energy proton upsets, result primarily from events in other than the memory cells, probably in the bit lines or the sense amplifiers. As the proton energies increase the events become more randomly distributed in memory and zero to one upsets increasingly appear. This may reflect a transition from "p, alpha" events to spallation events as the dominant mechanism for soft errors. The high energies released in the latter events make additional circuit elements available for soft errors.

There is as yet no reliable single parameter which can be used to classify particles according to whether they will induce soft errors in space. The value of the particle's

7Yaney, D.S., Nelson, J.T., Vanskike, L.L., "Alpha-Particle Tracks in Silicon and their Effects on Dynamic MOS RAM Reliability", IEEE Transactions on Electron Devices, Vol. ED-26, January 1979, pp. 10-16.

8Guenzer, C.S., Wolicki, E.A., and Allas, R.G., "Single Event Upset of Dynamic Rams by Neutrons and Protons", Proceedings of the IEEE Conference on Nuclear and Space Radiation Effects Santa Cruz, Calif., July 1979.

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10Croft, T.A., "Nocturnal Images of the Earth from Space", Stanford Research Institute Report No. 68197, March 1977.

11Wyatt, R.C., McNulty, P.J., Toumbas, P., Rothwell, P.L., and Filz, R.C., "Soft Errors Induced by Energetic Protons", Proceedings of the IEEE Conference on Nuclear and Space Radiation Effects, Santa Cruz, Calif., July 1979.

12Pinsky, L.S., Osborne, W.Z., Bailey, J.V., Benson, R.E., Thompson, L.F., "Light Flashes Observed by Astronauts on Apollo II through Apollo 17" Science, Vol. 183, March 1974, pp. 957-959.

13Pinsky, L.S., Osborne W.Z., Hoffman, R.A., and Bailey, J.V., "Light Flashes Observed by Astronauts on Skylab 4", Science, Vol. 188, May 1975, pp. 928-930.

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16McNulty, P.J., "Light Flashes produced in the Human Eye by Extremely Relativistic Muons", Nature, Vol. 234, November 1971, pp. 110.

17Budinger, T.F., Bichsel, H., and Tobias, C.A., "Visual Phenomena Noted by Human Subjects on Exposure to Neutrons of Energies less than 25 Million Electron Volts", Science, Vol. 172, May 1971, pp. 808-870.

18McNulty, P.J., Pease, V., Bond, V.P., Schimmerling, W., Vosburgh, K.G., "Visual Sensations Induced by Relativistic Nitrogen Nuclei", Science, Vol. 178, October 1972, pp. 160.

LET is possibly sufficient to determine whether a cosmic ray particle will deposit sufficient energy by ionization loss to induce a soft error if it traverses a sensitive volume element. However, a low value of LET does not rule out soft errors because low-LET nuclear particles can induce errors through nuclear interactions. Since only those interactions which result in a threshold localized deposition of energy can be expected to contribute, the total cross sections for inelastic nuclear scattering also are not quantitatively useful. The situation is further complicated by evidence of more than one type of sensitive circuit element on both the devices tested.

The soft error phenomena is fast becoming a serious environmental problem for systems in space. Considerable data involving a variety of device types and a broad range of energies are needed before quantitative determination of the severity of the problem can be made.

Acknowledgements

The indispensable cooperation and many helpful suggestions of A. Koehler of the Harvard Cyclotron, S. Marino and N. Rohrig of the RARAF facility of Brookhaven National Laboratory, and P. Toumbas of Clarkson College are gratefully acknowledged. This work was supported in part by Rome Air Development Center contract number F30602-78-C-0102 and NASA Contract NSG 9059.

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- ⁶May, T.C., personal communication.

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23 Madey, R., and McNulty, P.J., "Frequency of Light Flashes Induced by Cerenkov Radiation From Heavy Cosmic-Ray Nuclei", Proceedings of the National Symposium on Natural and Manmade Radiation in Space, edited by E.A. Warman, January 1972, pp. 757-766.

24 McNulty, P.J., and Madey, R., "Direct Stimulation of the Retina by the Method of Virtual Quanta for Heavy Cosmic-Ray Nuclei", Proceedings of the National Symposium on Natural and Manmade Radiation in Space, edited by E.A. Warman, January 1972, pp. 767-772.

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27 McNulty, P.J., Pease, V.P., Bond, V.P., Filz, R.C., and Rothwell, P.L., "Particle Induced Visual Phenomena in Space", Radiation Effects, Vol. 34, March 1977, pp. 153-156.

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29 Bradford, J.N., "Expected Contributions to LSI/VLSI RAM Soft Error Rates by Solar and Cosmic Protons -- Some Implications For Beam Weaponry", Air Force Report RADC-TM-79-ES-02, March 1978.

³⁰Bertini, H.W., "Spallation Reactions: Calculations", Spallation Nuclear Reactions and Their Applications, Edited by B.S. P. Shen and M. Merker, D. Reidel Publishing Co., Boston, MA, 1976, pp. 27-48.

³¹Kolasinski, W.A., Blake, J.B., Anthony, J.K., Price, W.E., and Smith, E.C., "Simulation of Cosmic-Ray-Induced Soft Errors and Latch Ups in Integrated Circuit Computer Memories", Proceedings of the IEEE Conference on Nuclear and Space Radiation Effects, Santa Cruz, CA, July 1979.

Table 1 Soft Errors induced by low energy protons.

Energy MeV	Device	Instantaneous flux cm ⁻² sec ⁻¹	Number errors	Dose rads
0.93	NS-5	1.4x10 ⁶	0	25,000
0.93	Intel-14	1.4x10 ⁶	0	25,000
0.93	Intel-2	1.4x10 ⁶	37	3,600
0.93	Intel-2	1.4x10 ⁶	0	15,000
0.93	Intel-3	1.4x10 ⁶	3	465
1.3	Intel-3	8.6x10 ⁶	7	200
1.3	Intel-1	7.5x10 ⁶	2	15,000
1.3	Intel-1	1.5x10 ⁷	0	4,000
1.3	Intel-4	1.5x10 ⁷	0	22,000
1.3	Intel-4	9.5x10 ⁷	0	2,000
1.8	Intel-2	1.0x10 ⁷	0	1,060
1.8	Intel-3	1.4x10 ⁷	8	500