Reports

Visual Sensations Induced by Cerenkov Radiation

Abstract. *Pulses of relativistic singly charged particles entering the eyeball induce a variety of visual phenomena by means of Cerenkov radiation generated during their passage through the vitreous. These phenomena are similar in appearance to many of the visual sensations experienced by Apollo astronauts exposed to the cosmic rays in deep space.*

When a charged particle passes through the eyeball, a human subject may experience a visual sensation. It is now evident that the variety of particle-induced visual sensations (PIVS) cannot be explained in terms of a single mechanism. A laboratory experiment indicated that one mechanism for PIVS is Cerenkov radiation (*1*), but other experiments (*2*) were carried out under conditions such that either Cerenkov radiation was not generated or it was generated at intensities that were believed to be too low to be detected.

To further study the role of Cerenkov radiation in producing visual sensations, we initiated a series of experiments using the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory to measure the threshold intensity required for Cerenkov PIVS at different orientations under conditions in which Cerenkov radiation could be verified as the mechanism. Our preliminary results show the sensitivity of the retina to Cerenkov radiation to be in agreement with large-field optical measurements.

The experiments at the AGS involved exposing the right eye of dark-adapted human subjects to individually triggered bursts of positive muons of momentum 7.2 ± 0.8 Gev/*c*, or negative pions of momentum 725 ± 7 Mev/*c*. The beam lines and experimental facilities set up for the muon and pion exposures will be described in detail elsewhere (*3*). In both cases the particles are singly charged, relativistic, and minimum ionizing. Comparison of muon and pion exposures under the same conditions was necessary to demonstrate that the pion PIVS were not the results of secondary particles emerging from nuclear interactions.

For both beams the number of particles in each pulse is controlled by the current settings of the magnets in the beam line. The beam particles entering the eye are monitored by counter telescopes. Signals from these counters are then gated to record only particles that pass through the eye during the beam pulse. Both the muon and pion beam pulses are uniform in intensity to within 5 percent across dimensions corresponding to the cross-sectional area of the eye.

After aligning himself, the subject signaled when ready for a beam pulse. The beam pulse was delivered at the end of a foreperiod which was varied randomly from 1 to 3 seconds. Individual trials were separated by approximately 1 minute. Beam tuning and recording of pulse amplitudes were carried out in a separate room beyond the subject's hearing range. The subject was instructed to indicate a response of yes, no, or doubtful to each pulse. If the response was yes, the visual sensation was described, in terms of size, shape, color, brightness, and location in the field of view. The subject's responses were recorded by tape recorder and written record along with the total number of particles in the beam pulse. To be sure that each subject adopted a reliable subjective criterion for reporting a visual sensation, approximately 40 percent of the tests presented during each experimental session were catch tests. A catch test consisted of a pulse containing no particles. Threshold measurements have been made with both muons and pions for a number of orientations of the beam direction to the retinal surface. The number of particles in successive pulses was varied above and below the expected threshold intensity, which was estimated from pretrial data. The order of the presentation of beam pulses was randomized to eliminate order effects.

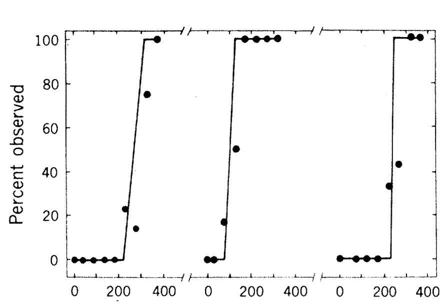

Fig. 1. Frequency-of-seeing curves for three subjects under identical viewing conditions.

We restrict ourselves here to a brief summary of the pion results. The frequency-of-seeing curves for three subjects exposed to relativistic pions distributed over a 1.3 by 5.1 cm cross-sectional area at roughly normal incidence to the peripheral retina is summarized in Fig. 1. In calculating the frequency-of-seeing curves, we combined the doubtful responses with the no responses because 5 doubtfuls out of 12 were in response to catch tests. The particles that passed through the eye were counted by a 1.3 by 2.5 cm section of a scintillation counter placed just before the eye. The three curves are typical of our threshold measurements and very similar to the analogous curves found with light (*4*). There are negative responses for small numbers of pions, then a sharp rise to 100 percent detection.

A comparison can be made with optical data obtained by Denton and Pirenne (*5*), who determined the threshold luminance for 23 young subjects exposed continuously to a binocular 47° field of white light. The mean threshold was 0.85×10^{-6} cd/m^2, while the individual values ranged from 0.4×10^{-6} to 5×10^{-6} cd/m^2. According to Denton and Pirenne, 0.85×10^{-6} cd/m^2 corresponds to about 27,300 photons (510 nm) per square centimeter per second arriving at the retina. If we take the short interval over which the retina integrates signal into account by considering the continuous exposure as a series of 0.1-second "looks," these optical thresholds range from 1,285 to 16,059 photons per square centimeter per look.

The PIVS data can also be represented in terms of an equivalent number of 510-nm photons at the retina. The median path length for a beam particle traversing the vitreous during the large-area exposures is 1.4 cm for an eye that has an interior diameter of 2 cm. The Cerenkov light that results from the passage of the entire burst is distributed more or less uniformly over the posterior hemisphere. The approximate number of photons incident per square centimeter can be obtained by multiplying the equivalent number of photons, corrected to maximum spectral efficiency, by $1.4/\pi$. Then the thresholds determined for the three subjects for the large-area exposures represented in Fig. 1 are 3604, 9192, and 9912 equivalent Cerenkov photons, respectively. These values are well within the range of optical thresholds measured by Denton and Pirenne.

The PIVS observed in these experiments are themselves the best evidence that Cerenkov radiation is the basic mechanism. At threshold, they typically appear as a large, crescent-shaped flash in the peripheral regions of the field of view. These threshold flashes may occasionally be as large as one-third to one-half the field of view. They consistently appear in the regions of the field of view that correspond to the portion of the retina near where the particles exit. Visual phenomena observed at the AGS to date include large cloud-like flashes, large crescent-shaped flashes, brighter smaller flashes, wide streaks or bands, and large flashes with dark centers.

A dramatic demonstration of Cerenkov radiation was obtained when a near-threshold pulse of 7 Gev/c muons entered the subject's eyeball through the rear and exited through the cornea. The visual sensations appear as large flashes of light with dark centers. The lighted section of the flash fills the far periphery, and the dark central region is often so large it includes regions corresponding to the most sensitive areas on the retina. To the best of our knowledge, flashes with dark centers have not previously been reported. Nor could we explain them by any mechanism except Cerenkov radiation. When informed of our observations, Pinsky *et al.* (*6*) briefed the astronauts on Apollo 17 to look for similar effects. The observation of large flashes with dark centers was confirmed on Apollo 17.

Some significant statements can now be made regarding the role of Cerenkov radiation in producing the Apollo light-flash phenomena. The sensitivity of the retina to visible Cerenkov light is in general agreement with earlier optical measurements and consistent with theory. When the count rates to be expected in deep space are calculated on the basis of the known cosmic ray spectrum and the results are expressed as a function of the sensitivity of the retina (*7*) count rates equal to the 1 to 2 per minute observed on Apollo missions 11 through 17 are obtained for reasonable values of retinal sensitivity. Apollo astronauts have reported visual phenomena (*6*) that are similar in description to each of the PIVS described in our experiments. Moreover, the astronauts must also be dark-adapted. One of the most serious objections to the Cerenkov explanation of the Apollo flashes was based on an impromptu experiment performed by astronaut Edgar Mitchell on Apollo 14, which indicated that dark-adaptation was not required for observing flashes (*8*). After one of us (P.J.M.) observed that the technique used by Mitchell was probably insufficient for light-adaptation, the experiment was formally repeated in three sessions on Apollo 15 and the need for dark adaptation was confirmed (*6*).

Our data and calculations (*7*) indicate that, at least for some subjects, the threshold value for individual ions will be atomic number $Z < 10$, which corresponds to particles that have already been accelerated to relativistic velocities at existing facilities. This is also consistent with the ability of our subjects to detect with low efficiency barely relativistic nitrogen nuclei (*9*).

P. J. McNulty
V. P. Pease

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

V. P. Bond

Brookhaven National Laboratory, Upton, New York 11973

References and Notes

P. J. McNulty, *Nature (Lond.)* **234**, 110 (1971); *Air Force Camb. Res. Lab. Rep. No. 71-0377* (1971).

F. J. D'Arcy and N. A. Porter, *Nature (Lond.)* **196**, 1013 (19 W. N. Charman and C. M. Rowlands, *ibid.* **232**, 574 (19 W. N. Charman, J. A. Dennis, G. G. Fazio, J. V. Jelley, *ibid.* **230**, 596 (19 C. A. Tobias, T. F. Budinger, J. T. Lyman, *ibid.*, p. T. F. Budinger, J. T. Lyman, C. A. Tobias, *ibid.* **239**, 209 (1972); J. H. Fremlin, *New Sci.* **47**, 42 (1970); T. F. Budinger, H. Bischel, C. A. Tobias, *Science* **172**, 868 (1971); C. A. Tobias, T. F. Budinger, J. T. Lyman, in *Proceedings of the National Symposium on Natural and Manmade Radiation in Space*, E. A. Warman, Ed. (NASA-TM X-2440, National Aeronautics and Space Administration, Washington, D.C., 1972), p. 416.

3. P. J. McNulty, V. P. Pease, V. P. Bond, in preparation.
4. M. H. Pirenne and F. H. Marriott, in *Psychology—A Study of Science*, S. Kich, Ed. (McGraw-Hill, New York, 1959), vol. 1, p. 288.
5. E. J. Denton and M. H. Pirenne, *J. Physiol. (Lond.)* **123**, 417 (1954).
6. L. S. Pinsky, W. F. Osborne, J. V. Baily, R. E. Benson, L. F. Thompson, *Science* **183**, 957 (1974).
7. R. Madey and P. J. McNulty, in *Proceedings of the National Symposium on Natural and Manmade Radiation in Space*, E. A. Warman, Ed. (NASA-TM X-2440, National Aeronautics and Space Administration, Washington, D.C., 1972), p. 757.
8. P. K. Chapman, L. S. Pinsky, R. E. Benson, T. F. Budinger, in *ibid.*, p. 1002.
9. P. J. McNulty, V. P. Pease, L. S. Pinsky, V. P. Bond, W. Schimmerling, K. G. Vosburgh, *Science* **178**, 160 (1972).
10. These experiments required considerable cooperation from the AGS support groups, the health physicists at Brookhaven, and the Columbia, Rochester, Harvard, and National Accelerator Laboratory muon collaboration. Particular thanks to W. R. Casey, D. Berley, H. Brown, Y. Lee, R. S. Stafford, W. P. Sims, and the members of the ad hoc safety committee. This research was carried out at Brookhaven National Laboratory under the auspices of the Atomic Energy Commission.

9 April 1975

High-Pressure Phase Transformation of $CaSO_4$ (Anhydrite) During a Nuclear Explosion

Abstract. *Examination of the postshot cores from the portion of the Tatum Salt Dome that had been subjected to a nuclear explosion (Salmon Event) has indicated evidence for the high-pressure phase transformation of anhydrite. This evidence consists of distinctly different optical domains within the shocked anhydrite. Evidence for the transition exists out to approximately 1.5 cavity radii. Excellent agreement exists between experimental work and the theoretical calculations of the predicted pressure profile.*

On 22 October 1964, a 5.3-kiloton device (Salmon Event) was detonated in the Tatum Salt Dome near Hattiesburg, Mississippi, at a depth of 2716 feet (830 m). The composition of the dome at this depth was approximately 90 percent NaCl (halite) and 10 percent $CaSO_4$ (anhydrite). The average in situ bulk density of the material was 2.24 g/cm^3 (*1*). The resulting cavity is approximately 55 feet in radius. Peak pressure and peak velocity have been calculated (*2*).

Stephens (*3*) reported a sluggish transition in the preshot anhydrite separated from the halite of the Tatum Dome beginning at 19.5 ± 0.5 kbar and ending at 34 kbar. The volume change was reported to be about 4 percent. Under the pressure regime generated by the nuclear explosive, one would expect the anhydrite to have un-

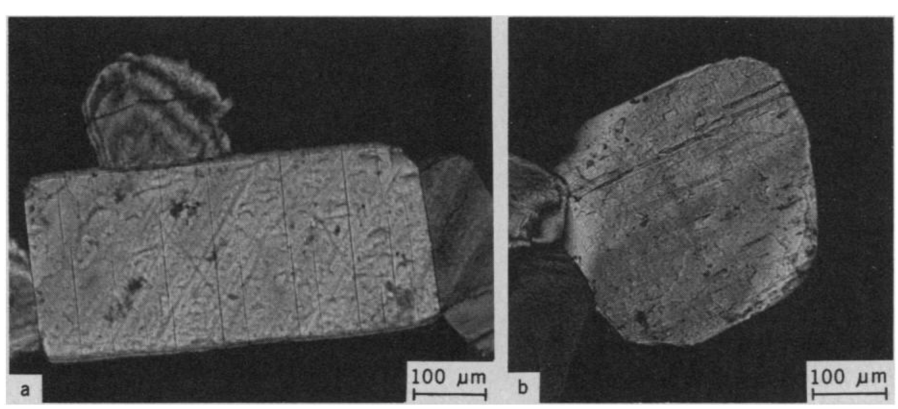

Fig. 1. Typical anhydrite grains in the Tatum Salt Dome; depth, 2726 feet. Crossed Nicols.