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OBSERVATIONS BY HUMAN SUBJECTS ON RADIATION-INDUCED LIGHT FLASHES IN FAST-NEUTRON, X-RAY, AND POSITIVE-PION BEAMS[*]

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In order to examine the hypothesis that light flashes seen by astronauts on lunar missions are the result of primary cosmic particles, two human subjects were exposed to a fast neutron beam (20 MeV to 640 MeV) at the Berkeley 184-inch cyclotron. Both subjects saw 25 to 50 discrete pinpoint bright momentary light flashes in response to a flux of 10^4 neutrons $cm^{-2} sec^{-1}$ (1 mrem dose). The star-like phosphene phenomenon in the neutron exposure is different from x ray induced radiophosphenes and from electrically produced visual flashes. No visual phenomenon was noted on positive pi meson exposure at 200 neutrons $cm^{-2} sec^{-1}$. We believe that bright flashes seen by astronauts are from primary cosmic particles traversing the retina. The mechanism is probably ionization, although light from Cerenkov effect has not been ruled out.

During the space flights of 1969 that carried man to his first lunar landings, Edwin Aldrin and other astronauts on Apollo 11, 12, and 13 observed a series of light flashes and streaks when they were in darkness at great distances from the earth.[1] It has been known for many years that relatively low doses of x rays impinging on the retina can cause light sensation and alteration of light sensitivity threshold;[2] however, the astronauts' descriptions of discrete flashes and streaks do not conform to the homogeneous flood of light characteristic of x-ray phosphenes.

During surveys of the radiobiological hazards of high-altitude flight and manned space exploration, one of us suggested that heavy cosmic ray particles might cause light sensations (" ... it would seem that a dark adapted person should be able to 'see' very heavily ionizing single tracks as a small light flash, since they would pass through several retinal receptors, enough to correspond to a visual object of greater than 1' angular aperture. If a track travels within the plane of the retina, several rods and cones may be inactivated ... ").[3,4] Although these suggestions were made in 1952 and 1958, it was not until after light flashes were seen by the astronauts that definitive experiments were commenced to elucidate the mechanism of the phenomenon and the validity of the above hypothesis.

It is possible that these flashes were due to ionization or some other form of interaction of primary cosmic particles with tissues. The streaks might be principally due to heavy primaries, and double points could be accounted for by one cosmic particle intersecting the retina at two points. Energy transferred to tissue by these particles is proportional to the square of their atomic number, and it also depends on their velocity ($\approx 1/v^2$). It is important for the safety of long interplanetary flights to understand such effects and the potential hazard they may cause. Further, knowledge about induction of light sensation by charged particles may also lead to a better understanding of the process of vision.

Other studies that bear on these effects include cosmic μ meson interactions, ionization from low energy protons, and the Cerenkov effect. On the basis of statistical analysis of coincidences in cosmic-ray counts and light sensations reported by subjects, μ mesons have been reported to cause light sensations.[5] According to a recent report, proton recoils from 3-MeV neutrons impinging on the human head during activation analysis can cause light flashes in the dark-adapted eye.[6] A suggestion was made by G. Fazio et al.[7] that the phenomenon observed in space may be due to light from the Cerenkov effect that accompanies fast particles.

In order to learn more about light sensation induced by fast atomic particles, we have made an initial exploration of visual phosphene phenomena due to a beam of fast neutrons at the Berkeley 184-inch cyclotron.[8] Subsequently, the tests were expanded to π^+ mesons from the Bevatron.

Very fast neutrons lose energy by elastic and nonelastic collisions with nuclei. These result in heavy ionizing nuclear recoils and in high speed nuclear spallation fragments. Although the range of these fragments is much less than that for primary cosmic ray particles, they might be able to cause qualitatively similar biological effects.

METHODS

Fast Neutron Exposure

A 0.64-GeV proton beam impinged on a 12-cm-thick beryllium target. Fast neutrons were collimated and channeled by a set of iron and lead apertures of total thickness of about 2 meters, shown in Fig. 1. Charged particles are either deflected away or absorbed by this arrangement, and the resulting beam consisted mainly of high energy neutrons in the domain of 20 to 640 MeV. The majority of the neutrons had energies near 300 MeV. These neutrons form a narrow, slowly diverging beam that emerges into a shielded room usually used for meson studies. Polaroid photographic paper was used with calcium tungstate intensifier to localize the beam and to monitor the overall exposures. The beam size was 6.5 by 5.2 cm.

Measurement of the neutron flux density for neutrons greater than 20 MeV in the beam was carried out by use of a plastic scintillator (4 in. diam, 1 in. thick), following prealignment of the beam and determination of its size. This previously calibrated instrument utilizes the production of radioactive ^{11}C by the (n, 2n) reaction from carbon by neutrons faster than 20 MeV for which the cross section is known as function of energy.[9] The scintillations are counted for ^{11}C decay immediately after neutron beam exposure. It yielded a maximum intensity of 1.04×10^6 neutrons cm^{-2} sec^{-1} when the primary proton beam intensity was maximized. The plastic scintillator was used to calibrate the beam monitor, which is a large scintillating crystal counter placed in the neutron beam downstream from the experiments. This monitor was used to lower the neutron-beam flux density by a factor of approximately 100; a level near 10^4 neutrons cm^{-2} sec^{-1} was used for the exposure of the subjects.

The ratio of slow to fast neutrons was measured by activated indium foils.

In addition, a tissue-equivalent liquid, simulating the human body in composition and shape, was also exposed to the neutron beam at high level (1.04×10^6 neutrons cm^{-2} sec^{-1}). By converting the ^{11}C counts obtained to dose in rem units, we obtained agreement within a factor of 2 with the plastic scintillator data. The conversion factor of 5.5×10^{-8} rem/neutron cm^2 was assumed. A separate determination of dose was made in a wood phantom having approximately the geometry of the head. Landsverk pocket electrometers (L-50) were used (full-scale deflection, 200 milliroentgens).

The subjects were dark-adapted by wearing a combination of green sunglasses and red x-ray dark-adapting glasses for more than 2 hours prior to exposure. During the last 15 minutes all light was excluded by a black hood which covered the entire head and neck region. This procedure is considered more than adequate for the usual dark adaptation and visual threshold experiments. The hood had four layers of black cloth. Both individuals wore film dosimeters near their eyes on both sides of their head for the duration of the tests. The subjects were exposed to the beam while in the dark-adapted state.

Two different geometries were used for the exposures. These are shown, schematically, in Fig. 2. In setup A, the beam was allowed to go through both eyes; the subject was facing perpendicular to the beam. It was believed that more streaks might be observed in this position, and that there would be a greater chance for more than one retinal rod, or cone, to be penetrated by the same nuclear recoil. The spallation recoils would tend to move forward and more tangential to the retina than in setup B, where one eye of the subject was exposed, facing the beam. In setup B, a single particle might affect fewer rods than with laterally directed beams.

DESCRIPTION OF EXPERIMENT

Dose

A flux density of 1.4×10^4 fast neutrons $cm^{-2} sec^{-1}$ was used and continuously monitored throughout the tests. The dose rate was measured by three independent techniques. Electrometer-type dosimeters at a position of the eyes in a phantom gave a dose rate of 0.1 mR/sec during a separate long exposure. There was a buildup of the dose in the phantom by a factor of two (compared with free air dose). The dose rate from the neutron flux measurements was calculated in rems by using the conversion factor of 5.5×10^{-8} rem/neutron. This calculated dose rate was 1.25 mrem/sec. The indium foil detectors yielded a dose rate of 0.78 mrem/sec. All three types of dose determinations are thus in reasonable agreement, if we assume a quality factor of 8 to 12.5.

The dose from slow neutrons was previously determined by the Health Physics Division, at the particular site, to be less than 2% of the fast neutron dose. Gamma rays from the beam cause less than a few percent of the dose.

The total dose received by both subjects together for the neutron experiment was less than 1 mR by pocket ion chamber determination. By the flux calculation method, CT received 8.5 mrem and TB 2.6 mrem. These doses in the beam path were less than the dose received in the chest in a routine diagnostic chest x-ray under the lowest dose conditions, and far below the permissible weekly exposures. Standard film badge dosimeters worn near the eyes of the subjects showed no measurable exposure. This confirms that the dose was low and that there was negligible x-ray or thermal neutron exposure.

Summary of Observations

When the beam was "on" both subjects experienced clusters of star-like flashes over their entire visual field. This phenomenon was never experienced by the subjects previously or during the waiting period, and it disappeared promptly, in a fraction of a second, when the beam was turned off.

DETAILED PROTOCOLS ARE AS FOLLOWS:

Subject # 1 (CT), June 19, 1970

Time: (hour) 1335 Sunglasses and red dark-adaptation goggles applied. A staging area for the neutron beam was prepared. The beam was centered in a 8-cm-diam metal pipe that was used as a positioning landmark for head alignment relative to the beam. The intensity was adjusted to 1.4×10^4 neutrons cm^{-2} sec^{-1}.

1613 Subject was enclosed in black cloth hood over goggles and sunglasses.

1630 The dark-adapted subject made observations of his pattern of visual sensations prior to exposure to any beam. With open or closed eyes he saw a very dark grey background with exceedingly faint blue-green light formations in slowly changing pattern. No light flashes or other rapidly changing light phenomena were seen.

1640 After 27 minutes under the black hood and more than 2 hours under dark-adaptation goggles, CT was positioned for exposure under a protocol that called for several small bursts of beam up to 200 seconds if necessary (maximum dose to be less than 10 millirads). Actually much less beam time was necessary to demonstrate the unequivocal effects. Subject was positioned in Position A (Fig. 2) for lateral passage of the neutron beam through both eyes.

First Exposure:

The beam was turned on for 1 sec and CT saw three or four star-like flashes. He had difficulty describing precisely the duration and color.

1645

Second Exposure:

The next exposure was for approximately 3 sec at 1.4×10^4 neutrons/sec. Unknown to the subject, but after the head was centered and all were ready, the beam was turned on. The subject immediately exclaimed that he saw flashes. The beam was left on for 3 sec, during which time the subject saw a cluster of small scintillations similar to luminous balls seen in fireworks with the initial tails fuzzy and the heads like tiny stars. His subsequent description and diagrams showed these to be comma-shaped (see Fig. 3). More of these were seen in the peripheral than in the central fields of vision. They had subjectively brief lifetimes, and extinguished completely. Attempts to "focus" the eyes on them were futile but several different shapes and intensities seemed to be present. Perhaps these attempts to "look at" the scintillations resulted in the appearance of the comet-like tails. The total number in the visual field at any given time was 25 to 50. The luminous dots were about as bright as the average stars in the sky, and while the subject was visualizing them, the background seemed to have turned very black. The color of the scintillations seemed white, with possibly on occasional color tinge on a few, as one sees on the star Betelgeuse.

1650

Third Exposure:

Subject was shifted to Position B, facing the beam path in such a way that the neutrons went through his left eye. The right eye remained unexposed. He saw flashes at both 1-sec and 3.5-sec exposures. They seemed somewhat harder to detect in this position than laterally and gave a dynamic picture of change, somewhat like a blinking, star-filled sky, or small tracks in a continuously expanding cloud chamber, with greatly accelerated sequences. The tests on CT were terminated after a total exposure time of about 9 sec.

The appearance of the visual field returned to normal in the immediate postexposure period. There were no other subsequent sensations or sequelae from this exposure. For all exposures knowledge that the beam was "on" came from visualizing flashes. This phenomenon was markedly different from any phenomena ever seen by the subject in the dark.

Subject #2(TB)

Time: 1315 Sunglasses and red dark-adaptation goggles were applied.
(hour)

1700
Fourth Exposure:

Subject was enclosed in a dark hood, having been wearing the red goggles and dark glasses for more than 2 hours. After 10 minutes of adaptation, his right eye was positioned in the beam (Fig. 2B), and a 3-sec exposure was given (Position B). Subject was not informed when the beam was turned on, and there were no audible cues to the best of our knowledge. The first thing the subject noted was a pin-like whitish-grey light in the mid-nasal field. His thoughts were that this represented a very weak reaction, if this was when the beam was turned on. Shortly thereafter, approximately a second and perhaps less, he noticed a splash of minute pin-like lights which he described as stars, white-blue in color, coming at him. There appeared to be approximately 50 in a total field, with most of them in the lower left, relative to the right eye. There were 5 to 10 in the upper right. The field seemed to be diffusely covered. There was nothing particularly noted in the center of the right visual field other than, perhaps, a paucity of these "sparks." The subject expected to see electrical phosphene-like phenomena with diffuse streaks or crescents, but these well-known phenomena were not observed. The subject noted two waves as if the beam had been modulated. The attached diagram shows what the subject saw (Fig. 4).

Subject TB queries whether there was a slow rise time for the beam, and that the initial point that he saw, approximately 1 sec before he exclaimed, was indeed due to a much lower intensity, by even an order of magnitude.

Summary

Both experimenters saw a number of pinpoint flashes while the neutron beam was on. Their descriptions were very similar. Each experienced light flashes intimately correlated with exposure to the beam. There appears to be some lag (less than 1 sec) in recognizing the flashes after the beam is switched on. Cessation of the flashes appears to be easier to detect.

POSITIVE PION BEAM EXPOSURE

To explore the possibility of Cerenkov radiation as the basic light-producing phenomenon from recoil protons in the above neutron experiment or from heavy charged primaries, a preliminary experiment was done with positive pions. Assuming the same interaction cross section for pions as for the previous neutron exposure, approximately one event per sec should be seen during a pion exposure with an incident flux of 200 particles $cm^{-2}sec^{-1}$. Exposures were done at the Berkeley Bevatron with 1.5-BeV/c momentum π^+ mesons. The dose and intensity measurements were based on total counts from the scintillator beam monitors. The maximum exposure was for 6 sec at 200 pions $cm^{-2}sec^{-1}$, with a total dose to the head of 0.2 mrem. The beam was free of protons and other particles. The series of three exposures is shown in Table I. The subject, TB, was dark-adapted for more than 1 hour.

Table I. Pion exposures

Intensity	Configuration	Result
< 1 pion $cm^{-2}sec^{-1}$	Whole body off beam axis	No visual phenomenon
2 pions $cm^{-2}sec^{-1}$	Head in beam line, beam plug in	No visual phenomenon
200 pions $cm^{-2}sec^{-1}$	Head in beam	No visual phenomenon

Summary of Pion Exposure:

The dark-adapted subject noted no visual phenomena during or after exposures. As the whole head was bathed in a pion beam of 200 particles $cm^{-2}sec^{-1}$, each eye received 800 to 1000 particles for a total exposure of about 5000 particles through each retina. Any interactions or Cerenkov light which occurred in the eye were not detected by the subject.

VISUAL OBSERVATIONS AT HIGH ALTITUDE

The same subjects flew repeatedly in commercial airplanes at 10 000 meters (33 000 feet) altitude and in one flight over the Atlantic at geomagnetic latitude 60° N. The cosmic ray particles are more numerous than at ground level by an approximate factor of 60. Subjects dark adapted for periods of 30 min, and, observing for 20 to 30 additional minutes, have not seen any of the star-like phenomena similar to those observed in the neutron beam.

X-RAY PHOSPHENE INDUCTION EXPERIMENTS

A Phillips 250-kV therapeutic x-ray machine was used. The experimental arrangement shown in Fig. 5 was similar to that used with neutrons. A horizontal x-ray beam of about 5 cm diam was produced at the dark-adapted subject's eye level. Dark-adaptation procedures were similar to those described above. The subjects were otherwise protected by a plywood and lead body shield. The x-ray machine was operated at the lowest rated current (3 mA at 250 kV). A lead pinhole collimator and several absorbers were used to get the dose rate sufficiently low. The dose rate and total dose were measured by the same Landsverk electrometers as used in the neutron experiments. To reach the lowest dose rate, 0.05 mR/sec, we used a stack of absorbers as follows: Sn (0.06 mm), Cu (3.25 mm), Al (1.0 mm), Pb (1.5 mm), Fe (2.75 mm). The beam, as it emerged, had a half-value layer of 4 mm Cu. Table II summarizes all exposures and observations.

Summary of Low-Dose-Rate x-Ray Exposure

The subjects observed no events at all, during any of the exposures, that were similar to the copious star-like scintillations seen in the neutron exposures. Therefore, we conclude that x rays at a dose rate less than 1.25 mR/sec do not produce phosphenes.

To compare the characteristic of the x-ray phosphene to the neutron beam phosphenes, two subjects were exposed for 1/30 and

Table II. x-Ray exposures

Dose rate (mR/sec)	Time[a] (sec)	Filters out (see text)	Subject and results
0.05	10		TB, negative
0.40	10	Pb 1.5	TB, negative for stars
0.60	20	Pb 1.5, Al 1.0	TB, negative for stars
0.40	15	Pb 1.5	CT, negative for stars
1.25	10	Pb 1.5, Al 1.0 Cu 20	CT, negative for stars

[a] Note that shutter time of a few seconds keeps the dose rate for the first 2-3 sec lower than given in column 1.

1/60 sec at dose rates of 144 mR/sec and 72 mR/sec respectively. The x-rays produced by a Picker clinical x-ray machine set at 80 kVp and 100 mA produced visual sensations at less than 2 mrad absorbed dose but at an intensity much higher than that possible in the neutron exposure. The light sensation is a soft bluish-gray-white diffuse light across the visual field of both eyes, if both are exposed, that does not resemble the star-like scintillations seen in the neutron beam.

x-Ray phosphene characterization studies are being conducted by one of us (TB) and thus far indicate the threshold for absorbed dose is below 0.3 mrad at a dose rate of 24 mrad/sec. This is comparable to the reported threshold of 0.5 mrad dose at a comparable dose rate.[10] This is still 240 times the dose rate at which neutron effects were observed.

ELECTRICALLY INDUCED VISUAL SENSATIONS

Subjective sensations of light flashes can be generated in humans by means of 0.3 mA across the head with a rise time of about 100 msec.[11] Subjects CT and TB observed electrical phosphenes to note any similarities to x-ray or neutron-beam phosphenes. The electrical phosphene is a diffuse bluish-dull-white splash of light usually in the temporal field if one electrode is placed over the right forehead and the other behind the neck. This sensation is one of diffuse light filling more than 10% of the visual field (depending on degree of dark adaptation and electrical parameters), and differs from the discrete star-like flashes of the neutron exposure.

DISCUSSION

There are clearly two kinds of phenomena observed in the course of this research. The star-like flashes, produced in neutron beams of low fluence, differed markedly from the phosphenes seen from a short burst of x rays delivered at higher dose rate. These latter were rather similar to electrical phosphenes. We shall examine several alternative explanations in an effort to understand the processes that have led to the phenomenon, and to obtain guidance for future experiments. In the following we shall assume that the relevant interactions must occur in the eye, that is, in the retina or vitreous fluid. The validity of this assumption will be examined later.

Assumption 1: The neutron-induced flashes were due to recoils or spallation products:

These would come from nonelastic collisions with carbon, nitrogen, oxygen, phosphorus, sulfur, calcium, or other nuclei in tissue. The ranges of elastic recoils are very short for all these nuclei except hydrogen, whose recoils have considerable range for energies involved. The number of events, E, expected per second in one eye are:

$$E = \phi \cdot t \cdot a \sum_j N_j \sigma_j \cdot$$

According to our measurements, ϕ, the neutron flux density, was 1.4×10^4 cm^{-2} sec^{-1}.

The number, N_j, of nitrogen, oxygen, and carbon atoms per cm^3 was assumed to be that characteristic of tissue shown in Table III.

Table III.

	Percent in tissue[a]	No. of atoms per cm^3 tissue, N_j	Nonelastic scattering cross section, σ_t [b]
C	7.2	1.0×10^{22}	$0.28 \times 10^{-24} cm^2$
N	1.2	1.4×10^{21}	$0.39 \times 10^{-24} cm^2$
O	27.1	2.8×10^{22}	$0.44 \times 10^{-24} cm^2$
H	64	6.6×10^{22}	$0.05 \times 10^{-24} cm^2$ [c]

a. Heavier tissue constituents such as P, S, and Ca were neglected due to their low abundance.
b. Taken for this beam. The cross section is largest at about 20 MeV and declines with increasing energy.
c. Total cross section.

The effective area of the retina was assumed to be $a = 4\ cm^2$; t is the effective range of the recoils, that is, the effective distance away from the retina within which the nonelastic collision must occur if the recoiling particle is to reach the retina. We assume for this critical distance, $t = 500\ \mu$ or 0.05 cm. This assumption is equivalent to assuming that in the collisions at least one heavy recoil has several MeV/nucleon kinetic energy, otherwise it might not reach the retina. Since spallation occurs, this recoil is probably lighter than the nucleus hit. These assumptions yield the number of events, E, as about 43 per second per eye.

There were 25 to 50 events observed, or about the same as the actual heavy recoils expected. However, our calculation could be in error by a factor of 100. For example, in view of the fact that light-sensing cells, the rods and cones, are only a few μ in size, t might be less than 500 μ -- perhaps even as small as 10 microns. Also, it is possible that a heavy recoil can cross the retina without causing a visible event.

The assumption that high-LET, heavy nuclear fragments cause the events is in agreement with the fact that no flashes were observed with π^+ mesons or with low-intensity x rays.

Assumption 2: Ionization excitations from proton recoils produced in the vicinity of the retina by the primary neutrons cause the majority of flashes:

Protons are produced in elastic collisions, by charge exchange, or in nonelastic collisions with nuclei. Many of them move forward with considerable energy. Thus, a considerable thickness of the tissue around the retina may serve to generate these. If we assumed this thickness to be $t_p = 2$ cm, the number of "proton events" is

$$E_p = \phi \cdot t_p \cdot a \cdot \sigma_p \cdot N_p .$$

The fluence of proton recoils for each eye, 370 sec^{-1}, is about 10 times the neutron-flash observations estimated by both observers. It seems plausible that some of the protons would miss the rods or that some of the faster protons would not register a flash due to their low LET and low yield of Cerenkov quanta.[12] If an experiment is conducted with low-energy neutrons, the number of proton recoils will be considerably higher than estimated here.

Slow protons might be more effective than fast protons in producing scintillations. The idea that slow protons with their higher LET could cause light flashes, whereas fast protons could not, is in agreement with the fact that the fast π^+ did not produce flashes; these particles ionize like fast protons, moving with the same velocity.

Assumption 3: The light flashes observed originated from Cerenkov light:

Fazio et al. made a suggestion that light flashes observed by astronauts in space flight are Cerenkov radiations from cosmic ray particles,[7] and previously, D'Arcy and Porter[5] claimed to have seen light flashes in coincidence with fast μ mesons, possibly due to this effect. In a medium of refractive index 1.34 (the vitreous fluid), only protons with greater than 470 MeV kinetic energy could produce this effect; these would be a relatively small fraction of the 370 protons per second produced in the vitreous fluid by the neutron beam.

In view of the fact that 1.5-GeV π^+ mesons did not produce light flashes in the retina, we doubt Cerenkov effect from protons as the cause of scintillation in this experiment. Contrary to the statistical conclusions of D'Arcy and Porter, we have not been able to see any flashes at ground level or in a plane at 10 000 meters that could be attributable to cosmic ray mesons. We are also informed that a number of astronauts, who have flown orbital missions below the Van Allen radiation belt in near equitorial orbits, failed to observe such flashes.

We conclude that Cerenkov effect from fast particles of charge $Z = 1$ did not cause the observations in the neutron beam at ground level. It is quite possible, however, that Cerenkov light could contribute to phosphenes produced by very fast heavy nuclei, since the intensity of the light varies with Z^2. Thus, Cerenkov effects may have contributed to the observations of flashes and streaks by astronauts in space, away from the screening magnetic field of the earth. These observations would then stem from heavy ions, not from primary protons.

It is planned to use charged particles in future experiments at accelerators. It might be possible to distinguish the effects due to Cerenkov radiation from those due to ionization. The former would be important only at high particle energy (> 500 MeV), whereas the latter might be most effective at low particle energy and high atomic number.

Assumption 4: Production of a visible light flash requires deposition of a minimal ionization energy within a critical time interval and spatial domain:

There have been indications from earlier work by Lipetz[13] that a single electron passing through a retinal rod in isolated frog retina can produce measurable alterations in electrical responses of single fibers in the frog optic nerve. If single electrons or ionization events could produce light sensation, we would see frequent scintillation-like flashes (when dark adapted) due to cosmic ray ionizations in the retina.

The experiments reported in this paper with x rays clearly demonstrate that x rays at low dose rate, below 1.25 mR per second, do not produce visible flashes in a period of several seconds. On the other hand, at a considerably higher dose rate of 24 mR $\sec^{-1}$, a dose of 0.3 mR was sufficient to produce a generalized white flash over the entire visual domain. This phenomenon is dependent on the dose rate of x-ray quanta, whereas all observations point to the expected proportionality between the number of flashes observed and the total number of neutrons.

The retinal architecture and neurophysiology are not known in sufficient detail to explain all phenomena with certainty. We offer the following as a starting point for more elaborate experimental approaches. We know that neural integration has a time constant: Events in sensory elements must be nearly simultaneous to contribute to an image. The time constant is related to the flicker-fusion frequency, which for light sensation, is about 20 to 60 per second.

It is well known that the threshold for light reception in the dark-adapted eye is about five photons distributed over a small area.[14] Thus several rods must receive one photon each in less than about 50 msec in order for the subject to perceive light. These individual rods are synapsed to neutrons (bipolar and horizontal cells) in the region between photoreceptors (rods and cones) and ganglion cells in a highly complex manner. The output of the ganglion cell to the brain thus represents the spatial summation of inputs from a variable number of rods depending on the cluster of photon-rod interactions and some as yet unknown bipolar or horizontal cell modulation (or both).

they mean neurons

We believe that the discrete star-like events that we have seen result from discharge of 20 to 100 rods in a very small area of the retina. High-LET particles have associated dense ionization, and we believe that they can cause energy absorption leading to electrical signals in a number of neighboring rods they cross. It is possible that in a 10-μ-diam region of the eye as many as 20 rods (1.3 μ diam) are activated, giving the sensation of a pinpoint bright light.

Diffuse light perception such as experienced by electrical or x-ray phosphenes probably results from the integrated response of perhaps one in 10 000 rods. The ionization created by x rays is relatively evenly distributed across the retina. Local energy density is nowhere high, and the mechanisms for creating contrast are absent. Thus, it is reasonable to expect a "gray" or "white" flash over the whole visual field; and this is what was observed. There is a low probability of many ionizing events in a local area, as is the case for high-LET particles. Hence, one does not expect to see luminous "stars" from diffuse x radiation.

There is a contrast mechanism that favors visibility of high-LET particles. At the low intensity used in our experiments, the energy is concentrated in the densely ionizing tracks; there is considerable distance between particles. In the intervening space there is practically no ionization at all, providing a light-to-dark contrast between track core and surrounding region.

Further studies are in progress on the dose rate and dose relationship of x-ray-induced flashes. It is quite possible that these will contribute to our understanding of some of the mechanisms by which our visual system operates.

Location of the Primary Interaction Between Radiation and Tissue to Produce Flashes

The studies described here suggest that exposure of regions at or near the eye is responsible for appearance of visual flashes. In both types of exposures at least one eye was included in the radiation field. It has been known for some time that photosensitive receptors or muscle fibers in various species can be stimulated to produce action potential or contraction (or both) with a much smaller radiation dose, by several orders of magnitude, than nerves, receptors, or muscle fibers that are not sensitive to light stimulation.[15] However, in principle, any part of the nervous system that participates in handling of visual information, including the optic nerve and the cerebral cortex, could be a site of interaction for a visual signal. For example, the occipital lobe has been suggested as a possible stimulation site.[16] However, it has been shown that x-ray phosphenes are not produced by irradiation of the optic tract and visual cortex.[17] It is, of course, possible to direct small doses of fast particles or neutron irradiation to a preselected site, and definitive experiments using neutrons or heavy-particle-induced phosphenes are planned to explore the role played by the optic track or visual cortex.

Within the eye, the retina is prime candidate for the locus of interaction with radiation. The vitreous humor and iris, though they strongly fluoresce, appear to play only a minor role as a site of action for production of x-ray phosphenes.[18] Lipetz[13] has shown that visual purple can be bleached in vitro by a very high dose of x rays. On the other hand, a few secondary electrons in an x-ray beam, impinging on the retina, can alter neural responses in the frog optic nerve.

In man, it is more likely that rods are affected, rather than cones, as evidenced by the lack of specific color of the flashes. If the action of particles is due to ionization or excitation, then it seems likely that the particles must pass through the light-sensitive cells (e. g., rods) that they affect. As assumed earlier in the discussion, the particles may originate at points distant from the retina.

The Possibility of Aftereffect

We already know that a small dose of x rays administered to the retina effects retinal threshold for an appreciable period afterwards,[19] and this is also true for electrical effects on frog retina.[13] Most of such effects are believed to be reversible. An important aspect of future studies should be evaluation of such aftereffects following heavy-particle exposure.

Geometric Considerations

Exposure to a lateral beam of neutrons that passed through both eyes caused sensation of small luminous stars with tails (Fig. 3), quite similar to the appearance of short electron tracks in the continuously expanding cloud chamber. When the beam passed head-on into one eye only, the stars appeared to be better localized and had no tails (Fig. 4). Subjectively, it was impossible to tell whether the observations were made with one eye or both eyes.

The appearance of tracks in lateral view might signify the existence of "streaks" or tracks within the retina, with the older part of the track appearing fainter as it becomes extinct. However, it is also possible that the tails are optical illusions and are the result of an unsuccessful effort to focus the eyes on the origin of the light. This is illustrated in Fig. 5. Initially, when the subject's eyes are pointing forward, a flash at A on the retina may cause the illusion that there is a luminous source at point P external to the subject. The subject instinctively turns his eyes toward P; during these eye movements the location of the source appears to recede to P' as light sensation fades. The subject thus has the subjective sensation of seeing a luminous star and a track between P and P'.

Two different stars produced simultaneosuly by two independent particles, one in each eye, may create the illusion that both images originate from one point in space.

Biological Effects of Heavy Ions in Relation to Light Flashes

Evidence is accumulating to show that light flashes and streaks observed in spaceflight are indications of heavy primary cosmic rays crossing the eye and retina. The spectra and abundance of cosmic particles are only approximately known. The flux of nuclei in the iron group is about 160 cm^{-2} day in a 4π solid angle, whereas that of the C, N, O group is more than 10 times as great.[20] The critical problem concerns the biological effects of such particles as they cross the eye, the brain, and the spinal cord. We know that x rays at 2000 R dose can cause irreversible degeneration of the light-sensing cells of the retina and of the electroretinogram;[21] however, the damage might be reversible at 1000 R.[22] The minute ionizing core of heavy nuclei represents an energy exchange that corresponds to more than 10^8 rads in dose terms within a few angstroms of the core. If passage of such particles causes irreversible deterioration of retinal cells and of neurons, then in spaceflights of long duration (several months or more) outside the earth's magnetosphere a significant degree of random cellular damage may result.

The neuroradiobiology of fast heavy ions cannot be conveniently and safely studied in man; however, it can be approached in other mammalian systems and in neuronal and retinal explants and tissue culture. Because most of our radiobiological knowledge is oriented toward understanding proliferative cell systems, study of the effects on nondividing cells is difficult. New methods must be developed to assay the biological effects. Such studies can be most efficiently performed at heavy-ion accelerators, rather than in space, where the fluence of particles is low. Full understanding of these effects must also involve some degree of understanding of the process of information handling by the nervous system. Perhaps heavy-ion research can make some contributions toward this horizon.

SUMMARY AND CONCLUSIONS

1. When a high-energy neutron beam from the Berkeley 184-inch cyclotron was passed through the region of one or both eyes in two human subjects, both subjects observed many small, star-like light flashes.
2. The energy of the neutrons was greater than 20 MeV and less than 640 MeV, with maximum fluence around 300 MeV. At 1.4×10^4 neutrons $\sec^{-1} cm^{-2}$, about 25 to 50 star flashes were seen at any given time in the visual field, seemingly more at the periphery and fewer at the center. The dose rate was about 0.1 mR/sec, or about 1.25 mrem/sec. The beam was on for several seconds.
3. The same dark-adapted subjects observed no similar star-like flashes, over a period of 1 hour, when the beam was off. The subjects saw no such light flashes over 30- to 60-min periods in dark adaptation while flying in a plane at 10 000 meters at geomagnetic latitudes of 60° N and 40°N.
4. A beam of π^+ mesons at the Berkeley Bevatron (momentum 1.5 GeV/c, fluence 200 mesons $cm^{-2} sec^{-1}$) failed to produce any kind of visual effect in one of the subjects, exposed for a total of 6 sec.
5. A 250-kV x-ray beam failed to produce any kind of light sensations at dose rate up to 1.25 mR/sec. This dose rate is 12.5 times the neutron dose rate that produced the star-like light flashes. It appears that single x-ray quanta or single secondary electrons are not able to produce light sensation.
6. Light flashes (phosphenes) due to x-ray exposure are seen only when the dose rates are twenty or more times as high as in the above cited neutron exposures. However, the dose necessary to see an x-ray flash can be small. Such x-ray phosphenes are not localized; rather they flash across the whole visual field; they are of whitish-blue color. At a dose rate of 24 mR/sec, a dose of 0.3 mR can produce a flash.

7. Electrical phosphenes that can be produced by passing an electrical current though the retina are similar in timing and appearance to the x-ray phosphenes. Electrical stimulation of the visual apparatus does not result in star-like or pinpoint flashes.
8. It appears likely from the above observations that star-like flashes in high energy neutron fields are due to high-LET nuclear recoils (from spallation) when the neutrons interact with the nuclei of tissue. Since most

recoil nuclei travel too slowly to produce Cerenkov effect, the visual phenomena are more likely due to ionization or excitation.

9. The lack of observations of light in a π^+-meson beam would indicate that Cerenkov light from singly charged particles might be too weak to produce frequent light flashes. It is possible that Cerenkov light from multiply charged, fast nuclei, such as the particles of heavy primary cosmic rays, could produce an effect.

10. Since visual effects can be produced by exceedingly low doses of fast neutrons and of other radiations, well below the recognized permissible exposure limits, it appears feasible and safe to further explore the visual effects produced by fast, accelerated particles and to compare such effects observed at ground level with light flashes and streaks that have been observed by a number of astronauts in lunar flights. Of immediate interest are (a) the location of regions in the eye and brain that respond to particles by producing light sensation, (b) the LET (linear energy transfer) charge and velocity of particles that cause these effects, (c) the effects of small radiation doses on the responses of the eye to light stimuli, and (d) reversible and irreversible sequelae of particle exposure and high energy proton irradiation on man's vision.

11. Since the star-like light flashes observed in space and at accelerators appear to be caused by high-LET particles, these findings call attention to the necessity of studying the biological effects of such particles, particularly in tissues with nondividing cells, such as brain and retina. In interplanetary space, astronauts are exposed to an incessant stream of heavy particles. The biological effects of such particles should be carefully evaluated before long-term, manned spaceflight in interplanetary space or to the planets.

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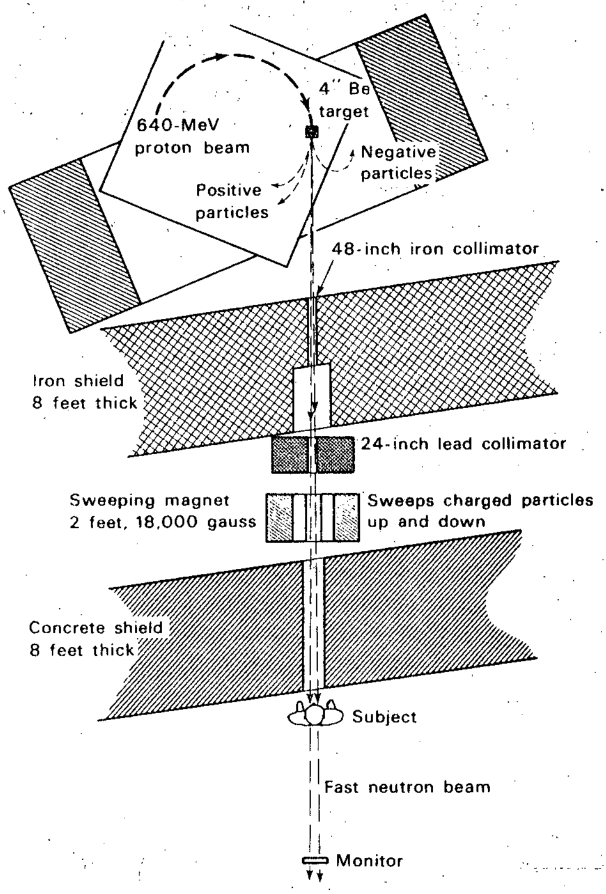

Fig. 1. Configuration used at the 184-inch cyclotron for fast neutron exposures in the region of the human eye. DBL 708-5870

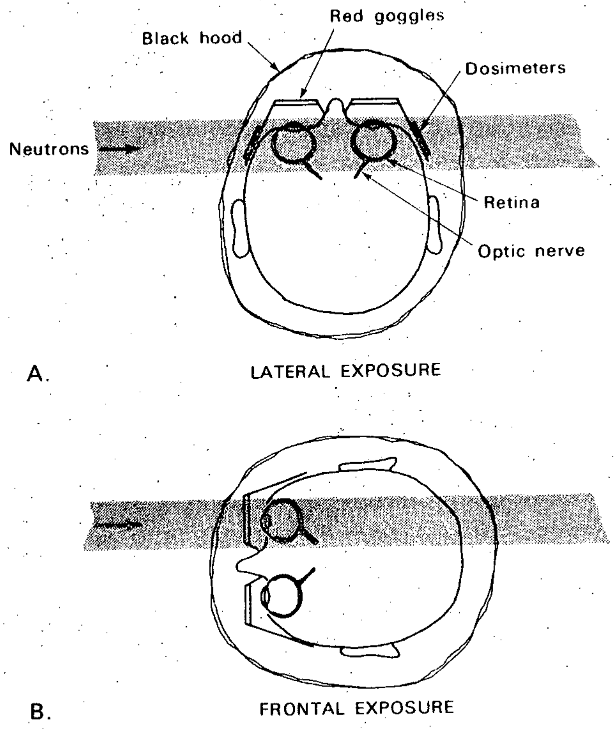

Fig. 2. Subject head positions relative to the fast neutron beam. DBL 708-5869

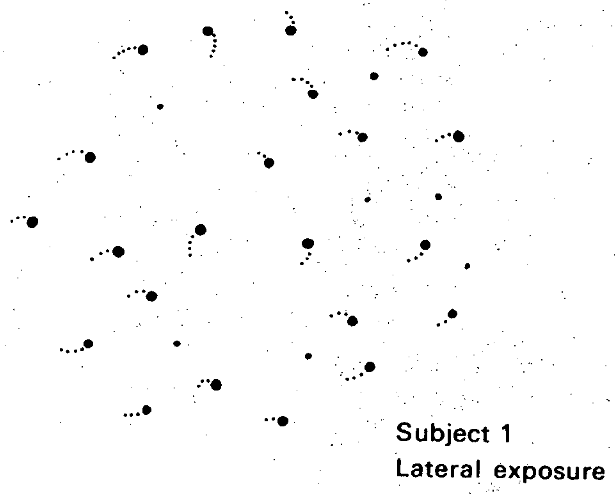

Fig. 3. Subject's representation of the relative size, shape and abundance of white flashes represented by black dots. Lateral exposure is position A of Fig. 2.

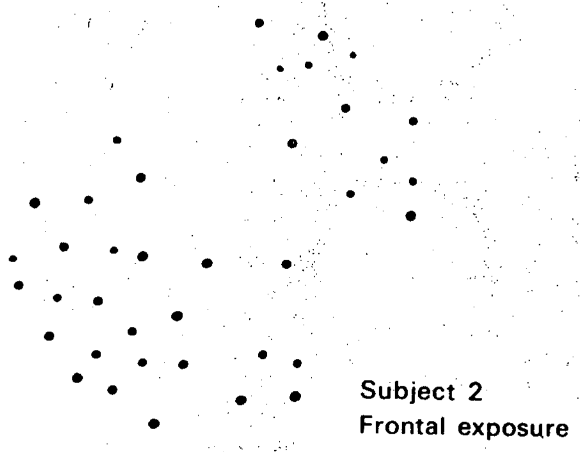

Fig. 4. Subject's representation of flash phenomenon seen on exposure in position B of Fig. 2. DBL 708-5868

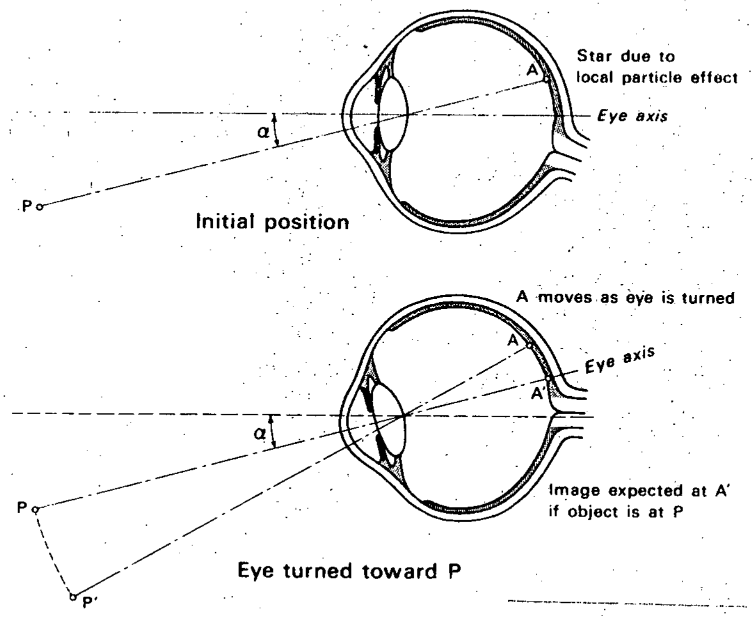

Fig. 5. An explanation of comma shaped flashes shown in Fig. 3. (See text for details.) DBL 708-5871

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