Title

BIOLOGICAL EFFECTS DUE TO SINGLE ACCELERATED HEAVY PARTICLES AND THE PROBLEMS OF NERVOUS SYSTEM EXPOSURE IN SPACE

Permalink

https://escholarship.org/uc/item/0t1652rs

Authors

Tobias, Cornelius A.
Budinger, Thomas F.
Lyman, John T.

Publication Date

1972-07-01

Talk presented at COSPAR Conference
Madrid, Spain, May 10-24, 1972

LBL-1011
c.1

BIOLOGICAL EFFECTS DUE TO SINGLE ACCELERATED HEAVY PARTICLES AND THE PROBLEMS OF NERVOUS SYSTEM EXPOSURE IN SPACE

Cornelius A. Tobias, Thomas F. Budinger
John T. Lyman
DONNER LABORATORY

July 1972

AEC Contract No. W-7405-eng-48

Biological Effects Due to Single Accelerated Heavy Particles and the Problems of Nervous System Exposure in Space.

Cornelius A. Tobias
Thomas F. Budinger
John T. Lyman
Donner Laboratory
University of California
Berkeley, California

During the historic flight of Apollo 11, astronauts Neil Armstrong, Edwin Aldrin and Michael Collins experienced sensations of streaks and flashes of light at occasions when the interior of their spaceship was in darkness. These visual phenomena were experienced on several subsequent lunar space flights, including Apollo 15, so that we are now in possession of fairly detailed information on light flash phenomena in space.

In the astronauts' own terminology, several types of events are seen. We attempt to reproduce these in Figure 1. The events are:

"Flash": Very brief, white star-like events, sometimes with short luminous tails.

"Streak": Brief, luminous, usually straight line of light, sometimes giving a sense of rapid motion and of direction.

"Double event": Interrupted streak.

"Supernova" (a term coined by the astronauts): Bright flash, surrounded by halo and minor flashes.

"Luminous cloud": Impression of light behind a cloud formation.

None of these light flash events was sighted by American astronauts in near equatorial orbits below the radiation belt. The events were usually seen at distances of 50,000 kilometers or more from the earth; in addition, Apollo 15 astronauts reported observing these phenomena while on the surface of the moon.

In several cases, dark adaptation of about 10 minutes was required before the light flashes were noted at irregular intervals. The events could be seen with open or closed eyes. Although there was no objective method of determining the location of light flashes, they were occasionally reported as being in a specific eye. In one instance, two astronauts in the same spaceship reported a "coincident" flash (i.e., simultaneous visual sensation in both men).

Some quantitative data on the time occurrence of light flashes were collected on Apollo 14. Scientist/astronaut Philip Chapman and physicist Larry Pinsky (1) analyzed these, and the results are shown in Figure 2. His time interval histogram shown here agrees with the statistical Poission process which gives a mean time interval of 38.7 seconds (for three astronauts).

After evaluating these observations, uncertainty exists as to the cause of the light flash observations in space. Many events are known that can cause luminous phosphenes. These include ionizing radiation, mechanical trauma, electrical currents, magnetic fields, stimulation of the cerebral cortex, and pathological situations. For example, flashes can be seen during stages of retinal detachment of unknown etiology and during the healing process following cataract surgery. Electrical currents, magnetic fields and mechnical trauma have been excluded as candidates because of their absence and the fact that they induce visual phenomena different from those seen by the majority of astronauts.

Wilhelm Roentgen reported in 1897, shortly after the initial discovery of x rays, that flashes could be seen by the unaided eye as diffuse light (2). For visible light, Selig Hecht and others have shown that, at threshold levels, more than one visual receptor cell in the retina must be activated in order to observe a local light event (3). Considering this information and pondering the possible effects that heavy cosmic ray primary particles might have on nervous tissue, it was predicted in 1952 (4) that these particles might produce the sensation of light streaks. Thus, it seemed worthwhile to test the effects of known fast particles on man in an effort to determine the precise origin of visual observations in lunar flights, and to learn about possible consequences of such phenomena on astronaut health and performance.

If radiation causes the light flashes observed in space flight, it is important to determine the site of the action in the body. Is it at the retina, in the vitreous fluid, in the lens, or in the optic nerve? Perhaps neural cells in the cortex of the occipital lobes are affected? It may be of interest also to study what type of visual effects different types of radiations might cause: are there special radiations that can cause streaks, while other kinds of radiations perhaps cause different effects? Next, it is of fundamental interest to know how ionizing radiations can cause light sensations. There are several possible approaches to this problem: first, it seems possible that ionization events themselves lead to light sensations. One third of the energy transferred goes into excited energy levels. Also, during recombination and deexcitation, light, ultraviolet and soft x rays are emitted. Fluorescence of the vitreous fluid has already been studied by R. Newell and W. Borley (8). Fluorescence in the eye lens due to alpha particles has been experimentally demonstrated by I. R. McAulay (9). Lipetz has already shown (5) that x-ray ionization causes electrical signals in frog retina in a similar manner as produced by light.

Another mechanism has been proposed by Fazio _et al_ (6), who believe that it is the Cerenkov light emitted by relativistic particles that causes the events observed in space. If Cerenkov light were the _only_ mechanism by which fast charged particles could cause visual effects, then one would not expect to obtain light flashes from slow particles. Richard Madey and P. J. McNulty (7) proposed another theory according to which "virtual quanta", a concept used in energy transfer calculations, might be the cause of visual sensations.

A number of experiments have now been carried out in various laboratories to clarify these concepts. For sake of brevity, we shall discuss these in three groups: a) _heavily ionizing nonrelativistic particles_; b) _particles moving with relativistic velocities_; and c) _x rays_.

Light sensations from heavily ionizing nonrelativistic particles.

All human exposures carried out in our laboratory were performed with mature scientists familiar with the physics of radiation and its biological effects, except for five patients who gave observations during diagnostic exposures. The exposures were authorized in each case by a medical committee, allowing limited exposure to a prescribed number of particles. This prescribed number was much lower than particle fluxes received by astronauts in lunar flights. Exposures were made to fast neutrons in the 300-600MeV energy domain at an exposure rate of $10^4 sec^{-1} cm^{-2}$. Neutron exposures at energy domains of less than 25 MeV were made in experiments at the University of Washington Cyclotron. Additionally, fission neutrons from ^{252}Cf were separately tested. Direct exposures to fast charged particles included experiments with the helium ion beam at the 184" cyclotron and with accelerated nitrogen particles of 3.9 BeV energy at the Bevatron (10) (11) (12) (13) (14) (15). Beams of neutrons, helium ions, and nitrogen ions caused visible light flashes, with the exception of fission neutrons from ^{252}Cf at an intensity of about 10^{-5} neutron $sec^{-1} cm^{-2}$.

In 1970, Fremlin reported on his observations of occasional light flashes in neutron beams (16). The high energy neutron beams from the 184" cyclotron (Berkeley) and the 60" cyclotron (Seattle), at an intensity of 10^4 neutron $sec^{-1} cm^{-2}$, produced many bright star-like flashes when the neutrons were directed to one eye from the anterior-posterior (A-P) direction. When the neutron beam was directed laterally through both eyes, flashes with weak tails were seen at both cyclotrons. Neutron beams of 0-25 MeV kinetic energy at the University of Washington cyclotron produced stars as well as short streaks in five subjects (11).

The method of exposure to the helium ion beam is shown in Figure 3. The dark adapted subjects wore individual black face masks; these could be positioned in the collimated beam with precision by methods used for local helium ion radiation therapy of cancer patients (12). The beam flux density was decreased from the usual level of 10^8 sec^{-1} cm^{-2} to about one sec^{-1} cm^{-2}. Each individual particle that passed through the collimator (diameter 0.4cm) was counted and tested by means of a scintillator coincidence arrangement. Subsequently the 910 MeV beam was moderated by interposing absorbers so that the energy was about 250 MeV at the point of entry into the body. This was further modified during the experiment by absorbers. Entry time for each individual particle was recorded along with response of the subjects.

Exposure to nitrogen ions was made possible by the successful acceleration of these particles in August 1971 (17) (18). Figure 4 shows the Bragg ionization curve in water. Since heavy particles ionize in proportion to the square of their atomic number, Z^2 , the ionization of these particles was 49 times that of protons moving with similar velocities. About 25-50 nitrogen particles were delivered in brief bursts. For the light flash experiments, the nitrogen beam was collimated to pass through a collimator of 0.6 cm. diameter. By means of interposed absorbers the beam energy was decreased so that the Bragg ionization peak was in or near the retina. The interposed absorber produced about 20% secondary particles of lower Z. The first experiment with the nitrogen beam is shown in Figure 5.

Figure 6 indicates three beam positions at which a number of observations were attempted. The helium beam produced mixed fields of stars and short straight streaks when the beam was passed laterally through the eye near the center of the retina. The nitrogen beam at the same position produced subjectively more intense streaks parallel with the beam direction. The appearance of some of these is shown in Figure 7. Interrupted streaks were seen also with the nitrogen beam. There were some intense events produced by the helium as well as nitrogen beam that might correspond to the "supernova" observed by astronauts in flight. "Luminous clouds" were not reported by subjects exposed to individual particles.

When helium particles were allowed to laterally cross the central region of the retina at random intervals, the efficiency of observing them as light flashes was a function of their flux density. At low intensities, when particles entered about once per second, only about 4% of the particles were identified as light flashes. Maximum detection efficiency was reached at an average rate of 10 per second, when the subjects discerned about four events per second. At higher rates so many events were present in the visual field that it was not practical to identify individual events. When a particle beam of 100 particles per second was turned on for one second only (to minimize the dose), the subject's detection efficiency of individual particles was poor, perhaps due to a fusion of simultaneous small flashes. At very low particle flux densities, an attempt was made to enhance the possiblilities for recognition by allowing each subject to trigger a sound click. At a particle entry rate of 3-4 per minute, this did not help. The sound clicks arrived somewhat later than the particle stimulus, due to the time taken for amplification. The sound probably suppressed the ability to observe light produced by individual particles. This type of suppression is well known in ophthalmology. If two stimuli follow each other in time, the more intense stimulus can suppress the weaker one (19), even if the weak stimulus takes place first.

Additional observations relate to the time delay encountered in recognising local flashes when the observer was in a dark adapted state. At a flux density level of 10 particles sec^{-1} cm^{-2}, there was a $\frac{1}{2}$ to 2 second delay before the observer recognised that the beam was "on" and a few seconds before the "steady state" detection efficiency was reach, at which he could also discern subjective shapes in the various light flashes in his visual field. Such time delays in cognitive organisation, particularly if the visual event was not in the central field of vision, have been studied by Sanders (20) who states that, "after arrival of new information a certain period of time is devoted to 'expectancy formulation.' This period will be dependent on the number of signal sources and probably on the amount of information that is provided by each of them." The expectancy formulation in Sander's study is 200 to 300 msec.

As to the detection efficiency of individual light flashes and its dependence on the flux density of flash-inducing events, similar data have been obtained for light-induced flashes by various investigators. Kelly (21) has pointed out that modulation transfer in the human eye depends on spatial as well as temporal components which should be analyzed separately. Van Nes, Bouman and co-workers (22) have analyzed the threshold for perception as a function of temporal and spatial components for light stimuli. They come to the conclusion that, when temporal frequencies are low, (less than 1 per sec), detection efficiency of intensity modulation is also low. They also showed that optimal efficiency reaches a plateau at temporal frequencies of 10-20 cycles per second, a frequency which fits with our observations.

When the helium ion beam stopped in the right side of the left eye, stars and streaks were reported by the observer as being in the left visual field. In this case, the helium ions passed through the left side of the eye with higher kinetic energies (about 200 MeV) and small linear energy transfer (about 5 keV/μm) than the same particles at the right side of the left eye, where they had kinetic energies of zero to 80 MeV and linear energy transfers greater than 10 keV/μm. We concluded that events were seen at linear energy transfers greater than 10 keV/μm but were not seen at about 5 keV/μm. When this kind of experiment was performed with the nitrogen beam, interrupted streaks were seen when particles passed through both sides of the left eye. The linear energy transfers of the nitrogen particles were 30 keV/μm or greater in all experiments.

From observations of this type and from the length of neutron-induced streaks, it was concluded that particles should have linear transfers greater than about 10 keV/μm in order to be reported as definite streaks or flashes. This statement is made with the understanding that, with careful dark adaptation procedures, experienced subjects might in the future be able to determine a lower energy transfer limit more precisely.

Applying these observations to cosmic rays, it would appear that most of the fast protons and helium ions in primary cosmic rays in space would not produce a visible flash; only those that have low residual range (enders) would have this effect.

Many of the cosmic ray carbon, nitrogen, and oxygen nuclei of any energy could initiate a flash however. It is possible that efficiency in reporting these in space flight, when spaced several seconds apart in time, is quite low.

When the beams were passed through the anterior part of the eye, or through the optic nerve but missing central portions of the retina, no flashes were seen. Thus, particles should pass through light-sensitive portions of the retina or its immediate vicinity in order to produce visual events. This observation makes it less likely that fluorescence in the eye lens, as reported by McAulay (9), is the cause of the events observed in space flight.

About 2000 accelerated particles were stopped in the left occipital lobe of one dark-adapted subject at the rate of 20-50 per second, and no flash events were seen. However, Brindley and Lewin have elicited light sensation by regular electrical stimulation at the occipital pole of the right cerebral hemisphere in a blind subject (23). Earlier works by Penfield (24) and others are well known. Using rats and small intense beams of helium ions, we have been able to stimulate the motor cortex directly (25). Thus, it will be of interest to carry out further work with heavy ion beams directed at the cerebral cortex with the possibility of eliciting light sensation. Accelerated heavy particles might also prove to be useful in the future, both in diagnostic studies and in studies exploring visual and neural mechanisms.

Light sensation from relativistic particles

Relativistic particles may be able to produce light flash events through three mechanisms: by energy transfer in the ionization track, by light from Cerenkov irradiation, and by fluorescence induced in some part of the eye. In a transparent dense medium of refractive index, n, such as the vitreous fluid of the eye, particles must move with velocities, v, greater than $v = \frac{c}{n}$ in order to produce Cerenkov light. The minimum energy required to produce this effect in the human eye is about 430 MeV per nucleon. Ten years ago, D'Arcy and Porter concluded from statistical arguments that light flashes are perceived by the eye in coincidence with cosmic ray mu mesons passing through it (26). Recently, at the Brookhaven synchrotron, P.J. McNulty observed visual effects in the form of a bright diffused flash produced by a beam of relativistic muons when the beam consisted of pulses of about 3×10^3 muons at a rate of one pulse every two seconds (27). These events were not discrete events, thus not similar to the astronauts' observations of single events. In Donner Laboratory at Berkeley, T.F. Budinger did not see relativistic positive Pi mesons at an intensity about five times lower than this (10). Quite recently, McNulty also reported on visual sensations produced by a relativistic nitrogen beam (530 MeV/nucleon) at the Princeton accelerator (28).

It can be concluded then that relativistic particles passing through the eye do cause light sensations. The role of the Cerenkov effect still needs further investigation, however. It is possible that Cerenkov photons formed in the lens and vitreous fluid produce the diffuse effect referred to by astronauts as "luminous cloud"; however this phenomenon was noted in less than 1% of the observations on only one flight. It is also possible that the Cerenkov light may cause streaks from relativistic particles to appear broader than streaks from particles

---

It is interesting to note that some of the first observations in connection with the discovery of the Cerenkov effect were visual. These have been described in a recent historical review by I.M. Frank, who personally observed Cerenkov light due to electrons and luminescent light from gamma rays that were allowed to enter his eyes (34).

with the same LET at nonrelativistic speeds. The problem is complicated since delta rays, fluorescence and soft x rays emerging from the track core may also have a broadening effect on the observed streaks.

Light sensations from x rays

X-ray beams can also cause light sensations, but the effect is not localized as in the case of heavy particles. Near threshold, it is seen as a general greying of the visual field affecting primarily peripheral vision.

At higher intensities some observers (including one of the authors, C.A.T.) have reported color sensations somewhat similar to the appearance of a clear sky just before sunrise.

Visual effects from x rays apparently depend on simultaneous activation of several receptors within flicker fusion time. For this reason there is a minimal exposure rate necessary to produce such effects. This exposure rate was measured at Berkeley to be between 1.5 and 24 mR/sec (10) at exposures of a fraction of a second for 100-250kvP xrays. A threshold exposure rate was earlier measured by Newell and and Borley (8), who found it to be 8 millirad $\sec^{-1}$ A careful measurement was made recently by T. Chaddock (29), who experimented with primates and obtained visual responses at dose rates above 2-3 millirad sec. In the Berkeley experiment, the total exposure time was less than 0.1 second, whereas in the Newell and Chaddock reports, exposures of about one second were involved. Taking these results into consideration, we find that the minimal x-ray exposure rate necessary to produce greying of the visual field is 20 to

240 times higher than the dose rate of neutrons which induced star-like flashes, and more than 100 times higher than the dose rate of heavily ionizing charged particles which induce streaks.

The nature of the critical physical interactions

From the facts that a period of ten minutes dark adaptation is necessary in order to see particle-induced stars and flashes, that most events are colorless, and that the phenomenon is produced only when particles pass through the retina, we may infer that the mechanism of flash induction involves the sensitive elements of the human rods; i.e., discs 30 nm thick, 1200 nm in diameter.

Two hypotheses which have physical plausibility for the non-relativistic particles are fluorescence from electronic excitation or rod membrane distortion by direct ionization events in the rod disc. At 10 keV $\cdot \mu^{-1}$, a single visual rod absorbs at least 10 keV of energy and about 100 delta rays are produced. It is plausible that electronic excitation of quanta in the visible domain (fluorescence) might be responsible for the events observed via light absorption by the rhodopsin molecules of visual purple. Cerenkov or fluorescent light from the vitreous fluid or lens would not be focused on the retina to produce distinct local images but might be responsible for the more diffuse type observations. It should be noted, however, Lipetz (5) observed x-ray induced signals in enucleated frog eyes and in retinal explants washed free from vitreous fluid, and 800 nitrogen particles passing through and stopping in vitreous fluid of the eye did not induce visual phenomena (13).

The disc membranes have a thickness of about 10 nanometers; when $\mathcal{E} = 10$ keV/μm, the energy absorption in the membrane from one single particle would amount to 100eV, or the equivalent of generating about

3 ion pairs within the membrane. High LET particles could act on these membranes directly, causing a change in their electrical conductivity, thus leading to creation of sodium-potassium ion currents across the membranes. Such currents would eventually cause electrical activation of rod cells.

It is appropriate to consider a simple model for analysis of our investigation. Assume the probability, P_r, that a single particle causes a visual rod to send out an electric signal is proportional to the magnitude of the transfer, ε, and the distance, d, the particle travels through the sensitive region of the retina.

$$P_r = \kappa \cdot \varepsilon \cdot d$$

where κ is a proportionality constant. Further let the probability of actually perceiving an event P_e depend on the firing of a minimum number, m, rods in the path of the particle; thus

$$P_e = p_r^m = \kappa^m \cdot \varepsilon^m \cdot d^m$$

Let $P_r = 0.8$ for an LET of 10 keV $\cdot \mu m^{-1}$ and $P_r = 0.4$ for $\varepsilon = 5$ keV$\cdot \mu m^{-1}$. If the minimal number of rods in a small region of the retina that must fire is 3, then the probability of actually seeing a flash, P_e, is 0.5 for 10 keV $\cdot \mu m^{-1}$ and 0.06 for 5 keV$\cdot \mu m^{-1}$. The choice of $\kappa = 0.08$ keV^{-1} gives results in general agreement with our preliminary observation, according to this model. A fit of data on the efficiency of detection for exposure to various particles of various energies to this simple model could yield information on the number, m, of rods along some path, d, necessary for perception of a visual event.

The model presented above would lead to the conclusion that x rays, at the threshold intensity, would cause electrical discharge in about one of every 10^5 rods. Coincidences between these would result in a low intensity diffuse or "sunrise" visual phenomena.

Because intensity is related to the density of rods firing in some small retinal region which can be defined by a constant path length, d, this model predicts all events for particles with $\varepsilon >> 10$ keV $\cdot\mu m^{-1}$ will be bright with little or no perceptible intensity discrimination between them.

In the case of x rays, a higher x-ray intensity would cause an increase of brightness, and x-ray discrimination over a 10^5-fold intensity domain should be possible.

The problem of biological effects of heavy cosmic ray ions

Observation of light flash events is not in itself an indication of hazard from primary cosmic rays. It is, however, a reminder that the effects from single heavy ions on cells of nondividing tissues should be assessed before man undertakes space missions of long duration, since about 40% of the galactic cosmic ray dose is made up of heavy primaries of $Z > 6$ (30).

Heavy ions exert potentially great effects on cells due to the dense ionization core in their tracks with ± 25Å radius (31). One may obtain an idea of the potential hazardous effects of heavy particles by calculating the fraction of various types of cells that would suffer a hit during a hypothetical space flight of one year beyond the Earth's magnetic field. Some neurons are larger in diameter than others; for these larger cells and for Pyramidal cells, percentage of whole cells hit for $Z \geq 20$ is greater than 10%. Two questions are of interest here:

> What is the damaging effect of a single particle to a neuron, if any?
>
> What does it mean for the individual if a certain percentage of his neurons are malfunctioning?

At the present time neither question can be answered with certainty, because high energy accelerated particles above $Z \geq 20$ are not routinely available in the laboratory. In the first consideration, however, it is possible that when the rate of energy loss exceeds a critical value, a single particle may produce a potentially irreparable nucleic acid or membrane injury. Often such injuries will not kill neurons immediately; they may, however, reduce neuron lifespan and temporarily or permanently impair cell functions.

Secondly, the meaning of such injury to the organism as a whole is not clear at present. In parts of the nervous system where redundancy is great, as in the cerebrum, cellular damage might not unduly impair function. The effects may exhibit themselves as the effects of other types of degenerative injury, e.g., response times of neural reflexes might increase, learning and muscular coordination might be impaired, and memory storage might diminish. Perhaps the effects of radiation damage will be more pronounced in regions of the nervous system where relatively few cells control important general responses. This might be the case in the hypothalamus, thalamus and the brain stem.

At Berkeley, we plan to use the newly rebuilt HILAC machine as an injector of heavy ions to the Bevatron. The HILAC can accelerate all heavy ions in the lower half of the atomic table to a kinetic energy of about 7.5 MeV nucleon^{-1}. These ions will be stripped and accelerated up to 2.8 BeV/nucleon in the Bevatron. This program will be known as the Bevalac program and, when completed, facilities will be available to scientists from various laboratories and from different countries. We expect to produce strong deflected beams of all ions including calcium (10^8 to 10^{10} particles per pulse), and weak beams of iron particles (10^6 to 10^8 particles per pulse).

We have already obtained evidence that single nitrogen and oxygen ions accelerated in the Bevatron can cause irreversible developmental malformations in plants and irreversible damage in hair follicles of mice (32). Small doses of nitrogen ions have caused degeneration in the outer segments of retinal rods in Necturus maculosus (33).

Work is also being carried out on the effects of heavy beams on the retina of pocket mice, rabbits and primates. These studies have not been in progress long enough to determine whether or not retina irradiated by heavy ions can repair (11) (14).

It will also be necessary for the safety of astronauts on longterm spaceflights to assess other chronic effects produced by heavy ions, such as carcinogenic effects and diminished longevity. Further, it might be useful to understand how radiation injury can interact with other radiation effects from onboard reactors and with physiological stresses produced by the environment in general.

Acknowledgments

The authors are indebted to their colleagues at the Lawrence Berkeley Laboratories, particularly to E. McMillan, J. Born, E. Lofgren, H. Grunder, W. Hartsough and J. Vale, for their collaboration and for the use of the accelerators. Drs. P. Chapman, L. Pinsky, W. Benson and C. Barnes of the Manned Spacecraft Center, and Drs. H. Bichsel, J. Denney and W. Nelp at the University of Washington, provided essential collaboration for this work. Research support was provided by the Biotechnology and Human Resource Division of Biology and Medicine of the Atomic Energy Commission.

REFERENCES

1. P.K. CHAPMAN, L.S. PINSKY, R.E. BENSON AND T.F. BUDINGER, Observationsof cosmic-ray induced phosphenes on Apollo 14, in: Proceedings of the National Symposium on Natural and Manmade Radiation in Space, Las Vegas, March, 1971, NASA TM X-2440 (January, 1972).

2. W.C. ROENTGEN, K. Akad. d. Wissensch, Berlin, Stizungsber., 1897, cited by W. ROHRSCHEIDER, in: The effect of Roentgen rays on the eye, Strahlentherapie 38, 665 (1930).

3. **S. Shlaer and M. Pierenne**, J. Genl. Physiol. 25, 810 (1942).

4. C.A. TOBIAS, Aviat. Med. 23, 345 (1952).

5. L.E. LIPETZ, An electrophysiological study of some properties of the vertebrate retina, Ph.D. Thesis, University of California Radiation Laboratory Report No. 2056 (1953).

6. G.G. FAZIO, J.V. JELLEY and V.N. CHARMAN, Nature 228, 260 (1970).

7. R. MADEY and P.J. MCNULTY, Direct stimulation of the retina by the method of virtual quanta for heavy cosmic-ray nuclei, in: Proceedings of the National Symposium on Natural and Manmade Radiation in Space, Las Vegas, March 1971, NASA TMX 2440 (January, 1972).

8. R.R. NEWELL and W.B. BORLEY, Radiol. 37, 54 (1941).

9. I.R. McAULAY, Nature 232, 421 (1971).

10. C.A. TOBIAS, T.F. BUDINGER and J.T. LYMAN, Nature 230, 596 (1971).

11. T.F. BUDINGER, H. BICHSEL and C.A. TOBIAS, Science 172, 868 (1971).

12. C.A. TOBIAS, T.F. BUDINGER and J.T. LYMAN, Human visual response to nuclear particle exposures, in : Proceedings of the National Symposium on Natural and Manmade Radiation in Space, Las Vegas, March, 1971, NASA TMX 2440 (January, 1972).

13. T.F. BUDINGER, J.T. LYMAN and C.A. TOBIAS, Visual perception of accelerated nitrogen nuclei interacting with the human retina, Lawrence Berkeley Laboratory Report No. 529 (December, 1971).

14. C.A. TOBIAS, T.F. BUDINGER and J.T. LYMAN, Potential hazard from heavy particles in longterm spaceflight, in: Proceedings of the IVth International Congress of Radiation Research, Evian, France, June 28-July 4, 1970 (to be published).

15. W.N. CHARMAN, J.A. DENNIS, G.G. FAZIO and J.V. JELLEY, Nature 230, 522 (1971).

16. J.H. FREMLIN, New Scientist 47, 1131 (1971).

17. H.A. GRUNDER, W.D. HARTSOUGH and E.J. LOFGREN, Science 174, 1128 (1971).

18. C.A. TOBIAS, Science 174, 1131 (1971).

19. G. VAN DEN BRINK, Addition phenomena in vision and hearing, in: Studied in perception, Institute for Perception on RVO-TNO, Soesterberg, The Netherlands (19--), p. 61.

20. A.F. SANDERS, Peripheral viewing and cognitive organization, in: Studies in perception, Institute for Perception on RVO-TNO, Soesterberg, The Netherlands (19--), p. 25.

21. D.H. KELLY, J. Opt. Soc. Am., 50, 1115 (1960).

22. F.L. VAN NES and M.A. BOUMAN, J. Opt. Soc. Am. 57, 401 (1967);
F.L. VAN NES, et al., 57, 1082 (1967).

23. G.S. BRINDLEY and W.S. LEWIN, J. Physiol. 196, 479 (1968).

24. W. PENFIELD, Some observations on the crebral cortex of man, in: Proceedings, Royal Society, London, Series B, 134, 329 (1947).

25. C.A. TOBIAS, The use of accelerated heavy particles for production of radiolesion and stimulation in the central nervous system, in: Proceeding of the International Symposium on the Response of the Nervous System to Ionizing Radiation, Northwestern Univ. Medical School, Chicago, September, 1960, (1962).

26. F.J. D'ARCY and N.A. PORTER, Nature 228, 260 (1962)

27. P.J. McNULTY, Visual sensations induced by relativistic muons, Nature 234, 111 (1971).

28. P.J. McNULTY, Visual sensations from relativistic nitrogen beams, in: Abstracts, American Physical Society (April, 1972).

29. T.E. CHADDOCK, J. Comp. and Physio. Psychology 78, 190 (1972).

30. M.C. WILKINSON and S.B. CURTIS, Galactic cosmic ray heavy primary secondary doses, in: Proceedings of the National Symposium on Natural and Manmade Radiation in Space, Las Vegas, March, 1971, NASA TMX 2440, (January, 1972).

31. C.A. TOBIAS, B. MARTINS, M. RAJU, R. ROISMAN and A. CHATEERMEE, Biological effects of a 266 MeV/nucleon nitrogen ion beam on

cultured kidney cells (to be presented at the Symposium on Radiobiology, Biophysics Congress, Moscow, August, 1972).

32. J. RISIUS, C.-H. YANG, J. LUCE and C.A. TOBIAS, Studies on geotropism and radiation in Phycomyces blakesleeanus, Lawrence Berkeley Laboratory Report 596 (January, 1972).

33. Y. ZEEVI, C.A. TOBIAS and E.R. LEWIS, Initial studies on vertebrate retinal interaction with the nitrogen beam, Lawrence Berkeley Laboratory Report 529 (December, 1971).

34. I.M. FRANK, On coherent radiation of the fast electron in medium, Dubna, Joint Inst. for Nucl. Res. (1971).

FIGURE CAPTIONS

Fig. 1. Representation of visual phenomena seen by Apollo astronauts and us, in ion beams. Cloud phenomenon is similar to x-ray, magnetic, or electrical phosphenes.

Fig. 2. Poisson interval distribution of all events reported by three astronauts during Apollo 14 (modified after Fig. 4 in: P. K. Chapman _et_ _al_. (1)).

Fig. 3. Schematic of the arrangement used for human exposures. The exposures were carried out using exposure facilities developed at our Laboratory over the past several years for helium ion therapy. Special devices were added to allow exposure to individual helium ions at 0 - 250 MeV kinetic energy. The subjects wore dark-adaptation hoods (Fig. 2, in P. K.Chapman _et_ _al_. (1)).

Fig. 4. Bragg curve of the nitrogen ion beam as measured in water. The inset shows diagrammatically the experimental step.

Fig. 5. First human exposure to accelerated nitrogen ions. Subject, center, received less than 2000 particles with alignment procedure of ± 1 mm accuracy.

Fig. 6. Left eye horizontal section showing three nitrogen beam paths. Visual phenomena seen in middle positions only.

Fig. 7. Representation of visual phenomena seen by three dark-adapted observers in a nitrogen ion beam. Duration of flashes is very short without after-images.

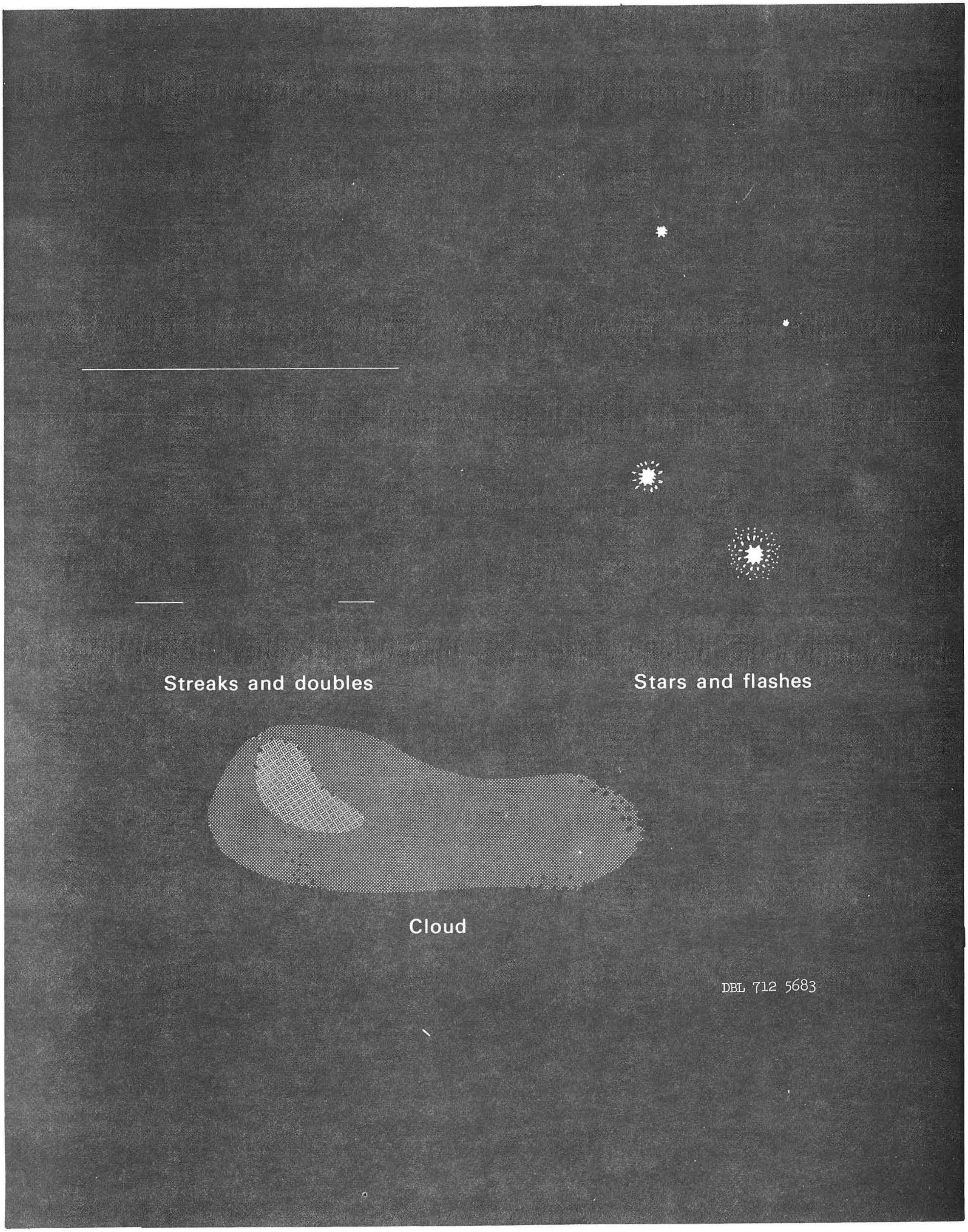
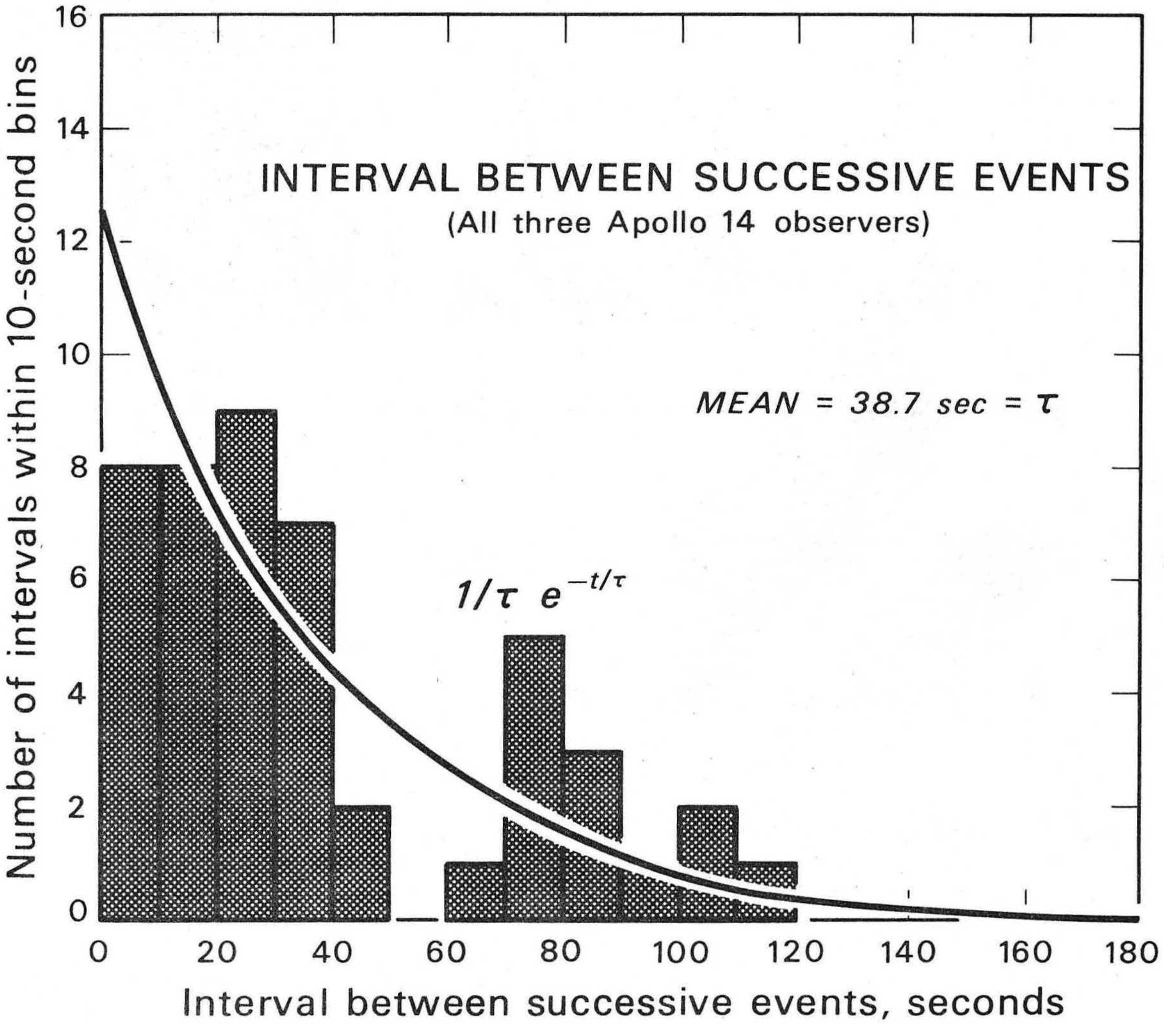
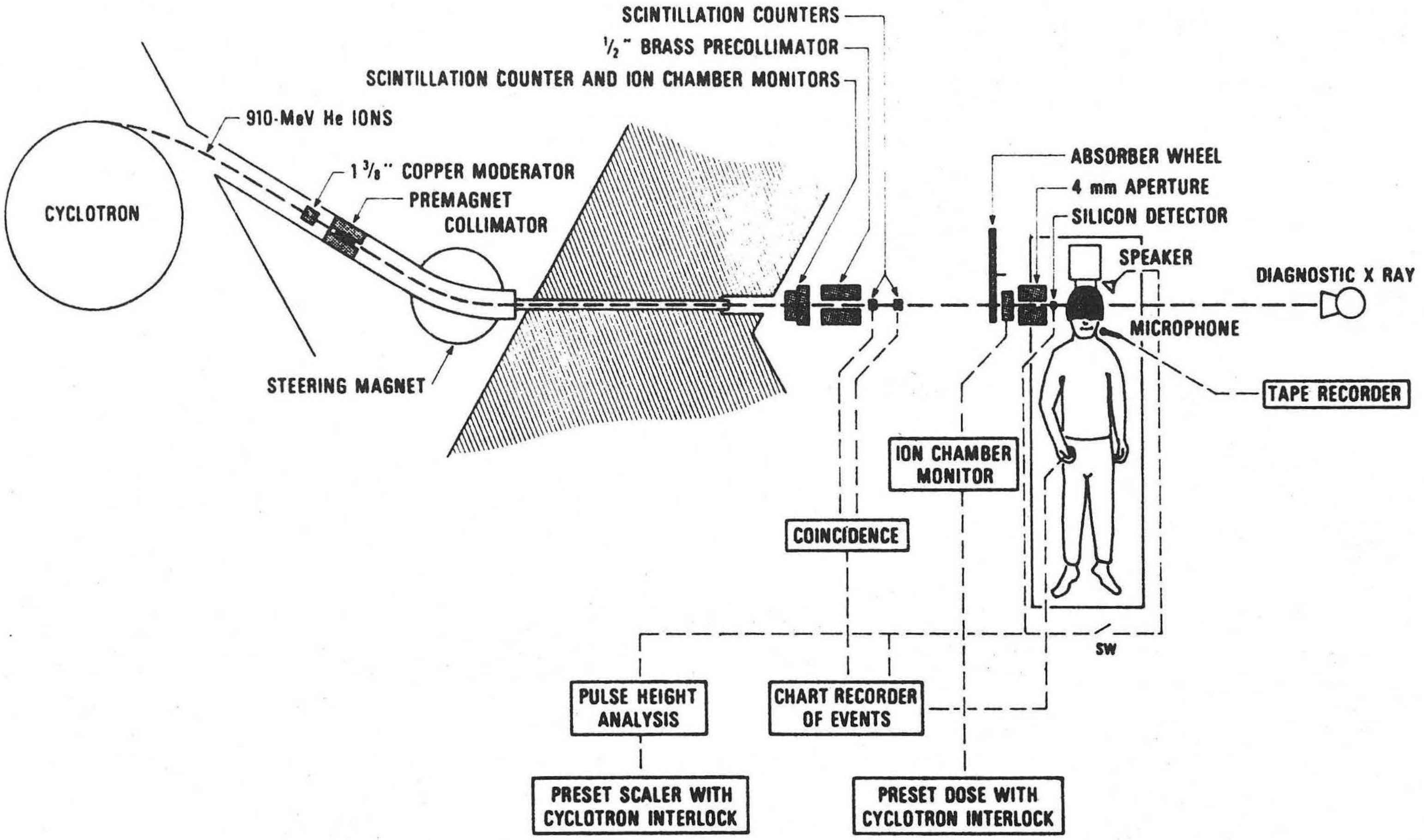


Fig. 1



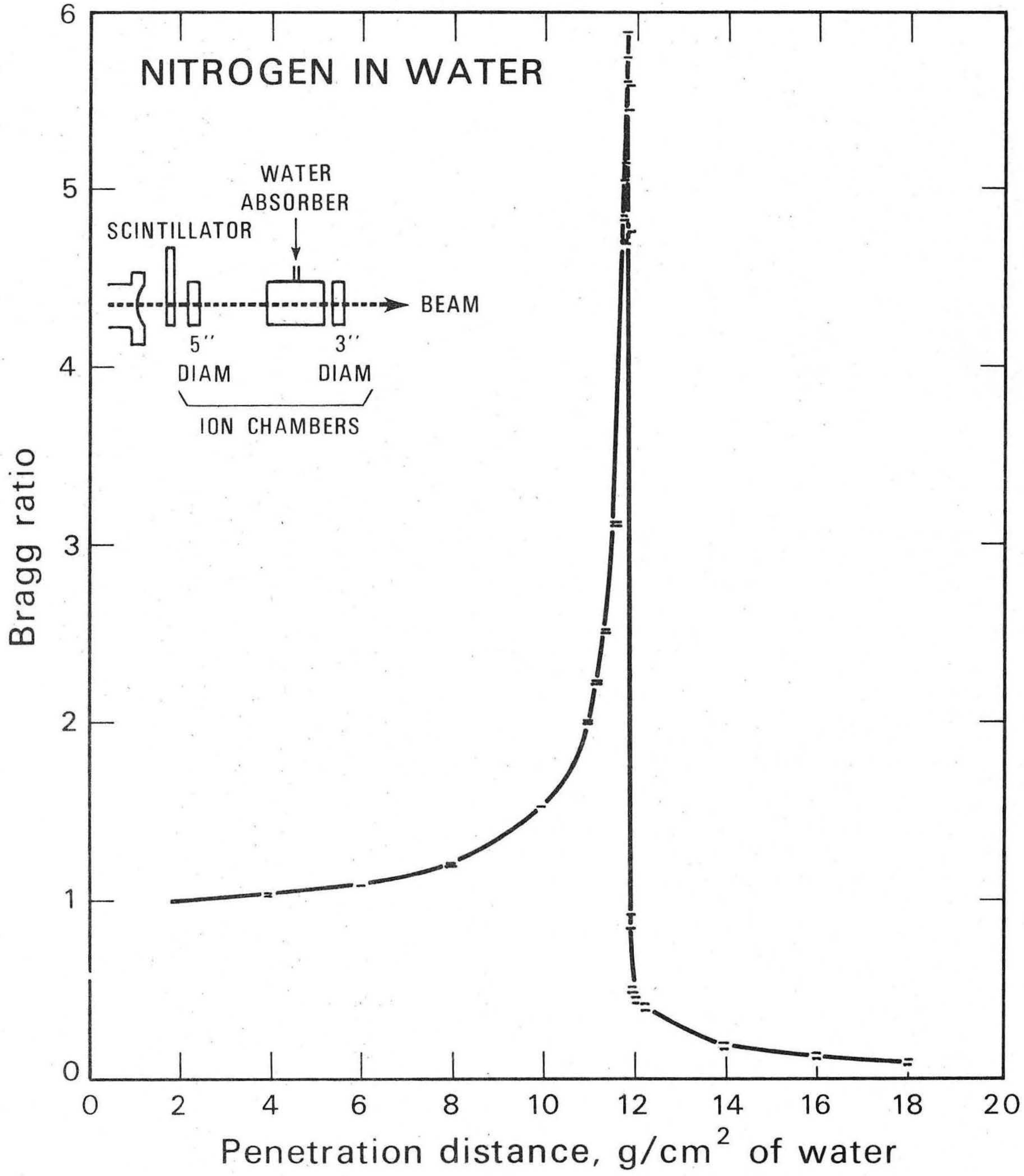
XBL 717-1224

Fig. 2



XBL 726-1205

Fig. 3

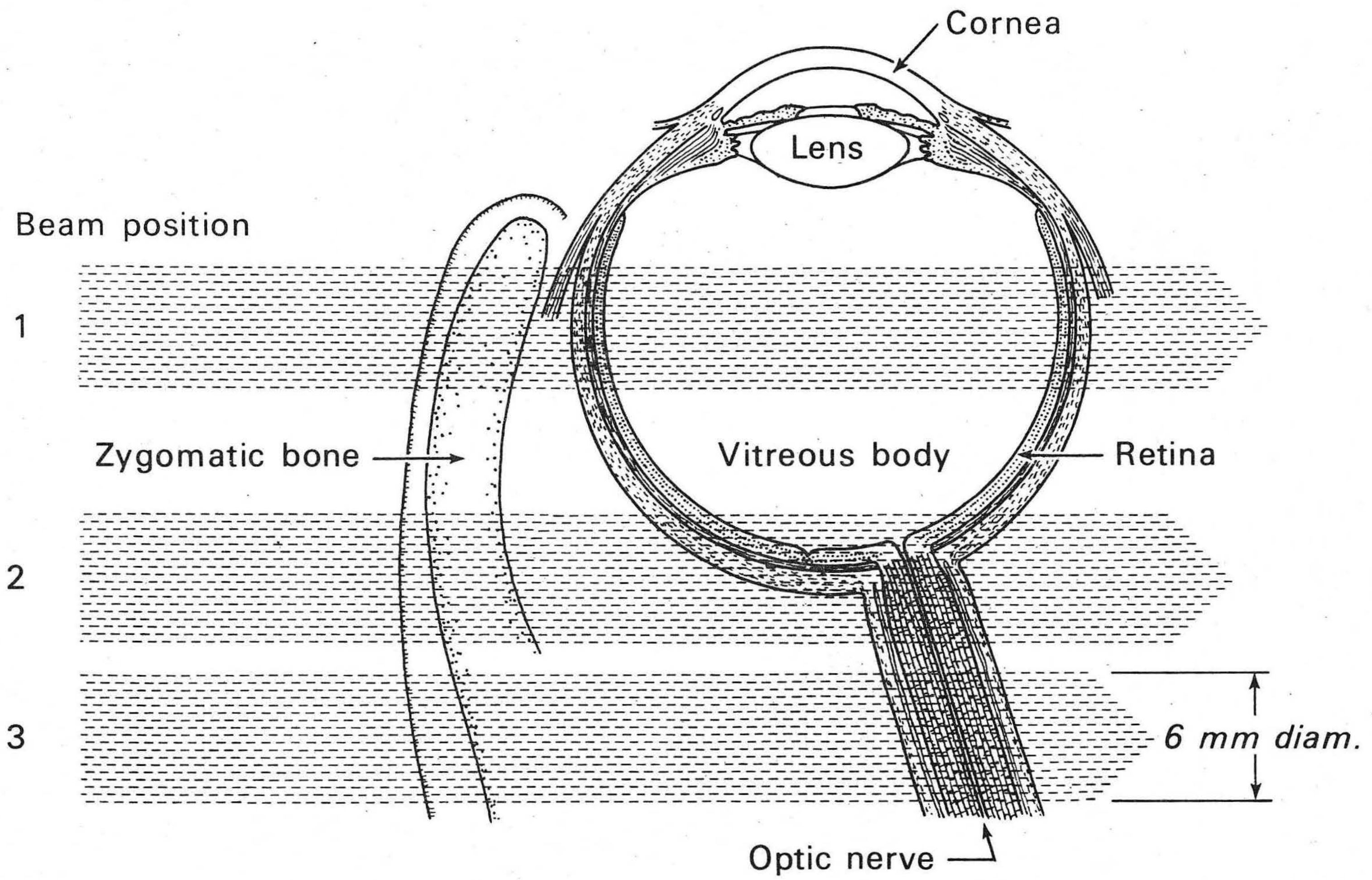


DBL 721 5109

Fig. 4

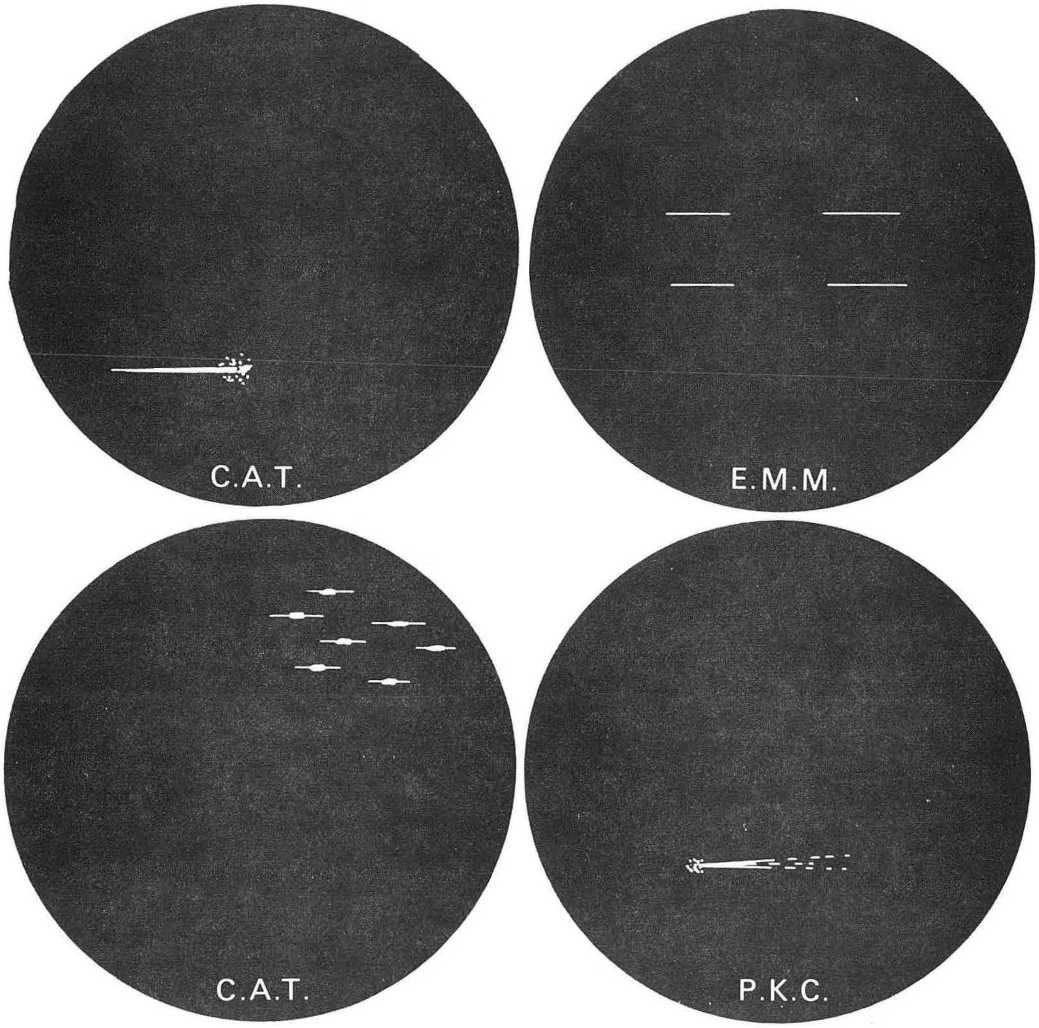
XBB 718-3822

Fig. 5



DBL 717-5921

Fig. 6



XBL 719-1392

Fig. 7

TECHNICAL INFORMATION DIVISION
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720