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48

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LIGHT FLASH PHENOMENON SEEN BY ASTRONAUTS

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INTRODUCTION

We wish to present the results of experiments conducted at the University of California, the University of Washington, the Manned Spacecraft Center, and on board Apollo 14. These experiments had as their common goal the characterization and elucidation of light flashes seen by astronauts on Apollo 11, 12, 13, and 14 during translunar or transearth coast. Astronauts on these missions experienced colorless light flashes during periods of dark in the spacecraft at a frequency of one to two per minute.* Pinpoints of light, double pinpoints, and streaks--most of which subtend an angle of 6 degrees--were seen by astronauts questioned about these observations. Results of our work at the University of California and the University of Washington, together with results of Apollo 14, have been presented previously; however, this is the first time all of these experiments and results have been presented as a whole along with relevant aspects of cosmic ray fluxes and associated radiobiological hazards.

Most of the studies were conducted as part of the general biomedical and biophysical program at the Donner Laboratory and the Lawrence Radiation Laboratory of the University of California, Berkeley. Although a phenomenon of light flash was suggested in 1952 by one of us (Tobias, 1952), it was not until June of 1970 that we undertook to experiment with visual phenomena produced by nuclear particles

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* Apollo 15 (August, 1971) astronauts saw light flashes at 3 to 7 times less frequency.

impinging on the human retina. These and subsequent experiments were designed to simulate cosmic ray particles by delivering neutrons to the vicinity of the retina with the hope that recoil atoms and results of nonelastic collisions such as alpha particles would have sufficient range and abundance in tissue to produce results similar to cosmic ray particles in space. In addition, just three weeks ago we completed experiments with individual high energy (50 MeV/nucleon) helium ions impinging on the human retina of two observers.

Our experiments argue that direct ionization or the results of local electronic excitation in the tissues of the retina by galactic cosmic nuclei is the preferred explanation for this phenomenon. Throughout the early portion of our experiments we entertained the alternate hypotheses that the light flash phenomenon experienced by the astronauts could be caused by electric, magnetic, x-ray, or psychological phenomena. For completeness, we will describe some of these modes of inducing light flashes and mention why these other mechanisms were excluded as an explanation for the light flashes seen by astronauts.

PRESSURE, ELECTRIC, MAGNETIC, AND X-RAY PHOSPHENES

Pressure phosphenes

The word phosphene is derived from two Greek words *phos*, light, and *phainein*, to show. A phosphene is the conscious sensation of having perceived light, colored or colorless, patterned or unstructured, on stimulation of man's visual apparatus by some manner other than exogenous light impinging on the retina. The best known phosphene is the pressure phosphene which consists of light sensations induced by pressure on the closed, but not necessarily dark adapted, human eye. These are also known as deformation phosphenes (Brindley,

1967) and have been recently described and illustrated by Oster (1970). As is true for all categories of phosphenes to be discussed below, there is a high degree of individuality and, in fact, some individuals perceive multicolored kaleidoscope-like patterns, whereas others see nothing when pressure is applied to the eyeball. The mechanism of phosphene induction is most probably cell discharges associated with membrane distortion. The short flash one notes on sudden eye opening after long periods of relaxation (sleep) is probably also a pressure phosphene from the fluid wave and eyeball deformation generated from lens, iris, and eye muscle movements during reflex accommodation.

Electrical phosphenes

For over 200 years it has been known that small currents (0.3 mA) of electricity through the human head can result in a subjective sensation of light. The earliest definitive report on this phenomenon was by LeRoy (1755) who reported the induction of flashes in a blind patient by using a Leyden jar discharge. The electrophysiology associated with electrical stimulation of the visual apparatus was studied by Volta (1796), who experienced a flash-like sensation of light when a small potential difference was induced between his eyelids and some other part of his body. Over the past five years the electrical stimulation of the visual apparatus (Fig. 1) has been explored in an attempt to build prostheses for blind individuals (Starkiewicz, 1967; Brindley and Lewin, 1968; Budinger, 1968). The reader can experience these electrical phosphenes by applying the leads from a 3-volt source (hand flashlight is adequate), one to the forehead and the other to the back of the

neck. Dark adaptation is not necessary, but the phenomenon will be observed best if the individual steps into a darkened room momentarily. With adequate electrode-to-skin contact facilitated by rubbing moistened table salt at the point of contact on the skin, the experimenter will experience a brief light "blink" as the current is turned on or, when on, turned off abruptly. A rapid rise time is important for successful stimulation. The phosphene is usually a brief, colorless, diffuse light haze in the temporal visual fields. These electrical phosphenes, although interesting and relatively easy to generate, are not relevant to the problem of streaks and flashes seen by the astronauts, as they are dissimilar in character, and there are no electrical or magnetic field changes present to induce such phenomena.

Light flashes, streaks, and patterns can be elicited by direct stimulation of the visual cortex (Penfield, 1947; Brindley and Lewin, 1968). The possibility of nuclear particle stimulation of the cortex as the mechanism for astronaut light flashes will be discussed below.

Magnetic phosphenes

A flash sensation can also be induced by immersing the head in induction coils, as was first discovered by d'Arsonval (1896) and carefully studied by Barlow and co-workers (1947) and Seidel and co-workers (1968). These magnetic phosphenes are induced by an a.c. magnetic field of about 1000 gauss per second. Both the magnetic and electrical phosphenes are believed to be generated in the retinal tissues. They are not dependent on a period of dark adaption, in fact the threshold increases with increasing time in the dark, which is just opposite, of course, to that observed for light

sensitivity. Spacecraft and orbiting laboratories of the future may have sufficiently high a c magnetic fields or gradients to induce these phosphenes.

X-ray phosphenes

Visual phenomena induced by x rays, known since 1896 (Lipetz, 1955; Brandes and Dorn, 1897), can be characterized as diffuse homogeneous floods of colorless light similar in character to electrical and magnetic phosphenes. Their appearance is dose rate dependent with the minimum dose rate for excitation near 24 mr/sec (Pape and Zakovsky, 1954). The response follows a dark adaption curve somewhat similar to visual spectrum photons, but with biophysically significant differences (Bachofer and Wittry, 1962; Hellerstein and Ballinger, 1970). Streaks and bright pinpoint flashes are not seen.

NUCLEAR PARTICLE EXPERIMENTS

High energy neutron experiments

Our first experiments (Tobias *et al.*, 1970) were designed to simulate cosmic particles of carbon, nitrogen, and oxygen by producing recoil carbon, nitrogen, oxygen and nuclear fragments in the eye using a neutron beam of 640 MeV maximum energy. Two human subjects were exposed to a beam of fast neutrons with energies between 20 and 640 MeV produced by 0.64 GeV proton beam impinging on a 12-cm-thick beryllium target. Most of the neutrons were at energies near 300 MeV and only 2% or less of the dose came from slow neutrons and gamma rays. The flux, continuously monitored, was 1.4×10^4 neutrons cm^{-2} sec^{-1}. The neutrons were collimated and channeled by a set of iron and lead apertures 2 m thick (Fig. 2).

On four exposures (total 8.5 mrem in the beam path) between 1 and 3.5 seconds, one subject saw pinpoint flashes coinciding with the presence of the beam, and the other subject during a 3-second exposure (2.6 mrem) saw between 25 and 50 bright pinpoint flashes, which can be described as small scintillations similar to luminous balls seen in pyrotechnic displays (Fig. 3). In general the events were colorless, but seemed to be wider on one end relative to an indistinct tail, although it was not clear whether the "tail" faded into the brighter "head" or the head faded into the tail. We recognized that any events from this high energy neutron beam could be caused by neutrons, proton recoils, nuclear spallation products, and even carbon, nitrogen and oxygen recoil atoms in the eye or other parts of the visual apparatus including the cerebral cortex for the frontal exposure. In addition, x rays could account for the phenomenon; thus it was important at the early stages of our experiments to ascertain the minimum x-ray dose threshold for visualization of phosphenes. The lowest dose rate capable of giving a flash sensation was 24 mr sec^{-1}, which is consistent with previously published values (Pape and Zakovsky, 1954). We experimented at lower dose rates between 0.05 and 1.25 mr sec^{-1}, and noted no phenomenon similar to stars and streaks seen during the neutron experiment (Fig. 4). Since the dose rate in the neutron experiment was below the threshold for induction of x-ray phosphenes, we could discount incidental x rays as the causative mechanism in our results.

Relativistic pion and high altitude observations

The visual phenomenon of brilliant stars noted in the neutron beam between 20 and 640 MeV was felt to have been caused by heavy recoils or products of nuclear reactions induced by the fast neutrons near the retina; however, Cerenkov radiation from recoil photons or pions could not be excluded unambiguously as the source of the effect, as some recoil protons would have energies greater than 470 MeV. Thus, we did a short exposure with 1.35 BeV kinetic energy (1.5 BeV/c momentum) plus pions at the Berkeley Bevatron. The maximum flux was 200 pions cm^{-2} sec^{-1}, and no phenomena were noted although the subject's dark adapted eyes were bathed in the beam (6 seconds). At fluxes hundreds of times higher than our exposure a brightening of the visual field was noted, but no stars or streaks (McNulty, personal communication, June, 1971). Previous investigations with mu mesons using a cosmic ray telescope showed a statistically significant coincidence between subjects' reports of some visual event and the arrival of mesons (D'arcy and Porter, 1968); thus we undertook some high altitude observations.

We took advantage of conference meetings over the past year to examine whether any phenomenon could be seen in the well dark adapted trained observer at 10,000 meters in commercial airliners. Two of these flights were at geomagnetic latitude 60° north, and two at 30° north. Since the cosmic ray particles at altitude are more numerous than at ground level by a factor of about 60, we expected to see frequent events after 30 minutes of dark adaption and 30 minutes of observation, if cosmic rays (electrons, mesons, and protons)

were observable at ground level. We were unable to detect any events though two observers pursued this project enthusiastically.

Low energy neutron experiments

Experiments were performed at neutron energies near 1 MeV using a californium-252 source. On left eye exposure at 10^5 neutrons cm^{-2} sec^{-1} for 12 seconds, and a longer exposure to both eyes of 70 seconds at 10^4 neutrons cm^{-2} sec^{-1}, one subject well dark adapted saw only one very brief teardrop flash which could not unequivocally be attributed to that exposure. During the 10^5 neutrons cm^{-2} sec^{-1} exposure near the left eye, a haze or general graying of the otherwise dark visual field was noted with an after effect lasting for ten seconds. As there was an abundance of proton recoils at this energy and flux, but very few alpha particles, it was decided to perform some experiments at somewhat higher neutron energies. We utilized an already established experimental protocol being conducted at the University of Washington for the whole body assessment of calcium by activation of patient calcium-48 to calcium-49 in a neutron beam from the 60-inch cyclotron (Nelp, *et al.*, 1970). In these activations the flux density is approximately 10^5 neutrons cm^{-2} sec^{-1} with a greatest flux at 8 MeV and a maximum at 25 MeV (Fig. 5). The exposure time is approximately 100 seconds for a total dose of about 200 mrads. Five subjects who were having routine activation analysis were dark adapted for varying periods under red goggles (usually more than 15 minutes), after which further dark adaption was achieved by mounting four layers of photographic dark cloth beneath tight fitting goggles for a period of over 20 minutes (in one case 10 minutes). All five

patients saw a multitude of bright, colorless flashes which were described as "a bunch of stars" that were moving or "blinking". All observers were consistent in indicating that there was some motion to the stars, and they also indicated there was some length to the streaks (equivalent to a few centimeters at a distance of one meter). Although reports varied, there was a slight lightening of the otherwise dark background at the time of appearance of the stars. These subjects reported seeing many events and tens to hundreds appeared at any one instant.

We postulated that alpha particles were involved as we had little or no results at lower neutron energies below the (n, α) threshold for α production from C and O. However, the neutron flux was only 10^5 cm^{-2} sec^{-1}, thus it is not possible that at any one instant "hundreds" of alpha particles from the (n, α) reaction on C, N, and O would arrive at or be produced in the retina. Therefore, a more careful experiment was done using one of us who had experienced the high energy neutron, fission spectrum neutrons and electrical phosphenes in order to better characterize the events seen by the untrained patients. A special exposure series was done with five short (5 to 10 seconds) and one 120 sec exposure with fluxes of 10^3 and 10^4 neutrons cm^{-2} sec^{-1}. Definite streaks, which would have been one to six centimeters long if the event had occurred at a distance of 1 meter, were seen on lateral exposure with some sense of motion along the beam direction (Fig. 6). These streaks were variously described as rocket exhausts, thin-downs, and tapering streaks, all of which were an effort by the observer to indicate a tapering shape. On frontal exposure the phenomenon is

best characterized as snow flurries flying at the windshield of a car driving in a light snowfall at night. The subject thought he could discern eight levels of gray, and noted that the flashes induced by these lower energy neutrons were not as bright as the higher energy exposures. His estimates of numbers ranged from 10 - 100 at any one instant (the integrating and cognitive period is 0.5 - 2 seconds). Table I shows the number of alpha particles reaching the retina for the ^{252}Cf fission spectrum and the higher energy cyclotron-produced neutrons at the University of Washington (Fig. 5).

Table I.

Number of alpha particles produced*
per cm^3 by flux 10^5 neutrons cm^{-2} sec^{-1}.

Element**	Alpha tissue range (micron)	(n,α) from 20-MeV deuterons on beryllium	(n,α) ^{252}californium
		Neutron Energy 7 MeV to 13 MeV	
Carbon	> 4	660	6.5
Oxygen	> 26	722	14
Nitrogen	> 45	35	1
		Neutron Energy ≥ 14 MeV	
Carbon	> 65	339	0
Oxygen	>117	257	0
Nitrogen	>150	0.4	0

*Calculated from: Events = Flux X cross section X atom composition.

**Percent atom abundance used: Carbon, 7.2; oxygen, 27.1; nitrogen, 1.2.

We conclude that proton recoils with a stopping power of 10 KeV μm^{-1} contribute significantly to the phosphenes seen in the neutron

beam because:

1) The abundance of events exceeds that theoretically possible from alpha particles only.
2) The length of the streaks are commensurate with an interaction of 1 to 2 mm on the retina. That range is reasonable for protons 10 to 25 MeV, but not possible for alpha particles produced.
3) The haze seen on ^{252}Cf 10^5 n cm^{-2} sec^{-1} exposures is best explained as the interaction of 100 - 1000 proton recoils of short range produced in or very close to the retina. Incidental x-rays during that exposure were at a dose rate 0.4 mR sec^{-1}, and thus not the causative mechanism.

On rotating from an anterior to a posterior position wherein the beam penetrated the back of the head, the frequency of events was much less for all six observers. This added observation argues for the eye, and most probably the retina, as the site of the phenomenon (Budinger, *et al.*, 1971).

Helium ion human retina exposure

From these experiments we are left with the hypothesis that either proton recoils or alpha particles, or both, are the most likely candidates for direct ionization or electronic excitations in or near the sensitive part of the retina. If we can show that charged particles above a certain stopping power give the effect, we have established the cause of the phenomenon and some calibration on man as a cosmic ray detector. A direct test of this conclusion involved the use of accelerated helium ions available at our

184-inch cyclotron at Berkeley in a beam which was aimed carefully at various portions of the posterior globe of human subjects. The objectives of our experiments with 240 MeV helium ions were to characterize any visual phenomenon as to brightness, character, and efficiency of detection (Tobias, *et al.*, 1971).

We found that the human eye could detect individual helium ions with an efficiency of approximately 40%. When helium particles were allowed to cross laterally the central region of the retina of the left eye at random time intervals with an average rate of 10 per second, both subjects saw two to five flash events per second. These events included streaks with motion sense in the beam direction similar to the phenomena "seen" in the neutron beam. At lower rates of approximately 1 per second and high rates of 100 per second, it was difficult to discern more than one event. These streaks appeared to be light flashes travelling horizontally across the field of vision with a length of 2 to 4 cm at 1 meter distance. The experimental set-up for these irradiations is shown (Fig. 7) in the biomedical exposure room where monoenergetic beams of about 910 MeV helium ions are used in the radiation therapy investigations on patients (Raju, *et al.*, 1969).

The subject is accurately aligned with respect to the beam using x-ray imaging techniques. Penetration depth was varied from 5 cm to 1.5 cm. We recognized after our initial failure at very low particle rates that careful attention must be given beam position, particle range, and the spatial-temporal thresholds of the visual apparatus. As is well known among the vision scientists and neurophysiologists, a light stimulus must have certain spatial and

temporal properties before it becomes recognized by the human observer (Westheimer, 1965; Van Ness *et al.*, 1967; Büttner *et al.*, 1971). Thus the spatial distribution as well as the range (stopping power) and intensity (number of particles in an interval) of events on the retina are important parameters in the final integration and recognition of visual phenomena. The beam entered from the side, and moved through a dark plastic mask, skin, zygomatic bone, soft tissues, and into the posterior globe. Before arrival at the subject's retina, a 10^6 to 10^8 particle cm^{-2} sec^{-1} helium ion monoenergetic beam is attenuated 10^8-fold to give a parallel stream of particles through a 4 mm aperture. Each particle is individually checked and recorded by means of pulse height analysis and coincidence counting. Beam tuning is used to exclude particles of unwanted properties. A record of one exposure is shown in Fig. 8. The total number of particles for one observer was 1150 and for the other 1500. The dose along the beam path, which is 4 mm in diameter, is less than 1 rem.

The length of the streaks was not greater than 6 cm, which is equivalent to one millimeter on the retina. Considering the thickness of the retina outer segment of approximately 10 microns and the curvature of the eye, the longest unbroken straight path through the retina is about 2 mm.

We observe four classes of events:

1. Stars--these were brief minute dim light flashes not dissimilar in character or intensity from "stars" seen by some observers on trauma to the head or at night when concentrating on visual sensations before passing into sleep.

2. Bright flashes were definite bright pinpoints of light that appeared as a star or stars in a cloudless night sky.
3. Streaks--pencils of light which varied from dim, thin lines to elongated teardrop shaped objects sufficiently bright that there is no mistake about the occurrence of the event, but not so bright that they were distracting or alarming.
4. Supernovae--these are bright single flashes of slightly more than momentary duration surrounded by a halo haze of less than half a degree aperture. Supernovae is a term coined by astronauts on Apollo 14 in trying to describe what we think is the same type of phenomenon.

We moved the beam in front of the retina (behind the lens) and into the optic nerve region, and in these two positions there was no response. These experiments definitely establish the fact that non-relativistic helium ions cause stimulation of the visual apparatus through interaction at the retina.

Apollo 14 experiments

During Apollo 14 experiments were conducted by the three crew members to help better characterize the light flash phenomenon with regard to size, shape, brightness and frequency of the events. The protocol for observation was worked out with the crew, A. Shepard, S. Roosa, and E. Mitchell during a briefing session prior to the flight. The essential aspects of the protocol were to select a time period in excess of 30 minutes when the crew is alert but relaxed, dark adapt by applying sleep goggles or some other blindfolds in the darkened spacecraft, and commence describing events in a fashion so that the temporal relation between the start of dark adaption and

the time of each event could be established. Various modes of communicating the types of events were worked out with the crew with drawings and actual simulations using lighted props so that the crew would have the benefit of previous observations on Apollo missions and our earth-based experimental results. An effort was made in this respect not to bias the crew; however, it was found that this effort was not necessary as each crew member was motivated to describe these phenomena for himself. A terminology was established for reporting shape, brightness, position in the visual field and frequency.

During the voyage to the moon, observations were made in the main by Dr. E. Mitchell and S. Roosa who used flashlights to light adapt. They noted immediately after light adaption the occurrence of pinpoint flashes and streaks. The observations on the way to the moon fell into four descriptive categories:

1. Flash, meaning a momentary brief light flash of a few minutes arc aperture;
2. Double, meaning two flashes across the visual field simultaneously, suggestive of particle interacting with two portions of the retina as it passed through the astronaut's head;
3. Streaks--these were long, narrow flashes without any particular shape, most of which appeared to be 6 cm at about a meter distance similar to the length of the streaks observed in the earth-based experiments; however, some subtended 55°, which is about half the visual field of one eye;
4. Supernovae--bright central flash surrounded by a halo of light or multiple smaller flashes peripheral to the central

flash. This phenomenon was observed during earth-based experiments in the helium ion beam when the particles were stopped in the retina;

5. Clouds--by this term the crew implied they observed a patternless light haze similar to atmospheric discharge (lightening) over the horizon. They had been briefed on this phenomenon which is more characteristic of electrical or x-ray phosphenes than particle phosphenes. The first astronaut to report the flash and streak phenomena on Apollo 11, Buzz Aldrin, was stimulated electrically in order to generate phosphenes. Although he described the usual temporal field "cloud" phosphene, he reported all phenomena seen in space were dissimilar.

During the return from the moon a special experiment was inserted into the mission Time Line in order to better gather data for ascertaining the frequency of events and relationship between observations and the degree of dark adaption. Approximately an hour was spent on this experiment. The basic plan was to expose the eyes to a flood of light from a hand-held flashlight, apply dark blindfolds in the darkened spacecraft, and report flashes as they occurred. The timing between completion of light adaption and each event was conducted at the Mission Control Center. The experiment was conducted with live interaction between the crew and members of the investigative team at the Manned Spacecraft Center and the University of California. Results of these experiments are summarized in Table 2 (Chapman *et al.*, 1971).

Table 2.

Tabulation of observed events

by classification.

		Streak	Star	Flash	Cloud	Double
LMP	Right eye	2	4	6	-	-
	Left eye	2	1	1	2	-
	Both eyes	-	-	-	1	-
	Not reported	1	-	1	-	1
	TOTAL 22	5	5	8	3	1
CDR	Right eye	1	1	5	1	2
	Left eye	2	-	2	-	-
	Both eyes	-	-	-	-	-
	Not reported	-	-	-	-	-
	TOTAL 14	3	1	7	1	2
CMP	Right eye	1	-	5	-	-
	Left eye	1	-	-	-	1
	Both eyes	-	-	-	-	-
	Not reported	-	-	3	-	-
	TOTAL 12	2	0	8	1	1
TOTAL	48	10	6	23	5	4

A total of 48 events were seen, with 28 in the right eye and 12 in the left eye, one was reported in both eyes, and seven were not reported with respect to eye of occurrence. Although the sensitivity of each human detector varied, when occurrence of flashes for all three detectors is plotted in terms of the interval between successive

events, the expected Poisson distribution of events is suggested, as shown in Fig. 9. The relationship between the frequency, brightness, and character of visual phenomena and the degree of dark adaption is one of the most important biophysical facts to be established. The eye threshold is lowered 10^4 by dark adaption (Fig. 10), thus if the mechanism is through direct excitation and not through rhodopsin conformational change, one would not expect the cosmic light flash to be closely related to the degree of dark adaption. The interval between light adaption and each event is shown in Fig. 11, which suggests for one observer after light adaption periods there is no relationship between the ability to see the cosmic ray light flashes and the period of dark adaption. However, the same observer reported these flashes were less bright than those seen by him on awakening. The statistics are poor, and hopefully future experiments will better elucidate this relationship of frequency of events to dark adaption.

The three astronauts went through a debriefing period wherein various aspects of their description and the experimental protocol were clarified, and once again a prop with a light source of variable strength was used behind different types of patterns so that the shape, character and brightness of these phenomena could be characterized. The brightness, shape and character were very much similar to the helium ion exposure; however, the length of some streaks were very much longer than those seen in the charged particle experiments on earth.

Galactic cosmic particles as the causative mechanism

The most plausible explanation for light flashes seen by astronauts is cosmic nuclei interacting with the visual apparatus. Cerenkov emission can be a contributing factor (Fazio, *et al.*, 1970), but it is unlikely to be the major mechanism. This conclusion is based on the fact that the same type of phenomena are produced by nonrelativistic nuclear particles in our earth-based experiments and corroborative experiments by Fremlin (1970) and Charman and coworkers (1971). The brightness and character of these streaks and flashes produced by nonrelativistic cosmic particles is similar to that described by the Apollo astronauts. The frequency of events of 1 - 2 min^{-1} as seen by astronauts when concentrating on observing phenomena agrees with the expected frequency of 2 - 4 cosmic particles with $Z \geq 6$ passing through the retina per minute (TFB). Further, our experiments would suggest that even slow protons and helium ions with a stopping power greater than 10^8 eV $gram^{-1}$ cm^2 (10 keV per micron) can cause the phenomenon in the dark adapted eye.

With regard to the fluxes of particles expected to penetrate the spacecraft and interact with the astronauts' bodies, it is significant to recall that near the earth protons comprise 88% of the cosmic rays, and helium ions comprise 10%; however, their maximum abundance is near 400 MeV per nucleon (Webber, 1967), thus only relatively few protons and helium ions have stopping power high enough to cause the effect. The particles most likely involved are carbon, nitrogen, and oxygen whose fluxes are about 5% the helium ion flux. The iron group ($25 \leq A \leq 28$) is about 0.3% the

helium ion flux in the energy range 150 to 250 MeV per nucleon. One can make estimates of the total number of particles which penetrate the body of an astronaut, and the number of particles that penetrate with high enough linear energy transfer to cause cell damage or death, based on published measurements and extrapolations for solar minimum (Fowler, *et al.*, 1967; Comstock, *et al.*, 1969; Freier and Waddington, 1968; Price, *et al.*, 1968; Wang, 1970; Comstock, *et al.*, 1971). Estimate of the total omnidirectional flux of ions heavier than helium bathing the spacecraft is 3 nuclei cm^{-2} sec^{-1} during solar minimum (Hafner, 1967); however, if one wishes to calculate the number of particles in a particular energy range interacting with each cubic centimeter of tissue, it is desirable to look at some actual measurements of heavy cosmic nuclei fluences. A conservative estimate of the potential hazards of high Z galactic cosmic rays can be made using data from the emulsion detector of Fowler and co-workers (1967). Based on an iron nuclei abundance of 0.4 particles m^{-2} $sterad^{-1}$ sec^{-1} (particles of kinetic energy greater than 1.5 GeV per nucleon) one can calculate that in a spacecraft which has shielding less than 4.5 grams cm^{-2} (the atmospheric penetration of their experiment), each square centimeter of the astronaut's body would receive an omnidirectional flux of 43 iron nuclei per day. There are between 10^9 and 10^{10} cells in the cerebral cortex only one-fourth of which are neurons. In any 1 cm^3 of this or other vital tissue (e.g., hypothalamus) there are about 10^6 neurons--cell diameter of 20 to 30 μm. Based on measurements of Fowler *et al.* (1967), Freier and Waddington (1968), Price *et al.*

(1968) and Munoz and Simpson (1970), one can show that at least 0.1% of the cells will be hit by an iron group particle per day. Assuming a nuclear diameter of brain neurons of 4 μm, 0.001% of nuclei would be hit. Then on a 1000 day mission 1% of the brain nuclei would be hit by a penetrating iron particle. The most conservative estimate is that based on the flux of charged particles that interacted with the astronauts' helmets. The energy transfer necessary to produce a track is greater than that for neon at 7 MeV/nucleon, which corresponds to the linear energy transfer of 530 KeV μm^{-1} which is probably more than sufficient to kill a cell in culture on nuclear hit (Todd, 1967). Based on measurements of Comstock and associates (1971), approximately 0.02% of the cells in the brain cortex would be destroyed on a thousand-day journey. For larger cells, such as Betz cells and cells found in vital centers such as the nuclei of the hypothalamus, the most conservative estimate is that 0.5% would be destroyed on a 1000-day mission. There is considerable damage to cells from particles with stopping power less than 530 keV μm^{-1}; thus we tentatively estimate a nonregenerating cell loss of 2% for a 1000-day mission during solar minima. Of course this hazard is diminished by a factor between 3 and 10 during solar maxima, but then other radiation hazards such as proton flares become important.

Because of CNS redundancy and clinically practical replacement techniques, even the loss of the cardiac pacemaker is not prohibitive to long duration missions, if we have anticipated such a compensable catastrophy. For other particles we do not know the percentage of hits which will lead to cell death. This most

certainly is a function of energy transfer, which is of course a function of particle charge and kinetic energy (Fig. 12).

The probability of destroying a vital center can be ascertained during the next few years through both theoretical, animal, and human experiments on earth and in space. There are a number of ways of obtaining ions to iron with energy near 500 MeV per nucleon in order to simulate cosmic rays. We plan to do these experiments at Berkeley where, hopefully, facilities and international experiments will gather to help elucidate the importance of high Z particles on long-term missions, and use heavy ions to probe biological systems.

Some of the ways of examining the effects of high Z particles on biological tissue are:

1. Mammalia cell curvival and repair studies (Todd, 1967).
2. Nerve culture survival studies (Mamoon, 1971).
3. Mammalian *in vivo* brain exposure (Haymaker, *et al.*,1970).
4. Insect mutation aberrations.
5. Seed response (Bücker, *et al.*,1971)
6. Whole animal survival studies in penetrating beams of carbon, nitrogen, neon, and iron.
7. DNA break and repair studies (Christensen, *et al.*,1971).
8. *In vivo* vital center exposure to charged particles at low dose rates (carbon, neon, and iron particles at 500 MeV/nucleon).
9. Retinal ERG and EEG decay vs. dose studies for various LET and dose rates (Gaffey, 1964).
10. Extrapolation from dose vs. histopathological effects on CNS tissue, e.g., retina.

11. Calculations of number of cells destroyed using cosmic nuclei abundance and energy spectra data, LET vs. survival.

Summary

Experiments conducted on earth at cyclotrons together with observations made by Apollo astronauts suggest with little doubt that cosmic nuclei interacting with the visual apparatus cause the phenomenon of light flashes seen on the four Apollo moon missions (Table 3). Our experiments with high and low energy neutron beams and 5 cm range helium ions suggest that slow protons and helium ions with a stopping power greater than 10^8 eV $gram^{-1}$ cm^2 (10 keV/micron) will cause light flashes and streaks in the partially dark adapted eye. We have demonstrated the fact that charged particles induced by neutrons and helium ions can stimulate the visual apparatus, and have indicated some approaches to understanding the long term mission effects of galactic cosmic nuclei interacting with man. Considering the redundancy of vital centers and regeneration capabilities and adaptation of the human system, it is unlikely that even two percent loss of nonregenerating cells will seriously hinder man's mission or postmission capabilities; however, ten percent cell loss on a long mission is still a possibility which must be evaluated in the next few years.

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Table 3

Source	Mechanism	Flux Density	Response
Mechanical	Probably retinal membrane distortion	Finger pressure to eye ball	Diffuse, sometimes colored visual patterns
Electricity	Induced action potential	0.3 mA	Brief, diffuse flashes, sometimes colored
Magnetic gradients	Action potential from induced EMF	1000 gauss/cm	Brief diffuse flashes sometimes colored
X-rays	Ionization and electronic excitation	$\geq$ 24 milliroentgen/sec	Diffuse light flood, left
Fission neutrons ^{252}Cf	Ionization by proton recoils and alpha from (n, α)	10^5 n cm^{-2} sec^{-1}	Graying of visual field. One teardrop flash
Neutrons (ave. 3 MeV)	" "	10^5 cm^{-2} sec^{-1}	Short streaks and flashes
Neutrons (ave. 8 MeV)	" "	10^4-10^5 cm^{-2} sec^{-1}	White streaks and flashes with motion sense
μ-Mesons	Ionization or Cerenkov	Cosmic ray	Coincidences of undefined visual phenomena
Pions (1.5 BeV/c)	Ionization or Cerenkov	200 μ cm^{-2} sec^{-1}	No visual response
Mesons, protons, and cosmic particles at 10,000 meters	Ionization or Cerenkov	4, 1 hr. observing periods. 30° N and 60° N	No visual response
Helium ions	Ionization	1 to 100 sec^{-1} through posterior retina	Discrete brief flashes and streaks equivalent to 1 mm image on the retina. Motion sense
Cosmic rays	Ionization or Cerenkov	~2 cm^{-2} min^{-1} ($Z \geq 6$) light and heavy particles	Various types of light flashes including long streaks

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ILLUSTRATIONS

Fig. 1: The electrical stimulation of the visual apparatus is a means of producing sensations of flash. Character of patterns varies with electrode position, rise time, and repetition rates. No pinpoint flashes of light or thin, bright streaks were noted by one astronaut and other observers with this mode of phosphene induction.

Fig. 2: Experimental setup for inducing light flashes using high energy neutrons at the Berkeley 184-inch cyclotron.

Fig. 3: Subjects' characterization of the discrete pinpoints of light seen on high energy neutron exposure.

Fig. 4: Experimental setup used to exclude x-ray phosphenes as the mechanism in the neutron phosphene experiment (Fig. 3).

Fig. 5: Comparison between the spectra of neutrons from the californium fission exposure and a 60-inch cyclotron exposure at the University of Washington. Neutron energies in the latter are above the 3 MeV threshold for (n, α) reactions on oxygen and carbon. Recoil protons from the higher energy neutrons have longer range, therefore higher probability of interacting with a number of sensitive elements in the neighboring region.

Fig. 6: Illustration of the streak seen in a low energy (~8 MeV) neutron beam from the 60-inch cyclotron.

Fig. 7: Experimental setup for the irradiation of the human retina with the helium ion beam at the Berkeley 184-inch cyclotron.

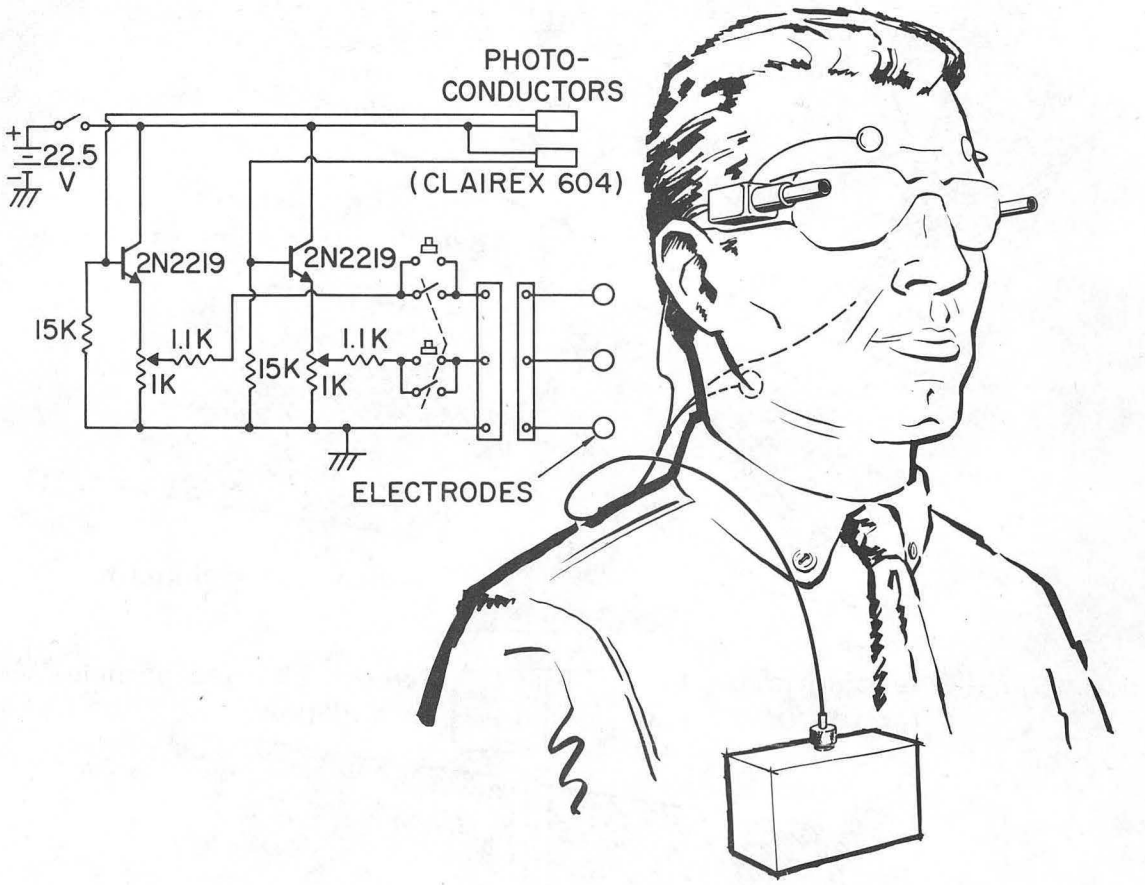
Fig. 8: A record of an exposure to 50 helium ions impinging on the human retina. Exposure of 6 seconds resulted in positive identification of 11 events, some of which were multiple streaks and flashes.

Fig. 9: Poisson interval distribution of all events reported by three astronauts during Apollo 14.

Fig. 10: Dark adaptation curve showing the 10^4 increase in sensitivity of the human eye to visual spectrum photons after adaptation (after Pirenne, 1962).

Fig. 11: Time of occurrence of events after light adaptation and commencement of dark adaptation. Shows no dependence of frequency of occurrence on degree of dark adaptation; however, statistics are inadequate for definite conclusion.

Fig. 12: Emulsion tracks of three ions showing size of track in relation to medium size nerve cell. Track width is a function of Z and residual range, thus the diagram merely emphasizes the problem of making biophysically meaningful calculations.



DBL 689-5446

Fig. 1

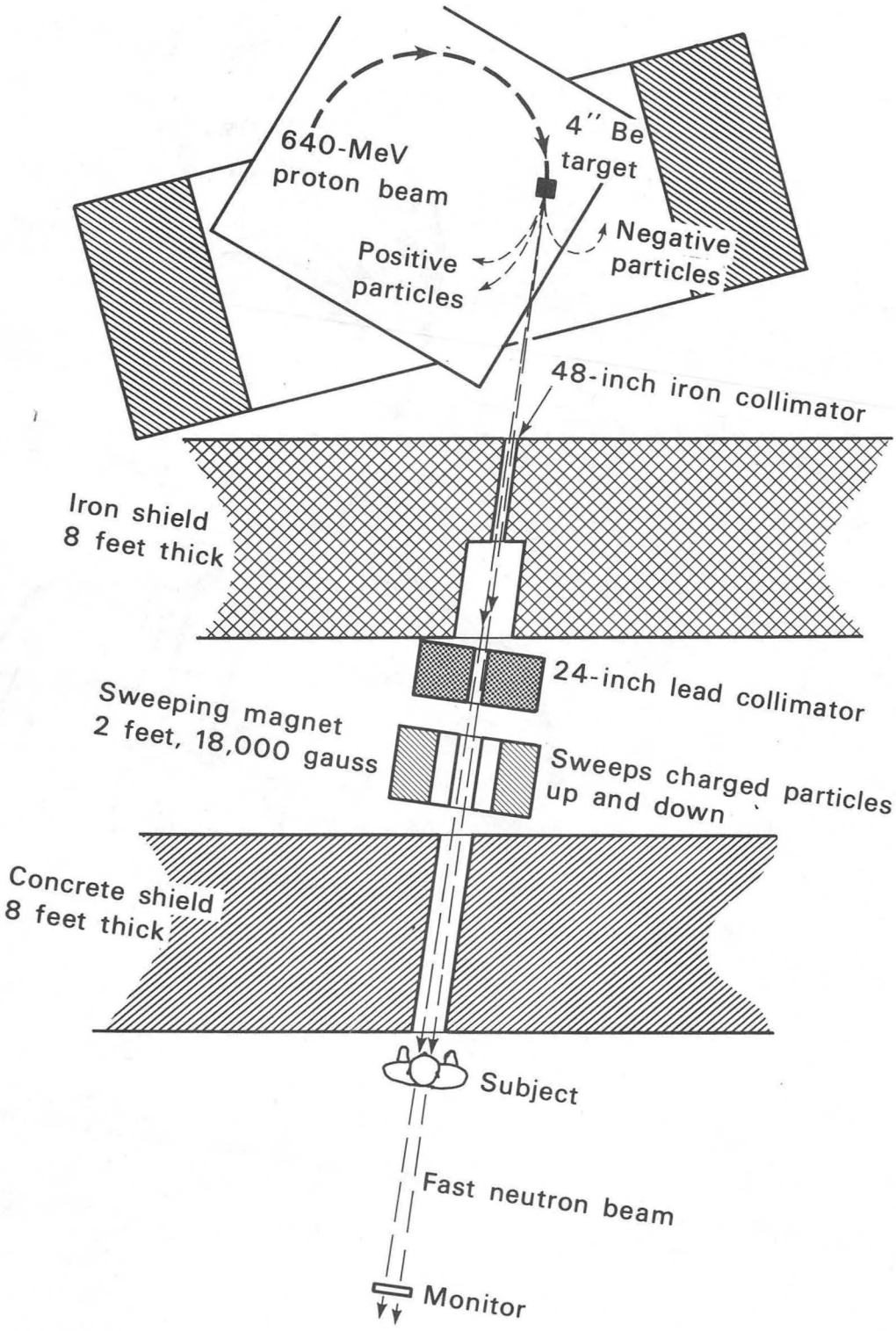


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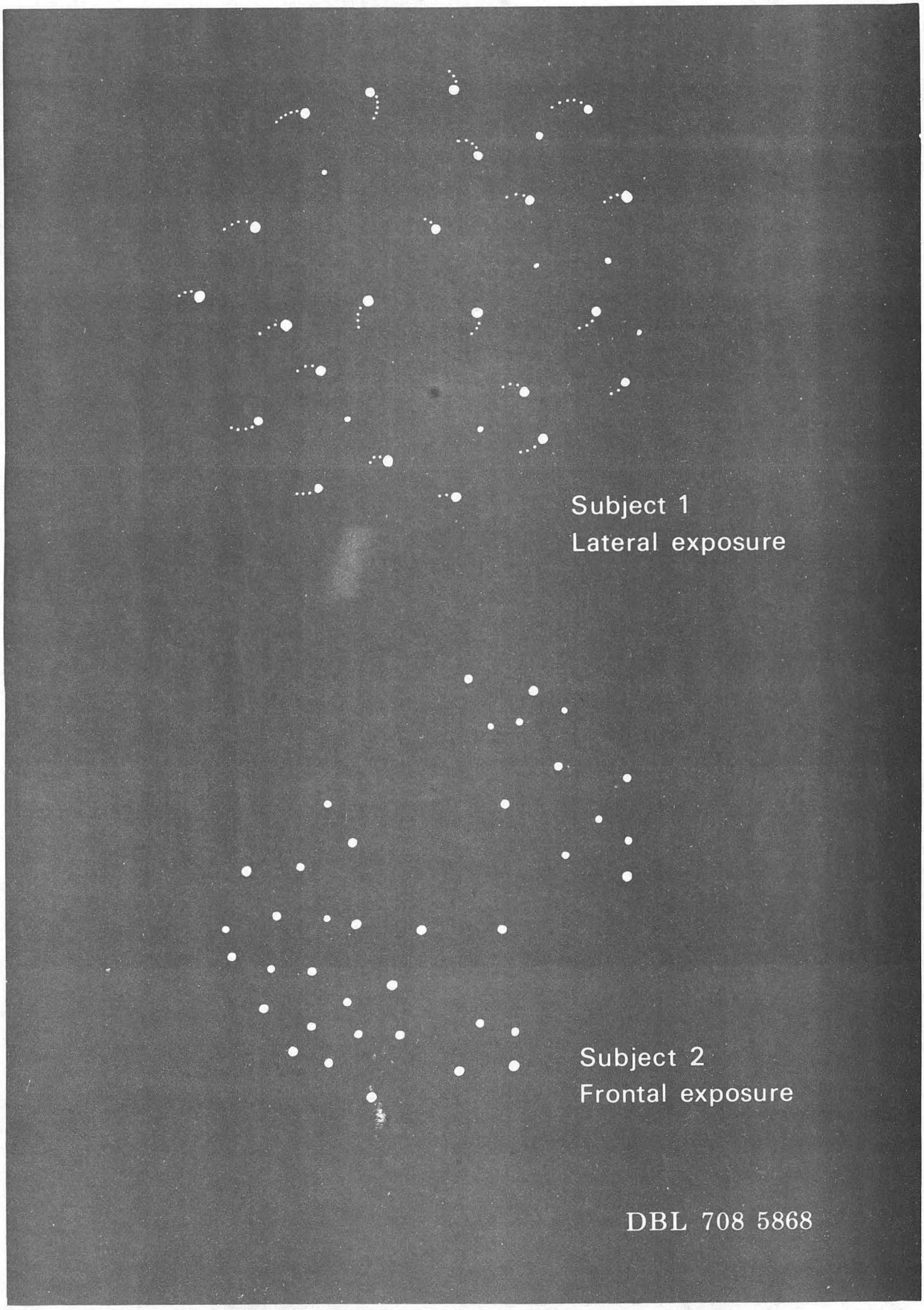
Fig. 2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Lateral exposure
Subject 2
Frontal exposure
DBL 708 5868

Fig. 3

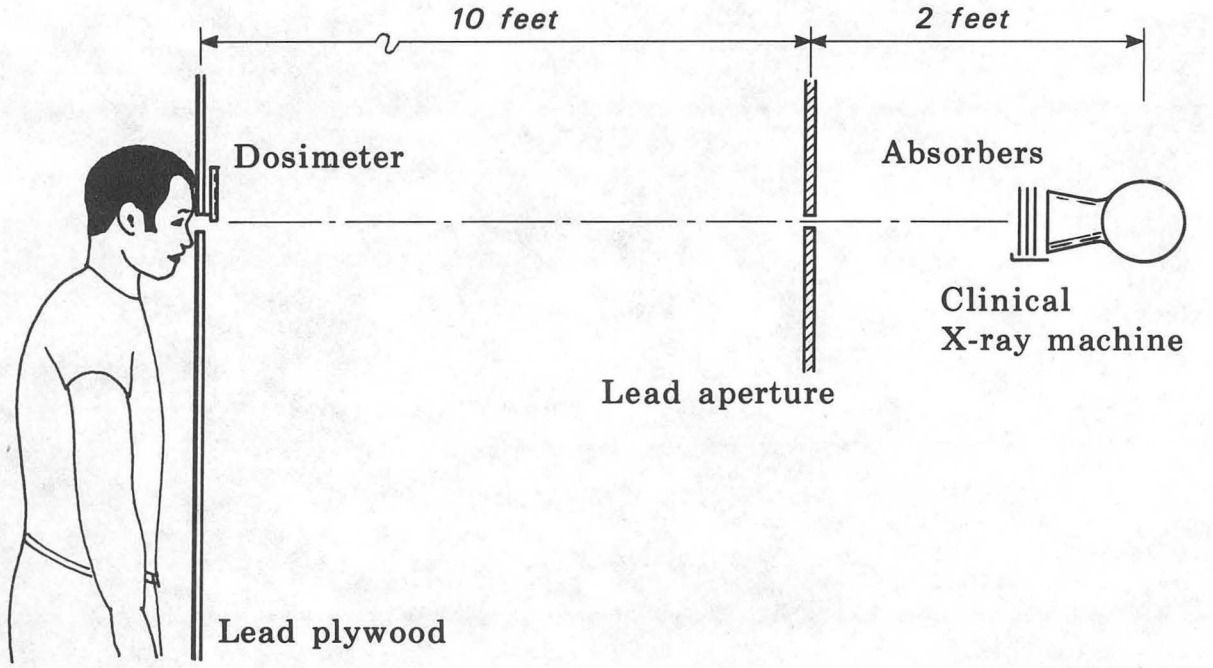

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Fig. 4

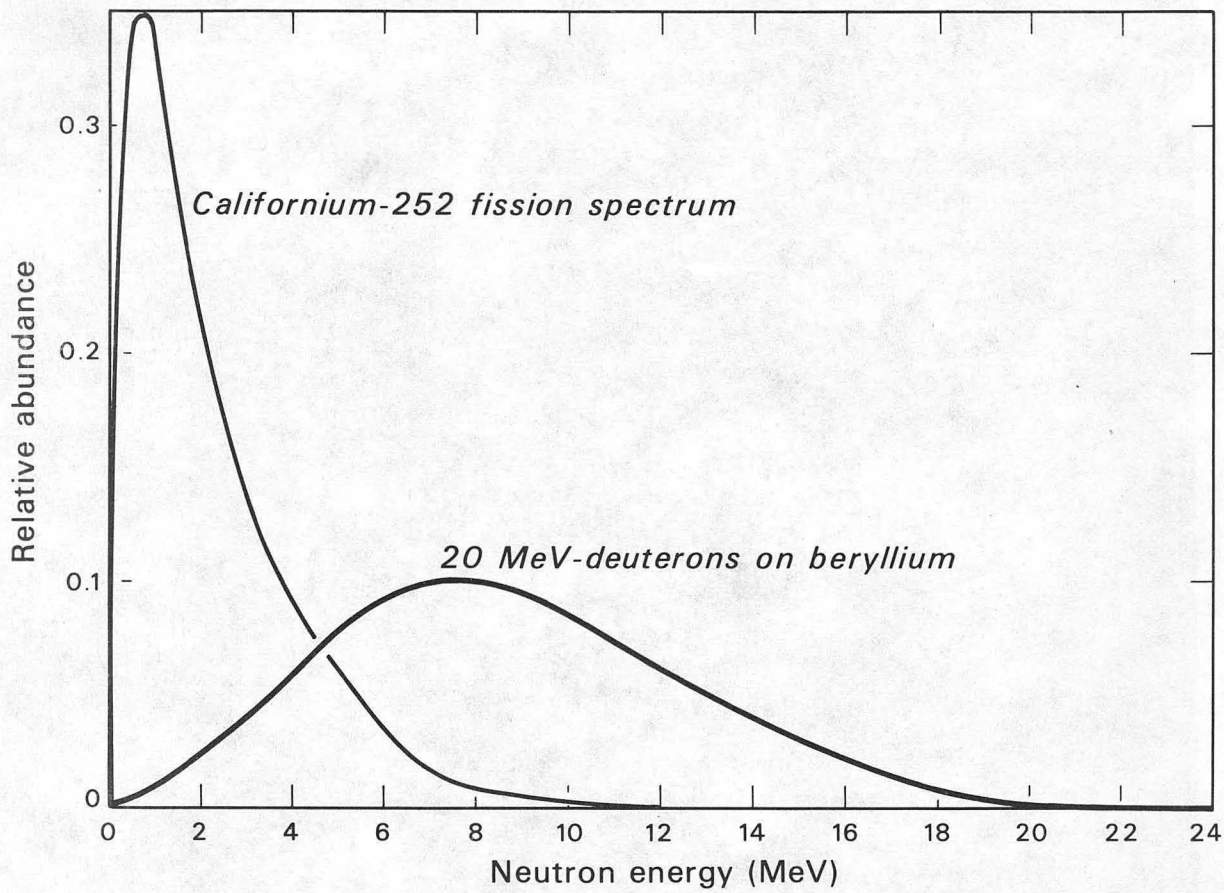

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Fig. 5

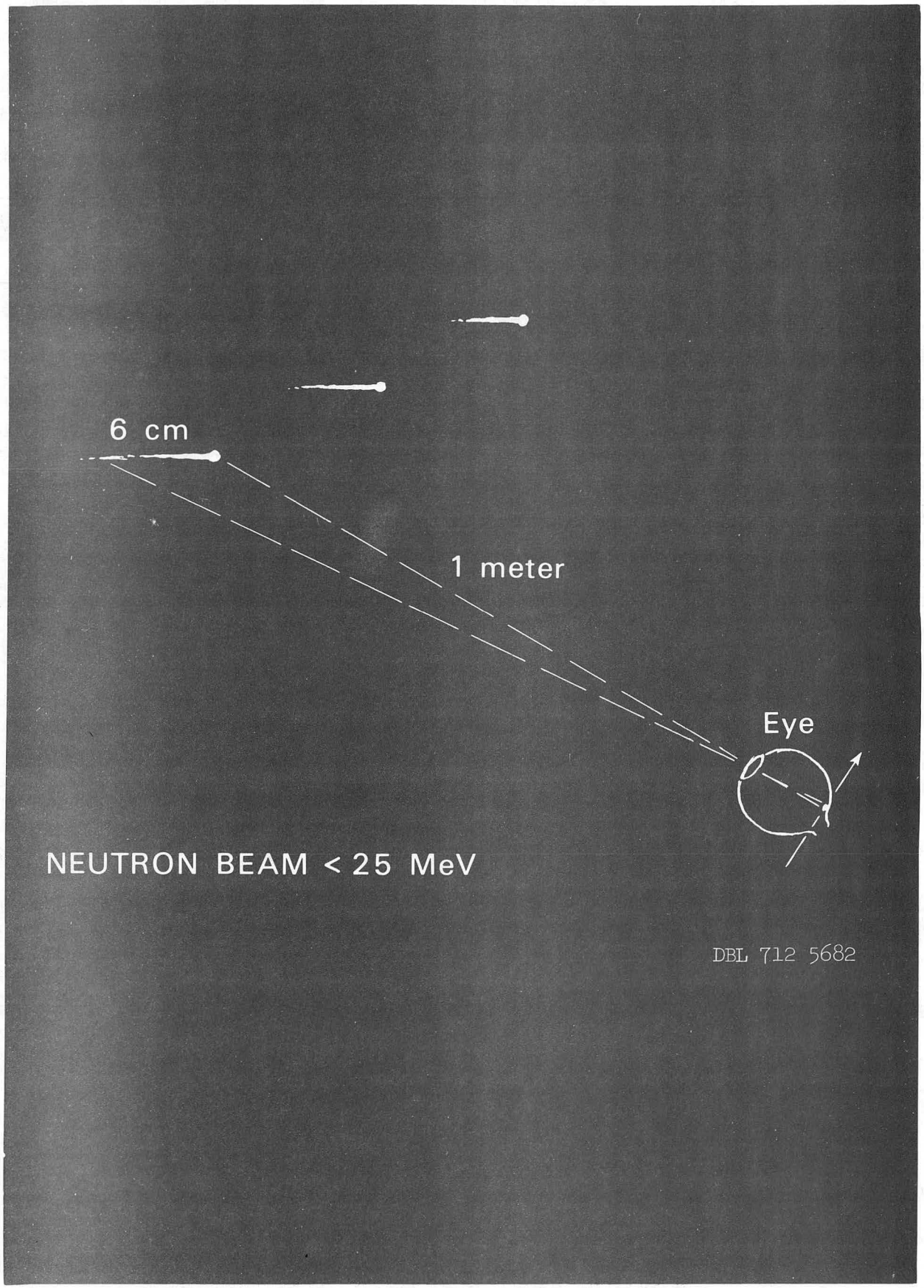


Fig. 6

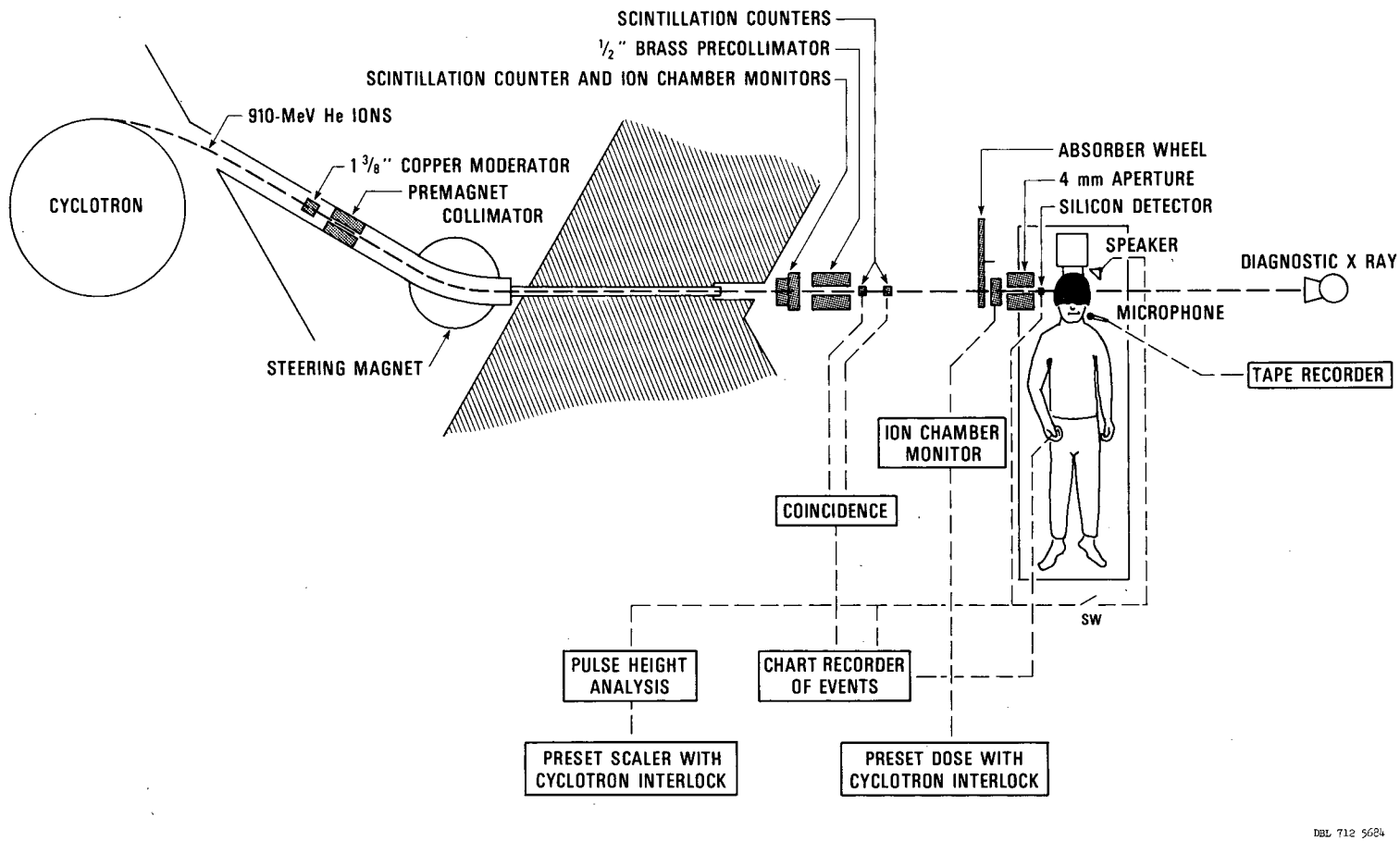

SCINTILLATION COUNTERS
1/2" BRASS PRECOLLIMATOR
SCINTILLATION COUNTER AND ION CHAMBER MONITORS
910-MeV He IONS
1 3/8" COPPER MODERATOR
PREMAGNET COLLIMATOR
CYCLOTRON
STEERING MAGNET
ABSORBER WHEEL
4 mm APERTURE
SILICON DETECTOR
SPEAKER
DIAGNOSTIC X RAY
MICROPHONE
TAPE RECORDER
ION CHAMBER MONITOR
COINCIDENCE
SW
PULSE HEIGHT ANALYSIS
CHART RECORDER OF EVENTS
PRESET SCALER WITH CYCLOTRON INTERLOCK
PRESET DOSE WITH CYCLOTRON INTERLOCK
DBL 712 5684

Fig. 7

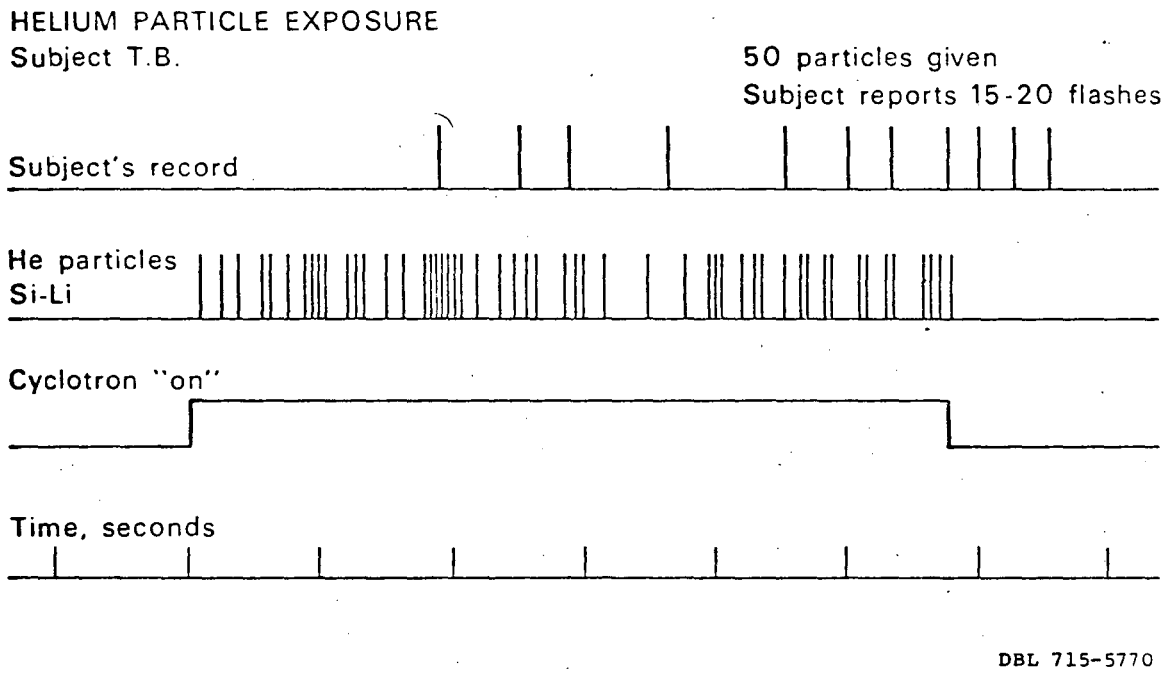

HELIUM PARTICLE EXPOSURE
Subject T.B.
50 particles given
Subject reports 15-20 flashes
Subject's record
He particles
Si-Li
Cyclotron "on"
Time, seconds
DBL 715-5770

Fig. 8

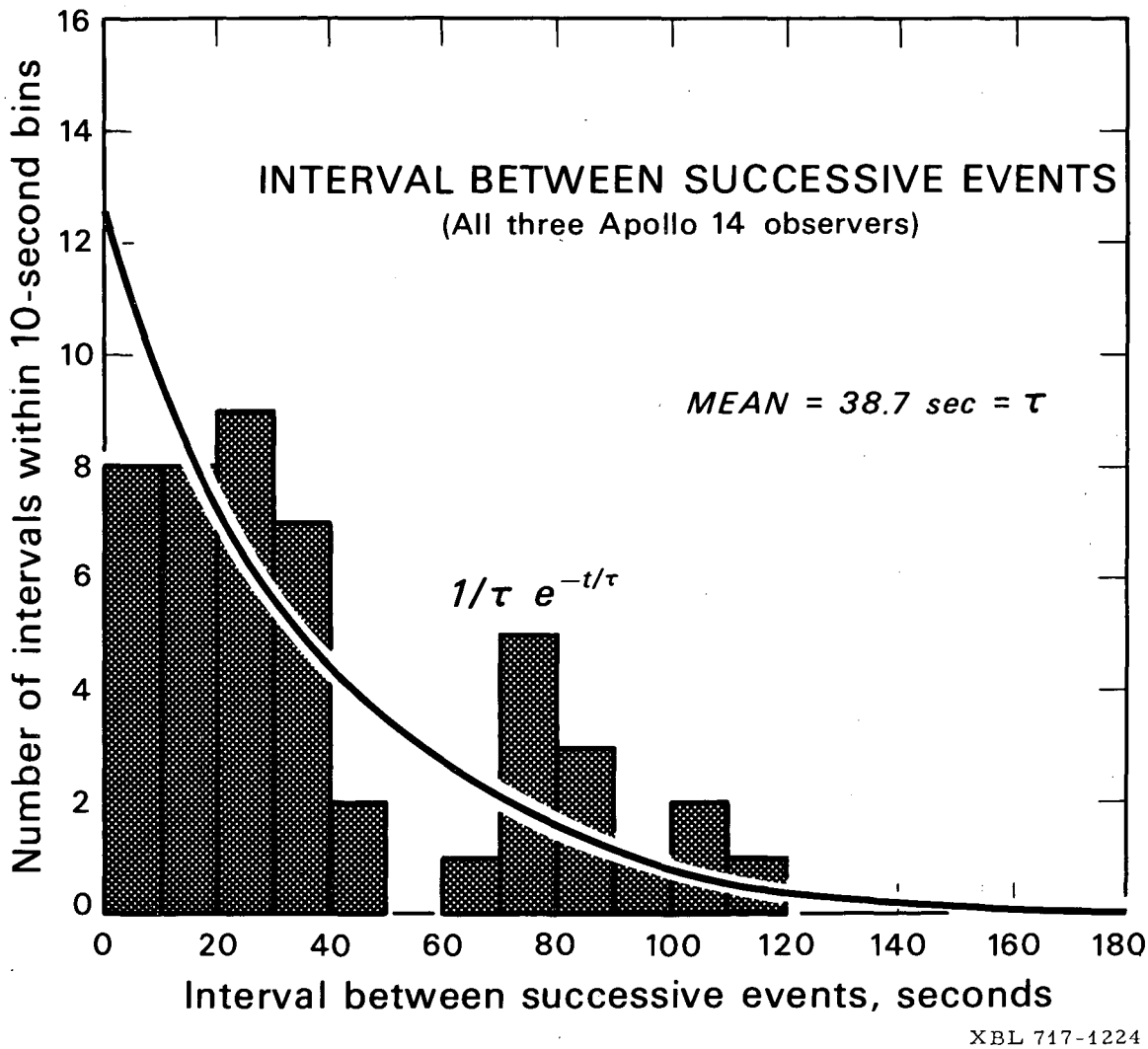
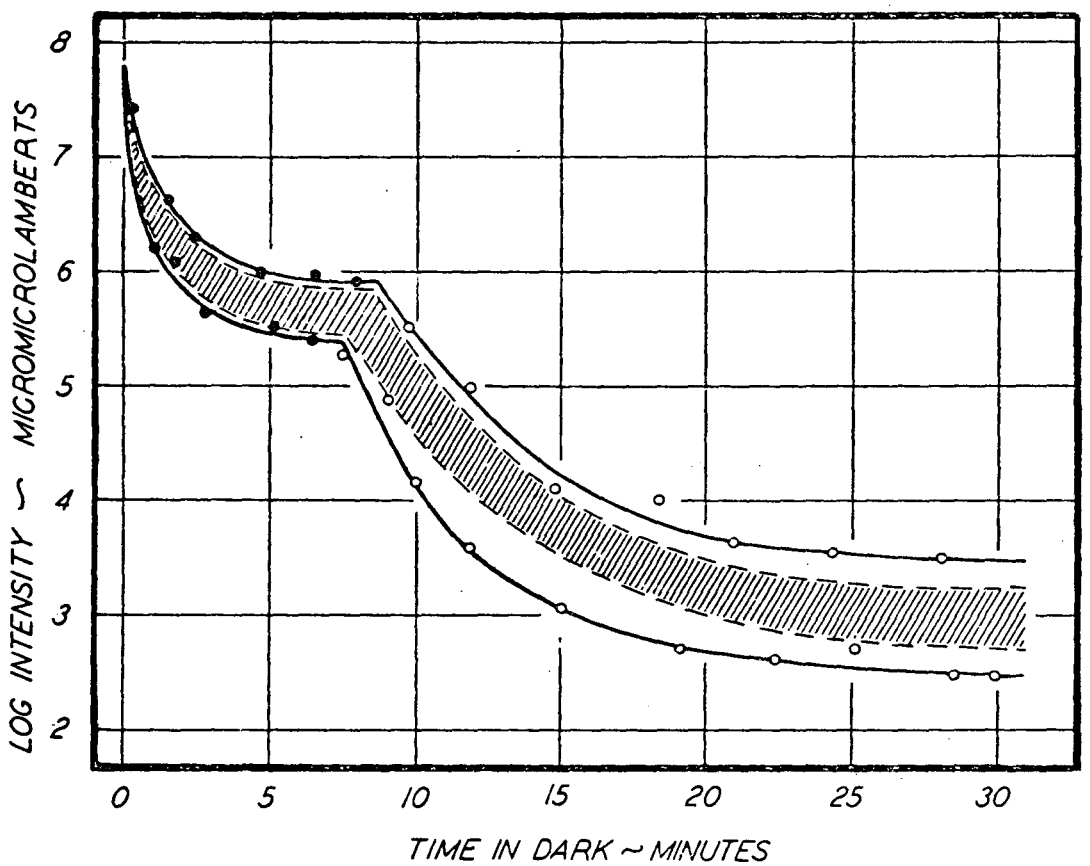

INTERVAL BETWEEN SUCCESSIVE EVENTS
(All three Apollo 14 observers)
MEAN = 38.7 sec = τ
1/τ e^{-t/τ}
Number of intervals within 10-second bins
Interval between successive events, seconds
0
2
4
6
8
10
12
14
16
0
20
40
60
80
100
120
140
160
180
XBL 717-1224

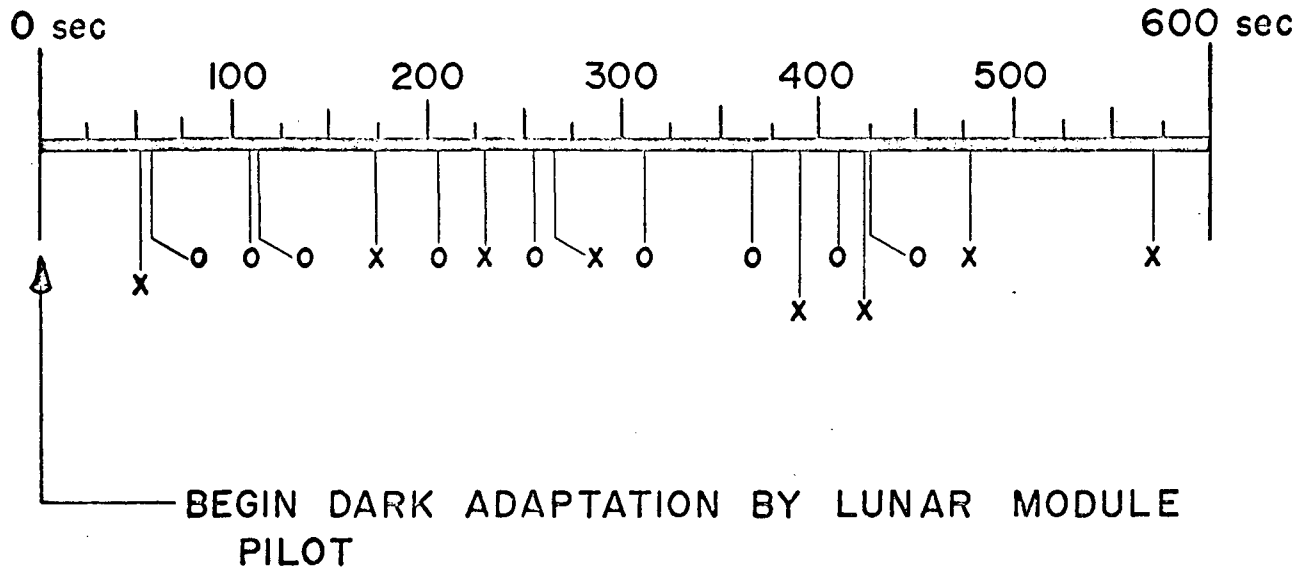
Fig. 9



XBL 716-1081

Fig. 10

DARK ADAPTATION TIME-LINE



X — EVENTS OCCURING AFTER THE FIRST ILLUMINATION

O — EVENTS OCCURING AFTER THE SECOND ILLUMINATION

Fig. 11

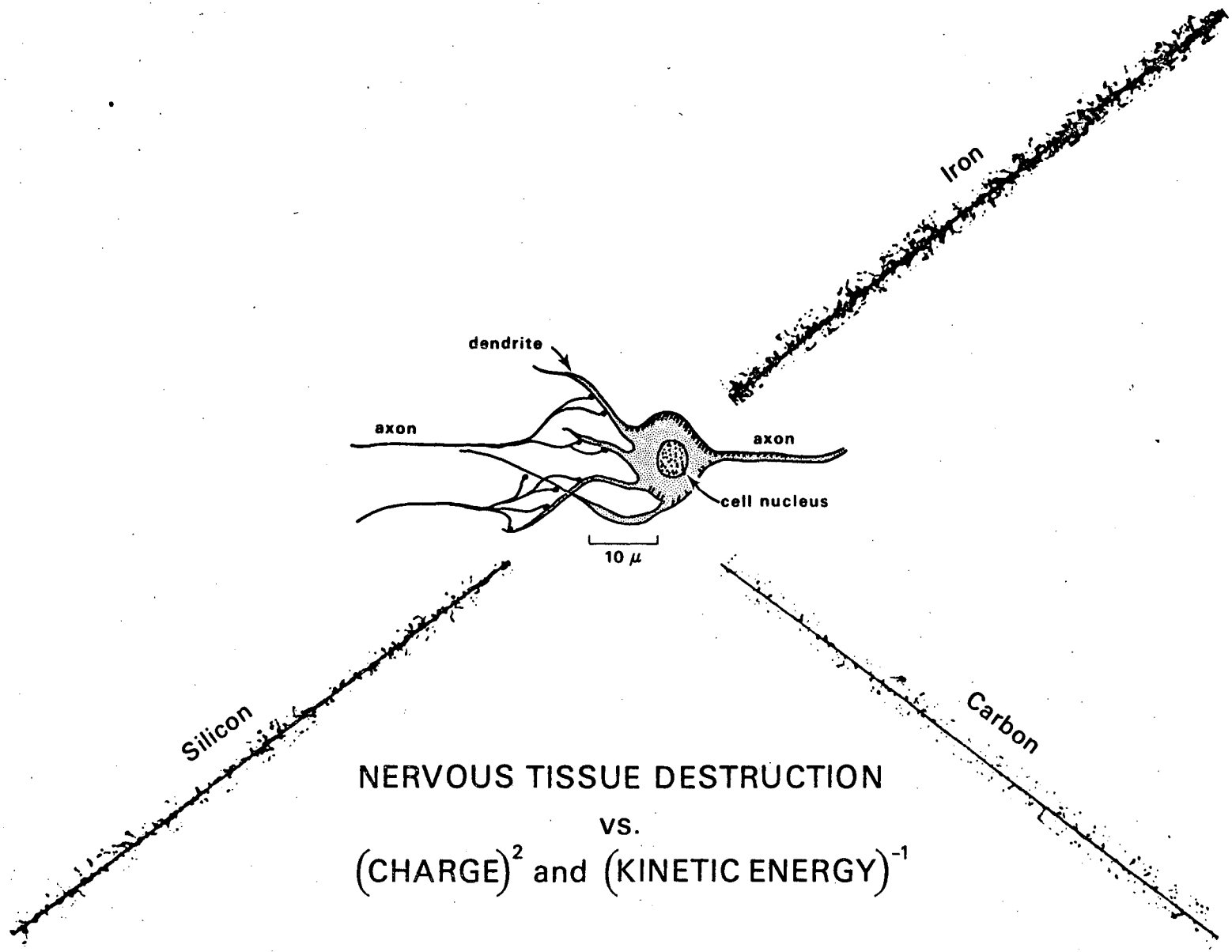

Iron
dendrite
axon
axon
cell nucleus
10 μ
Silicon
Carbon
NERVOUS TISSUE DESTRUCTION
vs.
(CHARGE)^2 and (KINETIC ENERGY)$^{-1}$

Fig. 12

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