Submitted to Science

UCRL-20240
Preprint c.2

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December 1970

AEC Contract No. W-7405-eng-48

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"VISUAL PHENOMENA NOTED BY HUMAN SUBJECTS ON EXPOSURE TO NEUTRON OF ENERGIES LESS THAN 25 MeV"*

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*This research is supported jointly by the U.S. Atomic Energy Commission, National Cancer Institute PHS Grant CA-12446, and National Aeronautics and Space Administration.

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Submitted to SCIENCE, 2/4/71.

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A B S T R A C T

Six subjects reported multiple star-like flashes and short streaks on exposure to neutrons produced by the impact of 22-MeV deuterons on beryllium. The probable mechanism is interaction with the retinal rods by proton recoils and alpha particles from (n, α) on C and O. These observations are similar to light flashes and streaks seen by astronauts who are exposed to high energy cosmic rays on translunar flight.

Astronauts on lunar missions (Apollo 11, 12, 13, and 14) have reported colorless light flashes during periods of dark in the spacecraft. We conclude from our discussions with astronauts Edwin Aldrin and Charles Conrad, together with debriefing records from Apollo 13, that light flashes and streaks of light are seen easily by observers in space far from earth at a frequency of 1-2/min. Explanations for these observations have been sought in terms of the interactions of cosmic ray particles with the human eye, either from direct light production by Cerenkov radiation or by electronic excitation in the eye or the retina (1, 2).

The visual phenomenon of brilliant stars reported by human subjects exposed to a neutron beam with maximum flux at 300 MeV at the Berkeley 184-inch cyclotron is most probably due to the effect of heavy recoils or heavy products of nuclear reactions induced by fast neutrons near the retina (1). Since the maximum neutron energy was 640 MeV, Cerenkov radiation from, e.g., recoil protons or pions cannot be excluded unambiguously as the source of the effect, although no visual phenomena were noted with 1.5 BeV/c (momentum) positive pions at 200 cm^{-2} sec^{-1}. Further experiments were therefore performed at lower neutron energies.

Spontaneous fission of ^{252}Cf produces approximately 3.8 neutrons per fission with an energy spectrum (3) somewhat broader than that for ^{235}U with a most probable energy near 1 MeV (Fig. 1). One human subject was exposed to a flux of 10^5 neutrons cm^{-2} sec^{-1} for 12 sec and 10^4 cm^{-2} sec^{-1} for

70 sec. He did not perceive starlike light flashes, but did notice a slight haze over the left visual field on left head exposure at 10^5 cm^{-2} sec^{-1} with an after-effect persistence of at least 10 seconds. During the 70 second frontal exposure the subject noted one tear-drop shaped brilliant white flash which appeared to be equivalent in length to 1 cm at 1 meter distance (a flash subtending 0.5 degree). The lack of frequent flash-like phenomena from this relatively low energy neutron experiment is in conflict with the results from 3 MeV (range 0.1 to 8 MeV) neutrons produced by 10 MeV protons on a lithium target for human body neutron activation experiments (4). Thus we were prompted to make observations at energies higher than the fission spectrum and took advantage of the higher energy neutrons produced by 22 MeV deuterons on beryllium during body calcium assessment by activation analysis being conducted by W. Nelp and associates (5) at the University of Washington.

In these activations patients are exposed to the neutrons produced by a current of 0.6 μA of 22 MeV deuterons from the University of Washington 60-inch cyclotron bombarding a thick beryllium target. The maximum energy is approximately 25 MeV with the greatest flux at 8 MeV (6) and a total flux of about 10^5 n cm^{-2} sec^{-1} (Fig. 1). Routinely two exposures are made, one with the beam directed at the front of the head (anteroposterior) and the other with the beam directed at the back (posteroanterior) with a total dose of 200 millirads for the whole exposure of approximately 100 seconds. The patient is located in a cubicle, and there is a TV monitor and intercommunication between the operators and the patient.

Prior to these experiments, subjects were dark-adapted for varying periods under red goggles, usually more than 15 minutes, after which further dark adaptation was achieved by mounting four layers of photographic dark cloth beneath tight-fitting goggles for a period of over 30 min (in one case 10 min). A plexiglass hood surrounding the head of the patient during the neutron radiation was lined with black paper to further prevent outside light entering the observer's eyes. During exposure of one of us, soft black cloth gogles and no plexiglass moderation was used.

Six subjects were irradiated, and all six saw a multitude of bright colorless flashes which were described as a "bunch of stars" 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 bright objects (equivalent to a few centimeters at one meter distance). In addition, although the reports varied, there was a slight lightening of the otherwise dark background at the time of appearance of the stars, and this haze appeared as if the stars were blinking behind a thin cloud. One observer characterized the events as bright stars in a dark moonless night without haze pollution. Subjects reported seeing many such events and tens to hundreds appeared at any one instant.

A special exposure series was done on one subject with four short (5-10 sec) and one 120-second exposure using fluxes of 10^3 and 10^4 n cm^{-2} sec^{-1}. Definite streaks which would have been 1 to 5 cm long if the event had occurred at one meter distance were seen on lateral exposure with some sense of direction. These flashes and streaks were like dim stars or thin whiffs of smoke, and in many respects similar in appearance to the visual phenomenon which occurs when driving in a light snow fall. The brightness varied (subject T.B. reported eight levels of brightness), and the low energy neutron induced flashes were not as bright as the high energy exposure flashes (1).

For the five other subjects who received radiation for activation analysis the onset and cessation of the phenomena were reported within one second of the beginning and the termination of neutron irradiation, which was given in four installments. The first two were done in the anterior position where the eyes were looking into the beam, and the second two in the posterior position where the neutrons had to traverse the head before arriving at the retina. On rotating from the anterior to the posterior position, the subjects reported a significant diminution in the number of events and a reduction in the intensity of the light foreground haze, as is expected considering the mean free paths of 4 - 12 MeV neutrons.

This unequivocal result of multiple, discrete, colorless flash sensations in dark-adapted patients irradiated by a neutron beam is consistent with the expectations based on the earlier experiments at 300 MeV (1) and Fremlin's results at slightly lower neutron energies (4).

A possible explanation of these effects is that recoil protons, alpha particles from the (n, α) reaction, or heavy recoils cause the visual sensation by interaction with retinal nervous tissue and probably the rod outer segment. The argument against other neural elements of the visual apparatus being the site of action is that no action potential has been produced by deposition of thousands of rads in other mammalian nervous tissue by X-rays, alpha particles or protons (6). The diminution in the number of events on exposure through the back of the head also supports the suggestion of the eye as the site of interaction.

Recoil proton interactions might be a mechanism for short streaks. No multiple discrete flashes or streaks were noted on californium-252 exposure, where the number of proton interactions is hundreds of times that from higher energy neutron exposures. Recoil protons of short range interact with only one or a few rods and in sufficient numbers probably produce an effect similar to X-ray phosphenes; i.e., a haze or graying of the visual fields; however, the recoil proton ranges for the higher energy (4-12 MeV) neutron exposure at the 60-inch cyclotron is sufficient to interact with many rods in a small space. Phosphorescence from protons is a possible mechanism for the haze or graying of the dark-adapted visual field, but cannot be the mechanism of brilliant, discrete flashes. Abundance and ranges of C, N, and O recoil atoms are so low that it is unlikely these particles contribute to the phenomenon during exposures to neutrons of energies less than 25 MeV. Gamma and X-rays are at dose rates too low to induce radiophosphenes (1).

Alpha particles from the (n, α) reaction, particularly from oxygen and carbon, are present in sufficient numbers with sufficient range to account for the discrete events if only single rod interaction is necessary rather than multiple rod "hits" in a small area during a short interval. An explanation of the lack of effect from the exposure to the fission-like spectrum of a ^{252}Cf source can be attempted either in terms of insufficient energy (range) of ion recoils produced by elastic collisions, or by the fact that the threshold for the substantial production of α-particles from C and O is above 3 MeV. While the threshold for alpha production from N is at 0.16 MeV, nitrogen has an atom density of only 1.2% in tissue, and relatively few alpha particles appear on a short exposure. Lithium and boron alpha particle contributions from thermal neutron (n, α) reactions are not significant because of the very low atom densities of these atoms. Taking into account the differences in spectra, cross sections for (n, α) reactions and kinetic energies or ranges of alpha particles released from the incident neutrons of the two spectra (Table 1), we find 200 more alpha particles are produced in or reach the retina from the neutrons produced from 22 MeV deuterons on beryllium than from the ^{252}Cf fission neutrons at the same total flux.

It is usually assumed that more than four rods in a small neighborhood must be excited in a short period of time to give the sensation of a flash from visual spectrum photons (7). However, one slow alpha or other charged particle passing through the retina might be sufficient to give the sensation of a discrete light flash through direct interaction with one outer segment or combined action of delta rays, X-rays and excitations affecting a number of rods in the vicinity of the charged particle track. An alternate hypothesis is that both alpha particles and proton recoils with sufficient energy to reach many rods can cause the phenomena of flashes and streaks on the retina 1-2 mm long.

The brightness and probability of detection may be sensitive functions of Z and energy. In the vicinity of medium and high energy particle accelerators under conditions of minimal or poor shielding, there might be sufficient high energy neutrons for the dark-adapted eye of a careful observer to detect this phenomenon. It remains for future research to characterize the relationships of flash brightness and shape with charge, momentum, and trajectory.

REFERENCES AND NOTES

1. C. A. Tobias, T. F. Budinger, and J. T. Lyman, Lawrence Radiation Laboratory, Berkeley, Document No. UCRL-19868, (1970). In press, Nature.

2. G. G. Fazio, J. V. Jelley, and W. N. Charman, Nature 228, 260 (1970).

3. A. Prince, Californium-252,U.S.A.E.C. CONF-681032, 23 (1968).

4. J. H. Fremlin, New Scientist, 47, 42 (1970); M. J. Chamberlain, J. H. Fremlin, D. K. Peters, and H. Philip, Brit. Med. J. 2, 581 (1968).

5. W. B. Nelp, H. E. Palmer, R. Murano, K. Pailthorp, G. M. Hinn, C. Rich, J. L. Williams, T. G. Rudd, and J. D. Denney,J. Lab. Clin Med. 76, 151 (1970).

6. E. Tochilin and G. D. Kohler, Health Physics 1, 332 (1958); J. N. Schultz and W. A. Glass, Health Physics 13, 1237 (1967). Available spectrum is for 20 MeV, although experiment was done with 22 MeV deuterons.

7. S. Hecht, S. Shlaer, and M. Pirenne, J. Gen. Physiol. 25, 819 (1942).

8. C. Gaffey, in International Symposium on the Response of the Nervous System to Ionizing Radiation, 2d, Los Angeles, (1963), T. J. Haley and R. S. Smith, Eds. (Little-Brown, Boston, 1964), p. 243.

9. We appreciate the cooperation of Drs. J. D. Denney and W. B. Nelp in the conduct of these experiments. This

research is supported jointly by the U. S. Atomic Energy Commission, National Cancer Institute PHS Grant CA-12446, and National Aeronautics and Space Administration.

Table 1.

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 (1).

**Percent atom abundance used: Carbon, 7.2; Oxygen, 27.1; Nitrogen, 1.2.

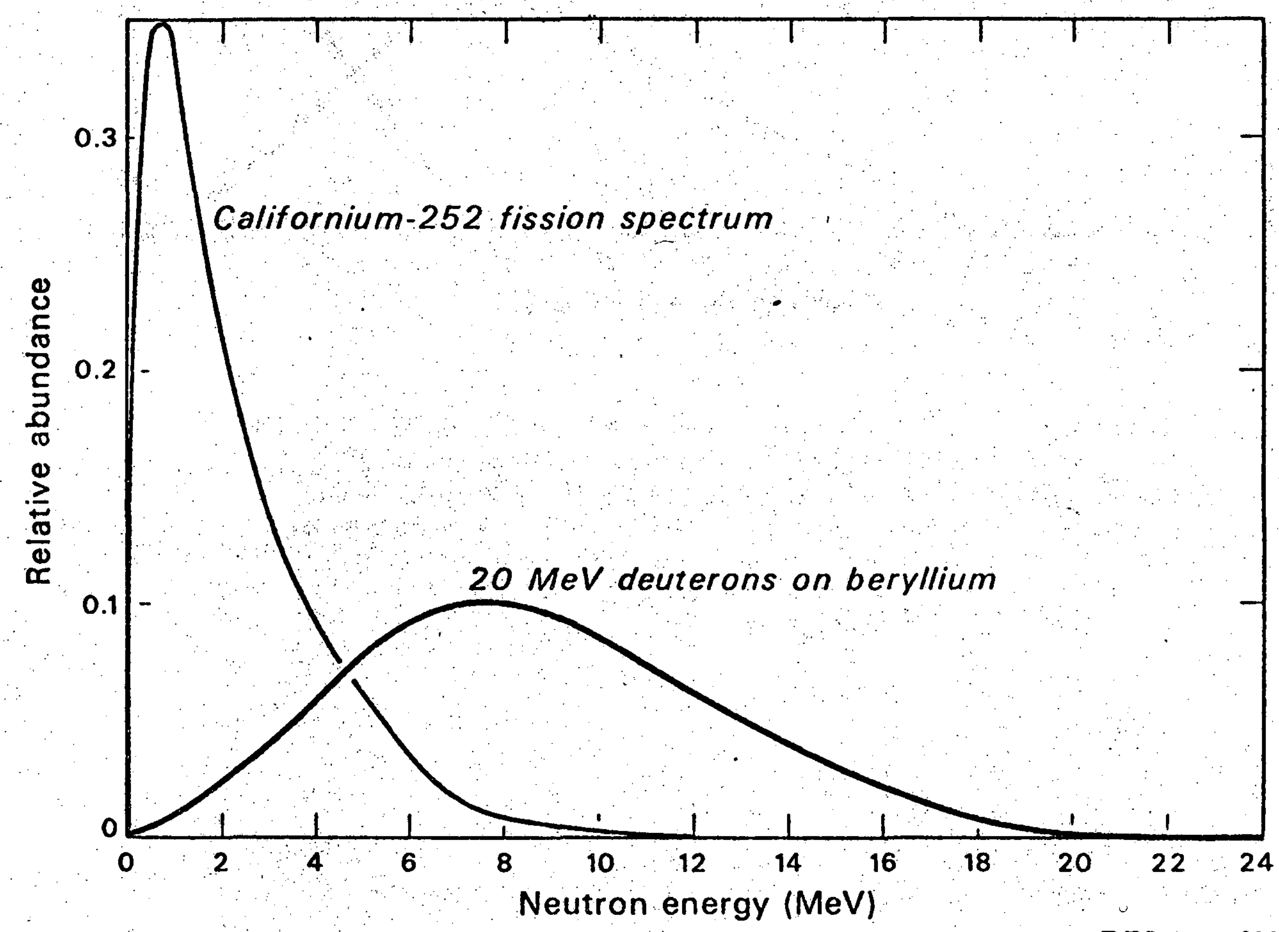

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Fig. 1: Neutron spectra normalized so that the integral of N(E) is equal to 1 for californium-252 (3) and the beam from 20-MeV deuterons on beryllium (6). Experiment used 22-MeV deuterons.

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