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The Production of a Beam of Fast Neutrons

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Well-defined, intense beams of fast neutrons have been produced by using shields of paraffin and lead in conjunction with the 8-Mev deuteron-beryllium source of a cyclotron. Essentially, the beam is delimited by an outward tapering channel through a wall of paraffin (or water) over 50 cm thick. Accompanying gamma-radiation was greatly reduced by lining the channel with 3 cm of lead and by walling the outside of the hydrogenous shield with over 2.5 cm of lead. Gamma-rays from the source are suppressed by a 3-cm thick lead filter in the channel. Ionization measurements and photographs showed that the fast neutron effects are mainly localized to a collimated beam which radiates out along the projection of the aperture through the lead channel. To distinguish between neutron and gamma-radiations the responses of small ionization chambers with different walls were studied. The ionization produced by the fairly uniform background of gamma-radiation is only a few percent of that caused by fast neutrons in the beam. With an ordinary deuteron current of 60 μa the ionization produced in air at the beam outlet by fast neutrons alone is 1.14 e.s.u./cc per min. To produce a neutron beam of this intensity would require a Rn-Be source of over 10^5 curies. The beam was found suitable for many physical and biological experiments.

INTRODUCTION

FOR the use of fast neutrons in many physical and biological experiments it is desirable to employ the radiation as a collimated beam. Although collimation is readily achieved with x-rays through the use of lead diaphragms, there is no correspondingly effective absorber for fast neutrons. Limiting diaphragms for these penetrating rays must consist of channels through large thicknesses of matter. Special problems then arise concerning the scattering of radiation by the sides of the apertures and the production of secondary radiation by the material of the diaphragms.

The design of an arrangement to collimate fast neutrons will depend on the uses contemplated for the beam. In the present case a beam was sought that would be comparable with those used in x-ray therapy, for example, a beam having an area of 50 to 100 cm^2 at 70 cm from the source with only a small intensity of radiation outside of the beam. Consideration must also be given to the thickness and type of materials for shielding the regions outside the desired beam, to the reduction of scattered and secondary radiations, and to geometrical factors that determine the disposition of absorbing material.

A further essential consideration concerns the intensity available at the outlet. Since fast neutrons necessarily demand thick diaphragms, a beam with an intensity feasible for many interesting biological experiments cannot be gained by close approach to the source but must be attained by the use of an intense source. Fortunately, the source used for these experiments, a beryllium plate bombarded by deuterons accelerated to an energy of 8 Mev in the cyclotron of Lawrence and Cooksey,[1] was adequate for the purpose; for with the prevailing deuteron currents of 60 to 90 microamperes, it was determined that the outlet of the beam could be 70 cm or more from the source and still give good intensities. This allows a thickness of 60 cm or more of absorber in the diaphragming arrangement. Fortunately, too, this thickness of paraffin or water is quite effective in attenuating the intensity of neutrons.

DESIGN OF THE DIAPHRAGMING ARRANGEMENT

As a result of its greater hydrogen content, paraffin effects a greater reduction of fast neutron intensity for a given thickness than any other practicable material, making it the most efficient and compact shielding material. Water has about 85 percent as many hydrogen nuclei per cc as paraffin, and, according to Dunning *et al.*,[2, 3] the mean free path of fast neutrons in water is 15

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[1] E. O. Lawrence and D. Cooksey, Phys. Rev. **50**, 1131 (1936).
[2] J. R. Dunning, Phys. Rev. **45**, 586 (1934).
[3] Dunning, Pegram, Fink and Mitchell, Phys. Rev. **48**, 265 (1935).

percent greater than in paraffin (5.9 and 5.1 cm, respectively). Other advantages of paraffin are that it can be molded into special shapes and stacked in various arrangements, but, where large masses of shielding material are needed, water is more economical and more easily transferable.

The shielding to be expected of thick, extensive diaphragms cannot be calculated without taking into account the resultant scattered radiation. Values given by Dunning on the transmission of fast neutrons out of spherical absorbers are pertinent to the present problem. These may be used in estimating that a spherical shield of paraffin with a radius of 55 cm around the source will reduce the fast neutron intensity, measured on the basis of recoil proton ionization, by more than a factor of one hundred. Such a reduction was noted in preliminary measurements with the cyclotron source.

If an open channel to the source is put through the shield, fast neutrons can emerge from this channel and elsewhere most of them will have been slowed down and largely absorbed. Preliminary tests with a channel through a wall of paraffin showed that the fast neutron intensity at the outlet of the channel was much greater than the intensities aside from it, but the arrangement was unsatisfactory for general purposes because it afforded very little shielding against gamma-rays.

Not only do gamma-rays come from the source to the extent of one or more quanta per neutron, but ultimately every neutron is absorbed in a nucleus and may give rise to several quanta. Gamma-rays from the source with energies above one Mev will scatter through a paraffin shield to a much greater extent than fast neutrons. Gamma-rays created by neutron absorption in hydrogenous shields, 2.2 Mev quanta from the formation of deuterons, and those created in other surrounding materials will add in making a general gamma-ray background.

Whether lead, which is ordinarily used for gamma-ray shielding, should be used in this case depends on how much gamma-radiation is created in Pb by neutrons. Fleischmann found[4] that the "infinite" thickness yield of gamma-rays from Pb by slow neutron bombardment is but a third of that for paraffin, an eighth to a ninth of that for Fe and Cu, and about a twenty-fifth of that for Cd whereas it is only about twice that of the lowest emitters, B_2O_3 and C. Investigations of the excitation of gamma-rays by medium energy neutrons have all shown that the maximum cross section occurs in the region of atomic number 50 and that for Al and Pb the cross sections are around a fifth of the maximum. For higher energy neutrons, above 4 Mev, Grahame and Seaborg,[5] and also Soltan,[6] report cross sections for inelastic scattering that increase with atomic number and are about 0.4 of the total cross section for absorption plus total scattering given by Dunning. In most places where lead shielding would be employed, however, the average energy of the neutrons would not be high. In any event, the gamma-ray yield by neutron excitation from a thickness of lead required for a certain absorption of incident gamma-rays will be less than that for a thickness of a lighter material needed to cause the same absorption.

The most direct way of obtaining a region for experiments at the outlet of the neutron diaphragm that is fairly free of gamma-rays would be to build a lead-walled box or room outside the neutron shield. If, however, a thick lead wall is allowed to extend across the opening at the receiver end of the channel, the fast neutrons encounter a mass of lead as they emerge and can be scattered sufficiently to destroy much of the collimation effected by the channel. If, on the other hand, an opening is provided through the lead wall at the channel outlet, gamma-radiation from a large region of material around the channel is admitted past the gamma-ray shield. Both of these difficulties can be overcome by lining the channel and covering the target end of the channel with lead.

The question arises whether a lead lining, which should be a few cm thick for the necessary gamma-ray shielding, will make the channel unsuitable for neutron collimation. Although Pb nuclei are not so effective as H nuclei in slowing down neutrons, the average distances between

[4] R. Fleischmann, Naturwiss. **22**, 839 (1934).

[5] D. C. Grahame and G. T. Seaborg, Phys. Rev. **53**, 796 (1938).

[6] A. Soltan, Nature **142**, 252 (1938).

collisions in lead and in paraffin are not much different as has been shown by Dunning. Although the collisions in lead do not result on the average in nearly so much loss of energy, a neutron that undergoes even a fairly small angle of scatter in the lead will have a good chance of suffering its following collisions in the surrounding paraffin and there being robbed of its kinetic energy and absorbed. If the amount of lead used does not materially reduce the extent of paraffin shielding, the greater transmission of neutron energy that occurs in the lead will not be serious.

With these points in mind, an arrangement was set up in which some lead shielding was employed. The neutron diaphragm consisted mainly of a 55 cm thick wall of paraffin which occupied the available space between the coil tanks of the cyclotron magnet and which had a channel through it lined with an inch of lead. The receiver side of the paraffin wall was covered, except for the channel opening, with an inch of lead. To prevent energetic electrons ejected from the lead by gamma-rays, or the soft x-rays that follow ejection of electrons from Pb atoms, from affecting things exposed on the outside of the lead shield, the whole receiver side, including the end of the channel, was covered first with a sheet of Cu, 0.5 mm thick, and then a sheet of Al, 1 mm thick. At the target end of the lead-lined channel there was space provided for a filter, as much as 6 cm thick, to be penetrated by the radiation before entering the opening down the lead-lined channel. Generally a 3 cm thick lead filter was used at the target to insure that all the gamma-radiation coming from the source as well as that from the paraffin shield would be attenuated by at least an inch of lead before emerging on the receiver side of the collimation arrangement. The opening through the lead channel tapered from 3 cm by 5 cm at the target end to 7 cm by 7 cm at the receiver end. Because of the space allowed for filters at the source and for the lead shield on the outside of the paraffin, the end of the channel was 70 cm from the target. For reasons of convenience the channel was not directed along the forward direction of the deuteron beam but at an angle of about 30 degrees from it away from the cyclotron vacuum chamber. Gamma-ray shielding was not attempted in other directions than toward the source, the paraffin shield, and the cyclotron vacuum chamber. Shielding was thus not provided against gamma-rays coming from the 30-inch thick tanks of water that surround the cyclotron magnet for purposes of protection nor from parts of the cyclotron magnet and coils. Such shielding would have been heavy and awkward to handle, and it was not introduced after it was found from ionization measurements that the simple shielding already described was sufficient for many experiments.

Considerable use was made of this first arrangement, but the intensity at the outlet was less than expected. Measurements on the distribution of neutron intensity around the source showed that the intensity could be approximately doubled by having the direction of the channel coincide with the direction of the deuteron beam instead of at 30 degrees to it. Some obstructions were removed to permit this, and the second arrangement, shown in Fig. 1, was set up.

Other changes were also made in setting up the second arrangement. The central portion of the neutron diaphragm was changed from paraffin to a tank of water in order to allow draining for ease of removal. The tank also makes a support to which a double row of one-inch thick lead plates can be bolted, an increase of one inch over the first arrangement. The lead shielding is of larger extent, reaching over to the magnet yoke, which itself is a good shield. Paraffin blocks were put around the target between the magnet coils in order to slow down and absorb the neutrons at the rear of the target, thereby decreasing the amount of neutron and gamma-radiation scattered from matter outside the forward shielding and coincidentally the amount of gamma-radiation formed by neutron absorption in regions past the lead shields.

The outlet of the channel was increased to 10 by 10 cm and the opening at the target end was increased to 2.5 by 7.5 cm to allow the use of a greater portion of the deuteron beam. The source and channel are thus wider. For convenience in making clinical tests the end of the lead lining of the channel was designed to protrude 10 cm past the lead shield and to form a rounded, removable cone, the outlet of which is 70 cm from the target. When a tapered insert

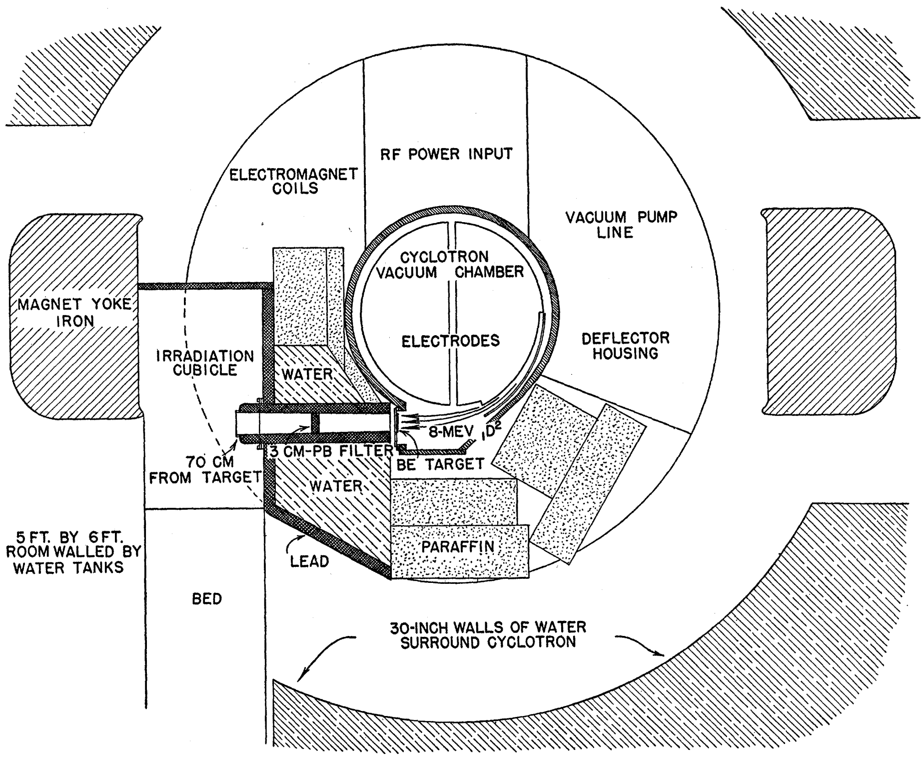

FIG. 1. Horizontal section of an arrangement used to obtain a beam of fast neutrons. In vertical directions, shielding is afforded by the poles, yoke, and coil tanks of the cyclotron magnet itself.

cone is put in the channel and a smaller sized end cone is used, a 7 by 7 cm outlet is obtained. In some experiments the removable cone can be left off and exposures can be made closer to the source. The removable cones and the lining of the channel (master cone) were cast in forms made of one-eighth inch brass sheet. This brass covering not only adds strength but eliminates any secondary electrons from the lead. Since 10 cm was taken up by protrusion of the cone and 5 cm by the lead shield, a tank of water only 50 cm thick could be used. The intensity is sufficient to allow a thicker tank, hence greater target-to-outlet distance, but the outlet then is too close to the magnet yoke for some uses. Rotation of the cyclotron chamber could avoid this.

MEASUREMENT OF THE BEAM BY IONIZATION

Because of the connection of this work with biological experimentation, the radiation measurements were made with small ionization chambers. Under conditions given by Gray[7] the ionization that occurs in a small chamber can be related to the energy absorbed from the radiation by the material of the wall. Accordingly, if the wall is comparable in composition with tissue, the ionization can be correlated with the energy absorbed from the radiation by tissue. Although accompanying gamma-rays also produce ionization in the chambers, the ionization caused by fast neutrons alone can be determined by a comparison of the ionization responses of chambers with various walls.

Technique of measurement

A series of thimble ionization chambers were made all identical in construction but of different materials. The hydrogenous materials chosen were amber, Bakelite, Celluloid, hardwood, and hard rubber. The nonhydrogenous materials suitable for the construction were carbon, aluminum, copper, brass, zinc, cadmium, tin, and lead. The chambers were cylinders with walls 1.0 mm thick, an internal diameter of 10.3 mm, a length of 21 mm, and a gas volume of 1.75 cc.

[7] L. H. Gray, Proc. Roy. Soc. London **A156**, 578 (1936).

The ionization produced in the chambers was measured by means of the Victoreen condenser-chamber and electrometer arrangement used for x-ray dosage measurements. Each chamber can be mounted coaxially on a cylindrical amber condenser of 48 cm electrical capacity which can hold several times more charge without significant leakage than the total charge (of one sign) on ions formed in the chamber by the exposures. The inner coating of the condenser is connected to an aluminum wire which extends into the chamber along its axis and serves as a collecting electrode. The outer coating of the condenser connects with the conducting part of the chamber wall, which for the hydrogenous walled chambers was an extremely thin layer of graphite. The system consisting of the collecting electrode of the chamber, the inner coat of the condenser, and the fiber of the electrometer is charged to 400 volts at the start of an exposure while the chamber wall, outer coat of the condenser, and the electrometer case always remains at ground potential. A collecting field then exists in the chamber of about 400 volts/cm at the walls and about 1000 volts/cm at the wire. During exposure to radiation this field causes a flow of ions that discharges the electrode system and the exposure or amount of ionization produced is proportional to the resultant change in potential of the system. When used with the Victoreen string electrometer of 12 cm capacity, a charge of 1.14 e.s.u./cc collected from the ionization chamber causes a shift of the electrometer fiber of one division or a change of potential of the system of condenser and electrometer of ten practical volts. In order to prevent discharge of the electrometer itself by extraneous radiation, the chamber and condenser are disconnected from the electrometer and exposed to the radiation while the electrometer is maintained charged. The only discharge is then caused by the ionization in the ionization chamber itself. At the end of an exposure the condenser and chamber are returned to connection with the electrometer and the reading is the same as if the connection had been maintained during irradiation and no ionization had occurred in the electrometer. In order to maintain an adequate collecting field, readings are not taken for a fall of potential below 200 volts. The amber insulation that is between the

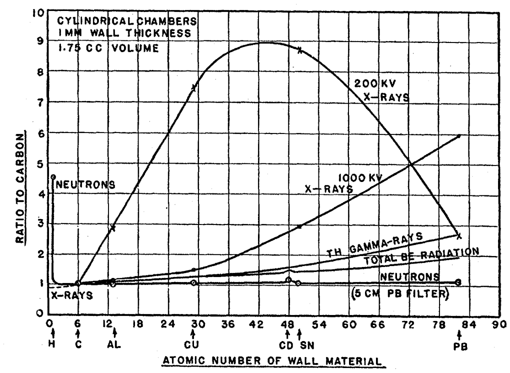

FIG. 2. Relative responses of thimble ionization chambers of different wall materials to various radiations.

collecting electrode and the chamber wall is practically covered by an insert of the same material as the chamber wall to prevent amber from being the effective wall for this region of the chamber.

Responses of the chambers to different radiations

Exposure of these ionization chambers to different kinds and qualities of radiation has shown that their relative responses are characteristic of the radiation and that a comparison of the responses is valuable in diagnosing the character of a radiation that arises for measurement. The results of exposing the chambers to x-rays, gamma-rays, and neutrons are shown in Fig. 2. The reading of each chamber relative to that of the carbon chamber for the same exposure is plotted against the atomic number of the material of its wall. The abscissa marked H does not represent a pure hydrogen wall but instead, amber, the material used having the most hydrogen per gram. The values for the latter were plotted at this position to indicate the effect on the response of adding H atoms to the wall material.

The curve marked 200-kv x-rays was obtained with the x-rays from a 200-kv x-ray apparatus after filtration through 0.5 mm of Cu. The average energy of the quanta was around 100 kev. One sees that there is a rapid rise of the response produced by changing the wall from C to Al to Cu, but that the rise from Cu to Sn is not large, while from Sn to Pb there is a large decrease in the response. The rapid rise is to be expected from an increased production of photoelectrons, the production per electron increasing as the cube of the atomic number. The actual response does not increase nearly so rapidly as this because for x-rays of this energy the main response in C and even in Al is the result of Compton rather than photoelectric absorption. The reason for the apparent decrease in the response in this case for the elements above Cu is that the photoelectric absorption increases so rapidly that the rays are greatly absorbed in going through the millimeter thick wall before they reach the thin, inner effective region of the wall. In order to reduce the absorption the wall should be no thicker than the range in the material of the most energetic electrons produced and even then a small absorption correction enters. For the more penetrating radiations, encountered generally in the collimation tests, the absorption in the wall is not serious.

The curve labeled 1000-kv x-rays was obtained with the x-rays from a Sloan type generator[8] after filtration through about 3 mm of Pb. The average energy of the quanta was around 500 kev. The curve is lower and the rise with atomic number is less than for the softer rays, but the difference is not so large as would be expected from the photoelectric effect alone because for 500-kev quanta the Compton process plays a large part. Since the absorption in the wall is much less in this case the curve continues to rise even up to Pb, although the Pb value would be about 20 percent greater if there were no absorption.

A curve was also obtained with the gamma-rays from a mesothorium salt after filtration by 4 mm of Pb and 2 mm of brass. The average energy of the quanta was in the region of 1 Mev. As a consequence of this further increase in the hardness of the radiation there is less photoelectric response in Pb and the rise in response from C to Pb is seen to be less.

If the only process occurring were the Compton process, the total energy of recoil electrons released per unit number of electrons would be about the same in C and in Pb. The ratio of the ionizations in chambers of these materials would be, according to Gray, the inverse ratio of the stopping powers per electron for these materials. The stopping power per electron for particles of the speed concerned is possibly 20 percent smaller for Pb than for C. Thus, if only the Compton process occurred, the Pb chamber would still read a little greater than the C one. The difference in the readings will be mainly, however, a measure of the electrons arising from other processes.

On the basis of the photoelectric process a continual increase in the energy of the gamma-rays should result in a continual decrease in the difference of the Pb and C readings. However, at energies above 1.1 Mev the formation of electron-positron pairs occurs. Since the coefficient per electron for the formation of pairs increases as the atomic number, here again is a factor which makes the Pb chamber read higher than the C one. This coefficient increases with the energy of the quanta, becoming equal to the Compton coefficient at 5 Mev and far surpassing it at still greater energies.

Since the photoelectric and pair production processes vary in an opposite manner with quantum energy, one should observe a minimum in the difference of the Pb and C readings for quanta somewhere between say 1 and 5 Mev. A given difference in the Pb and C readings could be caused by quanta either below or above this minimum. The different variation of the processes with atomic number would allow one to tell by using chambers made of other elements whether the energy of the incident quanta were lower or higher than the value at which the minimum difference of Pb and C occurs. The relative responses of the chambers have not been calibrated at enough quantum energies to allow their use in estimating the energy of incident quanta, but the method might be employed. The relative responses have been useful, however, in determining the presence of gamma-radiation.

Special mention needs to be made of the responses of the hydrogenous walled chambers to x-rays and gamma-rays. If H atoms were added to the atoms of the C wall, the response would fall slightly as shown by the dotted line labeled x-rays. However, since oxygen and traces of heavier elements are present in the hydrogenous materials that were used, enough greater photoelectric response exists for the 200-kv case to make the readings 2 to 4 percent greater than for

[8] Stone, Livingston, Sloan and Chaffee, Radiology **24**, 153 (1935).

carbon. For hard rubber, in which there is sulphur, the reading was 2.6 times that for carbon. For the 1000-kv case, all of the hydrogenous chambers gave readings practically the same as for carbon, except hard rubber which gave a 1.5 percent greater response. The Al value was only 14 percent greater than the C one. For the gamma-rays the chamber with walls of any of these light materials gave practically identical readings. The difference in the responses of hydrogenous walled and carbon walled chambers to gamma-rays will be negligible in these measurements.

The chambers were first tested for responses to neutron rays by exposure to the unfiltered radiation coming from beryllium bombarded by 6-Mev deuterons. The exposures were made 20 cm from the target so that the chambers would be closer to the target than to surrounding sources of scattered or secondary radiation. The curve marked total Be radiation was obtained. It shows a rise in response from C to Pb which is less than that for the gamma-rays from the thorium. Because of the rise analagous to that for gamma-rays, it was suspected that this rise might be caused largely by the gamma-rays that accompany the production of neutrons in this type of source. A block of Pb 5 cm thick and of sufficient extent was placed back of the target so that the radiation emerging in a large solid angle about the source was filtered through the Pb block. The observed rise of response with atomic number was then much less, as shown in the plot labeled neutrons. The responses relative to carbon for this case are Al 1.02, Cu 1.10, Cd 1.15, Sn 1.08, Pb 1.23. A further 2.5 cm of Pb filter was introduced to see if the Pb to C ratio could be further decreased. The result was Cu 1.04, Cd 1.15, Sn 1.03 and Pb 1.18. The additional 2.5 cm of Pb produced only a few percent decrease in the values relative to carbon, indicating that the 5-cm Pb filter had already absorbed most of the gamma-rays coming directly from the source. Scattered and secondary gamma-rays could still reach the chambers, and these could readily account for the 18 percent greater reading observed for Pb than for C.

The slightly greater responses for the chambers of elements heavier than carbon could also be caused by the neutrons themselves if (1) disintegrations, or (2) gamma-rays were obtained by inelastic collisions in yields that increase with atomic number. The first cannot be justified from known nuclear reactions, but the second occurs, as was first shown by Lea.[9] Grahame and Seaborg[5] using neutrons with energies above 4 Mev found a yield of gamma-rays per atom that increased with atomic number, while Kikuchi, Aoki, and Husimi[10] using monokinetic neutrons of lower energy (2.4 Mev) and Grahame and Seaborg[5] using medium energy neutrons found a maximum yield in the region of atomic number 50 and much lower yields in C and Pb. For the relative chamber responses cited above there were neutrons of all energies incident on the chambers. Putting a 1-mm thick cylinder of Pb around the C chamber made no appreciable change in the response. In a Pb-walled chamber, however, there would be more absorption of the resulting gamma-rays and for Pb atoms internal conversion is more probable; consequently it is possible that a good share of the 18 percent greater reading found for the Pb than for the C chamber could be caused by incident neutrons rather than by incident gamma-rays.

In conclusion, it seems quite safe to assume that the difference will be quite small between the response of the carbon walled chamber and that of say the Pb chamber when the effects of other radiations than fast neutrons are excluded. Since the recoils from such walls will contribute little to the ionization in chambers of the size used, the main response can be attributed to the gas inside the chamber. In the case of air, the recoil nuclei of N and O will have an average range much smaller than the dimensions of the chamber and the air can be considered to be practically under conditions of particle equilibrium. That this conclusion is justified was determined by varying the air pressure in the chambers. The ionization per gram of air remained constant from atmospheric pressure, at which the chambers are normally used, down to pressures below one-tenth of an atmosphere. Thus, for neutrons the reading of the carbon chamber can be taken as the value for the

[9] D. E. Lea, Proc. Roy. Soc. London **A150**, 637 (1935).

[10] Kikuchi, Aoki, and Husimi, Proc. Phys. Math. Soc. Japan **18**, 115 (1936); H. Aoki, Proc. Phys. Math. Soc. Japan **19**, 369 (1937).

ionization produced in air. Since carbon is effectively an air wall for gamma-rays, the reading of the carbon chamber is a measure of the ionization in air by either or both neutrons and gamma-rays.

Of course, for neutrons the chambers having hydrogen in the wall material give much larger responses than the carbon and metal walled chambers. The value of 4.55 times the carbon response, shown in Fig. 2, is for the amber walled chamber when 5 cm of Pb filter was used. No change in the ratio was detected, within an accuracy of 2 percent, when the filter was increased to 7.5 cm of Pb. When no filter was used, the ratio was only 3.70 because of the gamma-rays.

Identification of ionization caused by neutrons and by gamma-rays

It is now evident how one can obtain the ionization caused by only the recoil protons from a hydrogenous walled chamber, i.e., solely a measurement of fast neutrons. The ionization in the carbon walled chamber will in general be the sum of the response caused by incident gamma-rays and the response caused by collisions of the neutrons with the nuclei of the air inside the chamber. Both of these responses will be the same for an amber chamber as for a carbon one. Subtracting the carbon reading from the amber reading in effect subtracts from the amber reading the gamma-ray response of the chamber and the neutron response of the gas in the chamber, the difference being the reading produced only by the recoil protons from the walls.

Since the neutron ionization of the air in the Pb and in the C chambers is also equal, a similar procedure for the Pb and C chambers gives the ionization resulting only from the excess production of electrons in Pb, by any means, over that produced in C. The latter, which may be called the Pb-C electron production, can be used as measure of the presence of gamma-rays, although a small part of it may be attributable to neutrons that undergo inelastic collisions in the walls.

The effects on the responses of these chambers caused by varying the enclosed gas, the gas pressure, and the collecting voltage have been tested.[11] The results of the tests and a discussion of the validity for these measurements of the conditions specified by Gray will be the subject of a subsequent paper. For the present purposes it is sufficient to use the difference of the amber and carbon chamber readings to measure fast neutron intensity and the difference of the lead and carbon chambers to indicate the presence of gamma-rays. It is of interest to note that the hydrogen content per gram of amber is almost 95 percent of that of water and that calculations show the recoil proton response of the amber walled chamber to be within 35 percent of that of a tissue walled chamber, making it quite suitable for biological tests. Accordingly, the character, intensity, and definition of the beams achieved with the previously described arrangements were tested with these chambers.

Beam produced by arrangement 1

The first arrangement, with the paraffin diaphragm, lead shield, lead-lined channel, and 3-cm thick lead filter, was found to give a well-defined beam of fast neutrons. The intensity was fairly uniform over the area of the outlet, decreased abruptly at the edges, and then fell off from the edges of the beam with increasing distance. At 5, 10 and 20 cm away from the edge of the outlet the intensities were, respectively, less than 3 percent, 2 percent and 1 percent of the value in the beam. Increase of intensity as the edge of the beam is approached is the result of radiation that comes through the channel obliquely and thus traverses less material by going through the corners of the outlet. Such diverging radiation in the channel may arise both from a broad source and from scattering in the material around the channel. The definition of the beam at 40 cm from the outlet was still quite sharp, except for a small spread due to the extent of the source. This maintenance of definition, together with the fact that the intensity along the beam was found to fall off only a little more rapidly than expected from the inverse square of the target distance, showed that there was not a great deal of scattered radiation spreading out from the channel. Thus, the arrangement is not only a diaphragm for delimiting a beam of fast neutrons,

[11] P. C. Aebersold and G. A. Anslow, Phys. Rev. **55**, 680 (1939).

but the tapered channel, by not allowing a large divergence, effects a collimation as well.

Attenuation of the beam by paraffin was tested by putting thicknesses up to 6 cm at the target end of the channel. From the recoil proton response of the amber chamber, the mean free path of the fast neutrons in the paraffin was found to be 5.2 cm, a result close to the value 5.1 cm found by Dunning under very different conditions. That most of the ionization produced by the beam when filtered through 3 cm of Pb is caused by fast neutrons can be concluded from the ratios of chamber readings observed at the outlet: amber/C = 4.0 and Pb/C = 1.3. Adding 3 cm more Pb filter only increased the amber/C ratio to 4.2 and decreased the Pb/C ratio to about 1.2. It is to be recalled that without any collimation arrangement the Pb/C ratio was over 1.9 with no Pb filter, and 1.18 with 7.5 cm of Pb filter. Consequently, with just the 3 cm of Pb filter the gamma-ray content of the beam is effectively reduced, for then only a few percent of the ionization in the amber chamber, hence in biological material, exposed to the beam is due to gamma-rays. In most experiments the use of more than 3 cm of Pb filter would be inefficient because fast neutron intensity would be sacrificed just to suppress a little further the remaining gamma-rays.

Although introduction of the lead shielding greatly reduced the gamma-ray effects existent with a paraffin diaphragm alone, the shielding was not sufficiently complete to eliminate a general background of gamma-radiation. Ten centimeters from the beam the amber/C chamber ratio was only 1.03 whereas the Pb/C chamber ratio was 1.8. Putting a box with walls of lead 2.5 cm thick around the chambers outside of the beam reduced both the amber and carbon chamber readings by a factor of 6, the Pb/C chamber ratio being reduced to 1.6. This shows that the main background ionization is caused by penetrating gamma-rays. Surrounding the lead box with cadmium decreased all of the readings by about 25 percent. Thus a small amount of the background ionization results from thermal neutrons, some of which may be due to disintegration of the nitrogen of the air in the chambers.[11] The reading of the amber chamber 10 cm from the beam was 5 percent of its value in the beam. Since 5 percent or less of the reading of this chamber when in the beam is also due to gamma-rays, the gamma-ray intensity both in and out of the neutron beam is about the same. This is because there is so much scattering and production of gamma-rays in the paraffin and other surrounding materials that a nearly uniform background results. By placing lead blocks in various positions about the chambers it was found that the gamma-radiation came largely from directions in which shielding had not been attempted. If the one-inch thick lead shielding wall had been extended to form a complete box or room outside of the paraffin diaphragm, the gamma-ray ionization outside of the beam would have been less than 1 percent of the ionization in the amber chamber in the neutron beam.

Beam produced by arrangement 2

The beam of fast neutrons produced by the second arrangement, Fig. 1, also emerges from the channel and proceeds with well defined edges, but the background of neutrons outside the beam is considerably larger than for the first arrangement. The intensity drops abruptly at the edges of the outlet by a factor of ten, then continues to fall off slowly aside from the outlet. At 2, 5, 10, 20, and 50 cm horizontally from the beam the intensities are approximately 8 percent, 6 percent, 4 percent, 2.5 percent, and less than 1 percent, respectively, of the intensity in the beam. Tests showed that this larger neutron intensity out of the beam is the result of several factors: (1) a wider channel, which allows radiation to come more obliquely through the corners of the outlet, (2) the lesser neutron shielding afforded by the use of water instead of paraffin and of smaller thicknesses than 50 cm in places, and (3) a protruding end cone, from which radiation can be scattered laterally. Because the source extends only 2.5 cm vertically, whereas it is 7.5 cm wide horizontally, neutrons come through the channel less obliquely in vertical planes, and it is found, therefore, that the upper and lower edges of the beam are sharper and that the intensity near these edges is not so large. Also on the side on which the water tank is thicker the intensity is a little smaller.

The character of the beam was tested by chamber responses and by absorption. The amber/C chamber ratio was 4.25 and the Pb/C chamber ratio was 1.22. The addition of 3 cm further Pb filter in the channel did not change these ratios within the experimental accuracy, showing that already with the initial Pb filter only a small fraction of the ionization in the chambers is caused by gamma-rays. From the chamber responses and from ionization measurements in gases exposed to the beam, it is estimated that only about 10 percent of the C chamber reading (air ionization) and 2.5 percent of the amber chamber reading in the beam are caused by gamma-rays. The transmission of the beam through paraffin, C, and Pb absorbers placed in the channel was tested with the recoil proton ionization. The mean free path of the fast neutrons in paraffin was found to be 5.1 cm, agreeing with both the value from the first arrangement and that given by Dunning. For C (density 1.5) and Pb the values were 9.8 and 6.8 cm, respectively, which were also found with the first arrangement, but which are considerably higher than Dunning's values. The latter disagreements with Dunning's results could be explained by a difference of neutron energies, the paraffin values agreeing because of little dependence of the cross section of H nuclei with energy.

The background ionization by gamma-rays as compared with the neutron intensity in the beam is less with this arrangement than with the first for two reasons: (1) The neutron yield was about doubled by moving the channel to the forward direction of the deuteron beam, whereas the gamma-ray yield, which is nearly homogeneous around the target, remained the same. Accordingly, the gamma-ray contribution to the ionization in the beam was about halved, being approximately 2.5 percent of the amber chamber reading in the beam. (2) The lead shielding was extended and increased. The gamma-ray intensity outside of the beam behind the two-inch thick lead shield is in some regions about half that in the beam. In other regions where the shielding is less complete the value is about the same as in the beam. By providing one-inch thick lead walls against the coil tanks above and below the irradiation cubicle, the gamma-ray background could be reduced by over a factor of two. In any event, for most of the uses of the neutron beam this background is not important.

Although part of the more intense neutron beam obtained with the second arrangement could have been the result of increased target area, measurements of the distribution of neutron intensity around the target showed that the 30-degree change in the direction of the beam could account for the whole increase. It would have been convenient to use the neutron beam at 90 degrees to the deuteron beam, but with the uncollimated source the neutron intensity in this direction was found to be only a fifth of that in the forward direction. The greater flux of neutron energy in the forward direction of the deuteron beam is in agreement with the formation in the target reaction of a temporary B^{11} nucleus which, while moving with the momentum acquired from the deuteron impact, emits the neutron. At still higher bombarding energies of the deuteron the forward concentration of neutron energy flux will in itself be an aid in collimation.

Ionization effects by slow neutrons

The slow neutrons that occur with these arrangements need also to be considered, for they can result in ionization in two ways, first, by charged particle emission following absorption in the receiver itself and, second, by gamma-rays coming from absorption in the shields and other surrounding materials.

Although the first process occurs to a large extent in Li or B, it occurs only slightly in N and rarely in other elements. Thus, in tissue and most hydrogenous materials little ionization would be expected as a result of the slow neutrons present in the beam. This point was tested by putting B_4C or B_2O_3 screens, more than a cm thick, over the outlet of the beam or around the amber chamber in the beam. Effects of only a few percent were noted, which, because they could be duplicated with C screens, were attributed to scattering of the fast neutrons. Out of the beam, a small part of the ionization measured was ascribable to slow neutron disintegrations in the nitrogen of the air in the chambers. However, since the relative concentration of nitrogen in air is much larger than in tissue and since the biological effects of slow neutrons have not as yet been demonstrated, no serious attempt was made in this case to absorb the slow neutrons.

Since each neutron produced in the source can eventually give rise to a penetrating gamma-ray by the second process, this may be of more consequence in regard to the shielding than the first. Boron, because of its large cross section for slow neutron absorption (1500 times that of a proton) and its small gamma-ray emission, could be dispersed throughout the paraffin and water shields to reduce the resulting gamma-ray background. Simultaneously, the slow neutron background would be reduced. A test was made by adding borax to the water tank of Fig. 1 until a saturated solution was obtained. An inappreciable change was observed in the gamma-radiation observed beyond the thick Pb walls on the water tank. The test was not made without the Pb walls, for these are needed for shielding against gamma-rays from the source. Thus, unless a much greater concentration of boron could be used and unless it could be distributed throughout more of the regions around the source, little reduction of the gamma-ray background would be afforded by this method over that already produced by the necessary Pb walls. The borax did make a small difference in the slow neutron background, the ionization in a Li-lined chamber being reduced by 35 percent. Cd wrapped directly around the chamber, however, reduced the reading by over a factor of ten. Hence, the simplest and most direct way of shielding against slow neutrons, when it is desired, is to surround the receiver with a suitable absorber. Cd was found to give rise to a large gamma-ray emission, making B a much better absorber for this work. In conclusion, then, the slow neutron effects are best taken care of at the receiver, the resultant gamma-rays by Pb and the slow neutrons themselves by B.

Intensity of the neutron beam

The ionization produced in the small chambers filled with air measured at the neutron beam outlet (Fig. 1) in e.s.u./cc per microampere-hour of deuteron bombardment is 5.40 for the amber chamber, 1.27 for the carbon chamber, and 4.13, the difference, for the recoil proton response. At an ordinary steady running current of 60 microamperes the air ionization is 1.27 e.s.u./cc per min, or, subtracting a 10 percent gamma-ray contribution, 1.14 e.s.u./cc per min by neutrons alone. The strength of a Rn-Be source needed to produce this neutron ionization can be calculated from estimates given the author by Dunning which place the ionization by recoils in air at 30 cm from a one-curie Rn-Be source as approximately 1500 ion pairs/cc per sec. This is equivalent to 0.8×10^{-5} e.s.u./cc per min. at 70 cm from the source, the distance of the Be target from the channel outlet. Thus, a source of over 10^5 curies of Rn-Be would be needed to produce the above neutron beam. A beam that would require 10^6 curies of Rn-Be is readily obtainable. It should be remarked here that in comparing yields on the basis of the total number of neutrons emitted from the source the increasing forward concentration of neutron flux with increasing deuteron energy needs to be taken into account. Also in comparing the relative ionizations produced, it is to be noted that the ionization by the gamma-rays from a Rn-Be source exceeds by more than two thousand times the ionization produced by the emitted neutrons.

Photographs of the Neutron Beam

The photographic response was found to give valuable information in this work. Maps of the intensity of radiation in and around the beam outlet were quickly obtained by exposing films large enough to cover the whole region. Ordinary radiographic film was wrapped in black paper

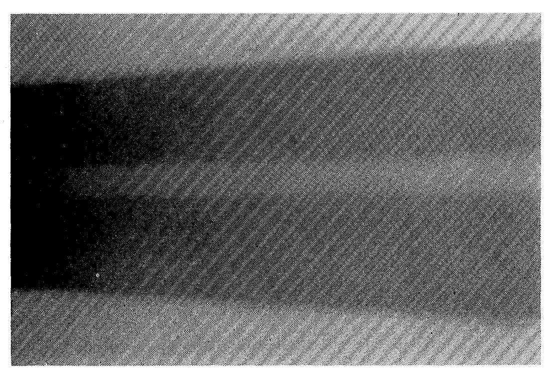

FIG. 3. Reduced reproduction of a film exposed along the axis of the fast neutron beam that emerges from the channel of the arrangement of Fig. 1. The darkly exposed region is the beam, and the lighter strip extending centrally along the beam is the shadow cast by a 3-cm thick strip of paraffin purposely inserted in the mouth of the outlet. The beam had traversed a 3-cm thick lead filter before incidence on the paraffin strip. The edges of both the shadow and the cone of radiation radiate out along sharp lines directed from the source.

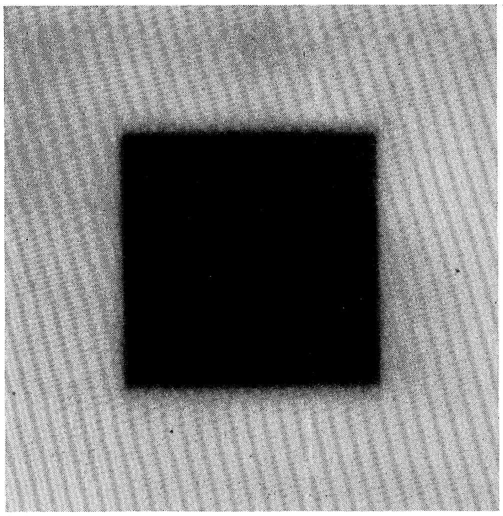

FIG. 4a. Half-scale reproduction of a film exposed perpendicularly to the beam at the outlet of the first arrangement. This film was at the surface of a body of paraffin over 20 cm deep in order to include the scattered and secondary radiations from such an irradiated body. The area exposed to the beam is seen to be sharply demarcated.

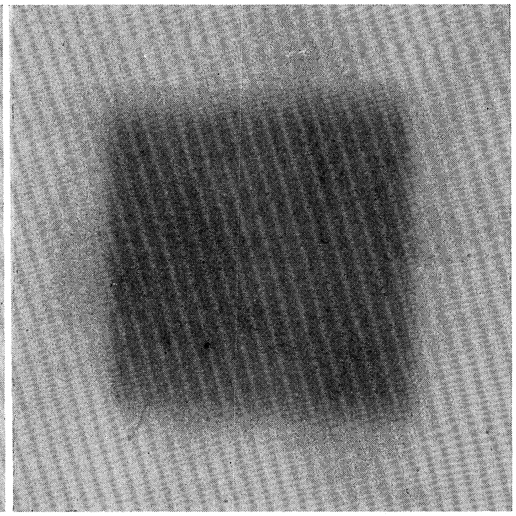

FIG. 4b. Film exposed simultaneously with that of Fig. 4a but at a depth of 11.5 cm below the surface. It is seen that a beam is maintained even through this depth of paraffin. Fuzziness of two of the edges is the result of the width of the source.

and exposed without the intensifying screens or cassettes employed in radiography. Under conditions in which mainly gamma-rays and fast neutrons are incident upon the film, the darkening can be assumed roughly proportional to the energies released in the emulsions by the radiations. A qualitative distinction of gamma-ray and neutron effects can be made by using absorption schemes or by placing emitters of secondary particles in contact with the film. The beauty of the photographic method lies in the graphic depiction of detail that is obtainable in a single exposure; also the results are more directly perceptible than those of a large number of ionization measurements. The neutron intensity could be mapped by the exposure of sheets of material susceptible to induced radioactivity, but, because of the special sensitivity of such detection to neutrons in certain energy ranges, this method is more selective than that desired in the preliminary work. If one were interested in the distribution of neutrons of specific qualities the induced activity method would be applicable.

A film was exposed in a vertical plane along the axis of the beam that emerges from the arrangement of Fig. 1. A strip of paraffin 3 cm thick was placed in the mouth of the collimating cone for the purpose of casting a shadow. In the reduced reproduction, Fig. 3, the beam appears as the darkly exposed region and the shadow cast by the paraffin is seen as a central lighter strip extending along the beam. That the beam is well collimated can be seen from the fact that the edges of both the shadow and the cone of radiation radiate out along sharp lines directed from the source. In the original the beam is 10 cm wide at the outlet and the film is 30 cm long.

Tests showed that fast neutrons are responsible for the darkening of the film along the beam. First, as seen in Fig. 3, after the radiation has traversed the 3 cm Pb filter a marked shadow is cast by 3 cm of paraffin. Second, ionization measurements showed a large difference in fast neutron intensity, but only a small difference in gamma-ray intensity, in and out of the beam. Third, thin pieces of C, Al, Cu, Pb, and paraffin placed in contact with the film gave no effects indicative of gamma-rays. Fourth, slow neutrons were eliminated as a cause of the exposures by taking pictures with the film between B_4C screens; moreover, the slow neutrons form a diffuse background. The contrast between the beam and the outer regions, which are affected mainly by gamma-rays, is not so large as it should be because of darkening due to unremoved silver, shown by development of unexposed films.

The photographic effect of the fast neutrons on the film can be readily ascribed to the recoil protons that arise in the film, the emulsion, and the paper envelope, all of which are rich in hydrogen. The exposure for the film of Fig. 3 as measured in terms of ionization at the outlet was 34 e.s.u./cc in the amber chamber (8 e.s.u./cc ionization of air). A comparison of the sensitivity of the film to neutrons and gamma-rays would be of interest, but this has not yet been undertaken. Although with high voltage x-rays only a few e.s.u./cc in air is a sufficient exposure, the exposure needed with gamma-rays would be considerably greater; consequently, it can be estimated that roughly the same ionization density in the film with both fast neutrons and high energy gamma-rays will produce the same darkening.

Penetration of the beam into a body of paraffin was demonstrated by the simultaneous exposure of one film on the surface and a second at a depth. Fig. 4a is a reproduction of a film exposed at the surface of a paraffin body consisting of slabs $3.5\times30\times30$ cm stacked to a depth of over 20 cm. Fig. 4b is from the film exposed simultaneously with that of Fig. 4a but between slabs at a depth of 11.5 cm. The beam of the first arrangement, 7×7 cm at the outlet, was directed through the body so as to pass perpendicularly through both films and thus give a cross section of the beam on each. At the outlet the beam is seen to be sharply demarcated. At the depths the intensity in the region defined by the projection of the channel is much more than that outside of it. The edges of the beam at the depths have a spread due to the extent of the source. Although scattered and secondary radiations result in about a doubling of the ionization intensity outside of the beam over that present without the paraffin, a primary beam is maintained through the paraffin that is traceable to large depths. At the 11.5 cm depth the reading of the amber chamber was about 25 percent of its reading on the surface, and the surface reading was about 10 percent greater with than without the presence of the paraffin.

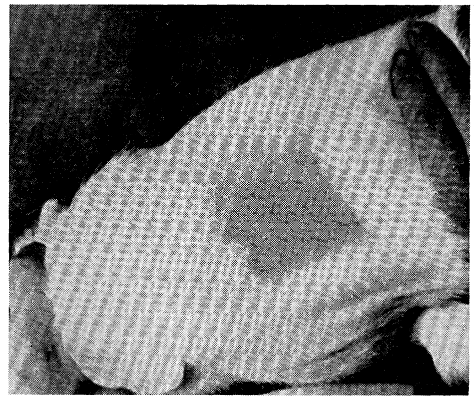

FIG. 5. Epilation produced on the back of a rabbit exposed to the fast neutron beam of Fig. 4*a*. The epilation started in two weeks and was complete after six weeks. The effect is seen to be sharply limited.

Biological Tests of the Beam

The suitableness of the beam for biological experiments that necessitate localized administration was tested by exposing the backs of rabbits to the 7×7 cm field of the first collimating arrangement. Graded exposures were given, and the region of exposure was watched every few days following the irradiation. In two to six weeks the hair on rabbits given sufficient exposure began to fall out of the exposed region. On those given large enough dosage the epilation in the region was complete after about six weeks. Fig. 5 shows one of the rabbits thus treated. The region of exposure is sharply demarcated. The small background dose of gamma-rays and slow neutrons caused no noticeable ill effects upon the rabbits as a whole, and they lived for over six months, regrowing their hair in most instances and appearing normal in all respects.

Mice could be exposed so that only their tails extended into the beam, the mice, of course, being quite close to the edge of the beam. Doses sufficient to cause the tails eventually to degenerate, about ten times the whole body lethal dose, could be given without any apparent illness of the mice.

Exposures of the human skin to the beam gave well demarcated regions of erythema, tanning, and epilation, followed by recovery.

The doses required for the rabbit epilation were between five and six hundred e.s.u./cc in the amber chamber. Tests with x-rays showed that a dose three to four times as great measured by ionization in the same chamber would be needed if the radiation coming from the outlet were x-rays or gamma-rays. Whether the effectiveness of the fast neutrons will also be greater when the dose is measured in terms of the ionization resulting in the tissue is of considerable importance and, although investigations thus far indicate an increased effectiveness that is dependent on the biological object employed, the important point for the present is that for the measurements as made the biological effectiveness of fast neutrons is greater. As a result the gamma-ray background will have less biological importance, making the biological dose in the beam from fifty to one-hundred times that outside of it.

Conclusion

Although enough arrangements have not been tried to arrive at the best choice and disposition of materials for the collimation of fast neutrons, these preliminary tests lead to some general conclusions: (1) A beam of fast neutrons that is satisfactory for some purposes can be obtained by means of a channel through a wall of paraffin. The wall should be 60 cm or greater in thickness and of large extent around the source. (2) Shielding is needed against gamma-radiation that originates not only in the source along with the neutrons but in surrounding materials as the result of absorption and inelastic scattering of neutrons. Several centimeters of Pb is sufficient to reduce the ionization caused by gamma-rays from the high energy deuteron-beryllium source to a small fraction of the ionization caused by the fast neutrons. Likewise, the scattered and secondary gamma-rays can be well suppressed by using Pb several centimeters thick to line the collimating channel and to form shielding walls outside the paraffin diaphragm. (3) The Pb lining of the channel is also satisfactory for delimiting a beam of fast neutrons and, because of a different angular scattering of neutrons in Pb, it may even be better for the collimation than just a paraffin channel. (4) The smaller the source and the longer the channel, the more sharply the beam will be defined. For the best collimation the channel should taper out radially from the source to the outlet. The effect of scattering material at the back and at the sides of the source in increasing the effective size of the source needs to be considered. Also in connection with scattered, as well as with secondary, radiation the effect of the position in the channel of the gamma-ray filter is still to be investigated. (5) To reduce effectively the production of gamma-rays by slow neutron absorption, boron would have to be dispersed throughout all the materials around the source in sufficient amount to be the predominant absorber of slow neutrons in all regions. This would also reduce materially the background of slow neutrons, but for this purpose alone the more direct method is to surround the receiver with walls rich in boron. (6) By taking advantage of the greater energy and number of the neutrons emitted from beryllium in the forward direction of a deuteron beam of high energy, not only is the most efficient use made of the source but the neutron beam is more intense relative to the gamma-ray background and the collimation is enhanced.

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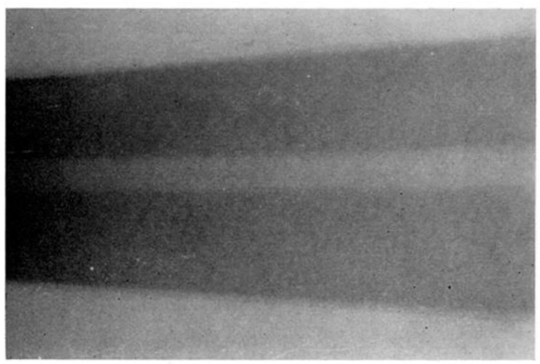

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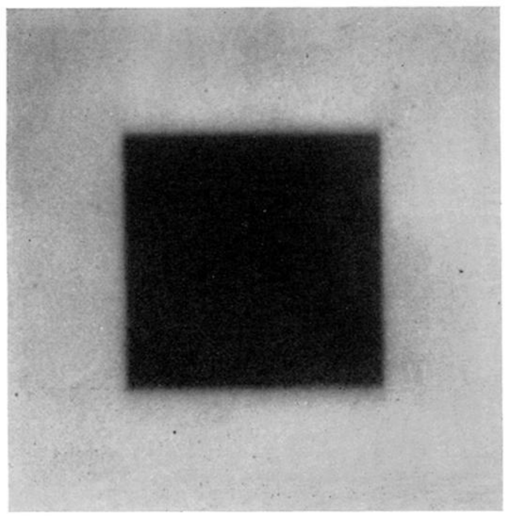

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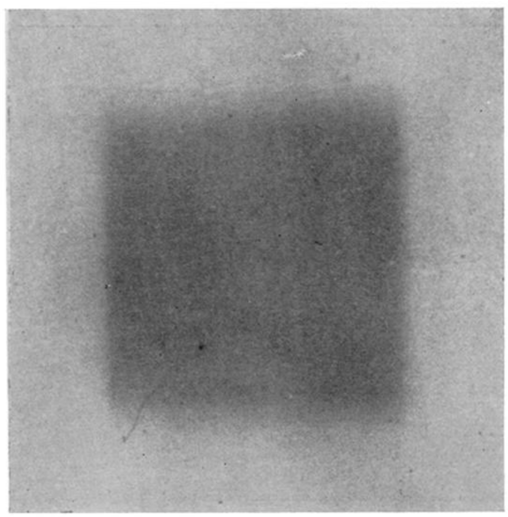

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