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The Emission and Scattering of Neutrons

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Be-radon sources, which utilize as high as 1800 millicuries of radon, and probably emit about 2 to 3 million neutrons per second, were used with an ionization chamber and an amplifier system capable of detecting individual neutrons in the presence of the gamma-radiation, to investigate the emission and the properties of neutrons. The energy distribution of the neutrons emitted under the bombardment of the three groups of alpha-particles present has been studied, and the results analyzed in terms of a number of neutron groups, which are discussed in terms of transitions involving neutrons and gamma-rays, with at least one, and possibly two resonance levels. The maximum energy of the neutrons appears to be about 14.2 MEV, and indicates a neutron mass of about 1.0068. Deuterium-radon and zinc-radon have been found to give, if any, less than 1 percent of the number of neutrons emitted by Be-radon. The interaction of high energy neutrons with matter seems to be largely one of approximately elastic collisions with atomic nuclei, resulting in scattering of the neutrons. The scattering of neutrons has been studied using interposed cylindrical specimens to scatter neutrons away from the ionization chamber, and using toroidal specimens to scatter neutrons into the ionization chamber. The collision areas computed from the scattering measurements increase with atomic weight in a manner that indicates that the effective volume of the nucleus is proportional to its atomic weight, but the classical elastic sphere collision theory is inadequate, and a wave theory of scattering must be used to obtain consistent quantitative results. The neutron "radius" indicated is of the order of 1.2×10^{-13} cm, and the nuclear radii appear to vary about as (atomic weight)$^{\frac{1}{3}}$, ranging from 2.5×10^{-13} cm for lithium to 7.8×10^{-13} cm for lead.

THE availability of large amounts of radon through the generous cooperation of Dr. G. Failla and the Memorial Hospital, has made possible the use of the comparatively high intensity neutron sources which were necessary in these investigations. The sources used in most of the work consisted of 3 to 4 mm diameter glass bulbs packed with fine Be filings, and filled with as much as 1800 millicuries of radon. Since alpha-particles from radon, Ra A, and Ra C′ are present, the beryllium is bombarded by the equivalent of more than 5400 millicuries of polonium. The total emission appears to be of the order of two to three million neutrons per second, depending on estimates of the efficiency of detection. A source of this type, small in size, highly efficient in its use of alpha-particles, and giving a large neutron emission uniformly in all directions, has advantages for certain types of experiments over the Po-Be sources of the order of 25 millicuries strength used by Chadwick,[1, 2] or those of about 150 millicuries strength used by Curie-Joliot.[3, 4, 5] In general, sources using radon and its equilibrium products do not lend themselves readily to experiments in which it is desirable to control the energy or direction of the alpha-particles, and the gamma-radiation complicates the detection problems somewhat.

DETECTION OF NEUTRONS

The neutron, as has been shown by various investigators, causes no appreciable direct ionization, but it is detectable through the ionization produced by any light nucleus projected by neutron impact from the gas in the ionization chamber, from the chamber walls, or from materials such as paraffin placed outside the chamber window. The kinetic energy transferred to the struck nucleus decreases with increasing atomic weight, and depends on the neutron energy, the direction of projection, and the nature of the interaction, while the observed

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[1] Chadwick, Proc. Roy. Soc. **A136**, 692 (1932).

[2] Chadwick, Proc. Roy. Soc. **A142**, 1 (1933).

[3] Curie-Joliot, Comptes Rendus **194**, 1224 (1932).

[4] Curie-Joliot, J. de Physique **4**, 21 (1933).

[5] de Broglie, D L'Tour, Le Prince Ringuet, Thibaud, Comptes Rendus **194**, 1037 (1932).

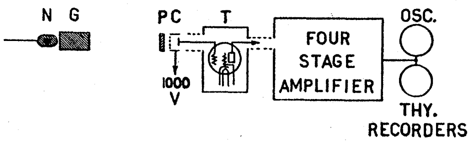

FIG. 1. Schematic drawing of apparatus.

ionization in a given chamber depends on the energy of the projected particle, its ionization per unit path (which increases with atomic weight), and the fraction of the total path lying within the chamber. Thus in a shallow chamber, the apparent ionization by a projected hydrogen nucleus (proton) may be less than that due to a short range, highly ionizing nitrogen nucleus.

A so-called linear amplifier system, with proper precautions, permits the detection of these projected nuclei in the presence of strong gamma-radiation. The features of design necessary to provide the required high sensitivity, high resolution, and discrimination against gamma-radiation are desirable in most linear amplifiers.[6, 7, 8] Fig. 1 shows the schematic arrangement of the apparatus for the detection of the neutrons. The source is placed in an approximately spherical platinum container at *N*. After traversing the 3 cm of lead normally interposed at *G* to cut down the gamma-radiation, a few of the neutrons, probably less than 1 out of 1000, passing through the paraffin disk at *P* make impacts which project protons into the ionization chamber at *C*. The rapid collection of the ions produced by a projected proton causes a sudden change in the potential of the collector and the grid of the vacuum tube *T*, and this small pulse is then amplified linearly until it is capable of operating recording instruments. The ionization chamber *C* was of the parallel plate type, 1 cm deep, and 2 cm in diameter, with a window of about 1 mm air equivalent, and sharply defined effective volume. The copper walls and Bakelite supports were made thin to reduce the scattering of neutrons into the chamber by adjacent matter. A collector potential of 1000 volts or more insured quick collection of the ions.

The initial pulse due to the collection of the ions produced in the chamber by the projected particle was first amplified by a slightly modified W.E. 259A tetrode, which was adopted after some experimentation because of its low noise level, low dynamic capacitance, low grid current, and non-microphonic characteristics. It is important however, that the internal grid current be made larger than the average value of the total ionization current from all causes for stable operation. The pulse was further amplified linearly in a four stage amplifier in which both high and low time-constant coupling circuits were used to increase the resolution, and to minimize the back-wave, the overall frequency response being approximately peaked in the region containing most of the energy of the pulse. The gain was held constant within about 1 percent over long periods by the use of balancing networks, large batteries, long-life tubes, and constant room temperatures, with slight readjustments in accordance with accurate gain measurements. The highly amplified pulse was recorded simultaneously on both an oscillograph-camera system, and a Thyratron system operating an impulse counter. To increase the resolution, the moving light beam oscillograph was designed to have a natural frequency above 5000 cycles, its sensitivity being about 0.5 mm per m.a.

Typical oscillograph records are shown in Fig. 2. The horizontal lines are 1 mm lines recorded for measuring purposes, and the lower dots are 1 minute timing marks. The base-line has a width of about 1 mm, the slight fogging near it being due to a small amount of scattered light from the optical system which shows up at very slow film speeds. The deflections are almost directly proportional to the ionization produced by the particles. Protons passing through the chamber at the optimum point of their range-ionization curve (near the end of their range) produce the maximum deflections of the size shown in 2b, while high energy protons which produce little ionization, protons just at the very end of their range, or protons crossing the corner of the chamber at a bad angle, produce small deflections.

The record by Be-neutrons shows the fluctuating background at the base-line produced

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[6] Wynn-Williams, Proc. Roy. Soc. **A131**, 391 (1932).

[7] Dunning, Phys. Rev. **43**, 380 (1933).

[8] Darrow, Bell Syst. Tech. J. **13**, 102 (1934).

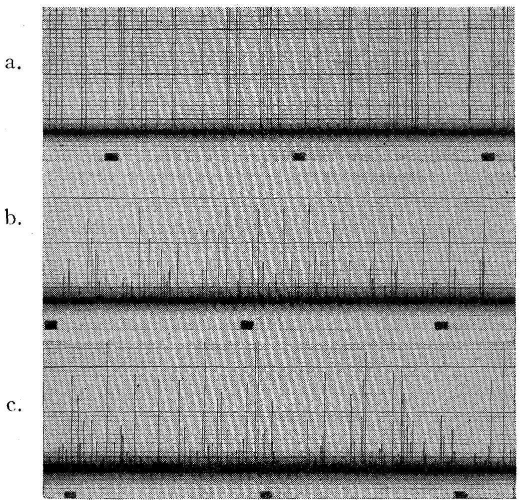

FIG. 2. Typical oscillograph records:
a. Alpha particles from polonium, reduced sensitivity.
b. Al-Po protons.
c. Be-radon neutrons.

by strong gamma-radiation. The secondary electrons caused by the gamma-radiation produce an ionization per cm of path too small to record individually, but since it is impossible to attain infinitely high resolution in such an amplifier, when very intense sources which produce large numbers of secondary electrons are used, the gamma-radiation does show up to some extent, through the small statistical fluctuations in the comparatively large ionization current due to these secondary beta-particles, because some of these fluctuations resolve into frequency components lying in the band passed by the amplifier. The effective d.c. ionization current component is suppressed, and both the high and low frequency components are highly attenuated, so that while the gamma-radiation produces very little effect, the pulses due to protons show up practically the same as in 2b. In other words, 2000 ions suddenly produced by the entry of an ionizing particle will be collected and recorded in about 1/5000 of a second, but 1,000,000 ions from gamma-radiation collected more or less uniformly over a period of one second will not be appreciably recorded. The pulses in Fig. 2c are due to two main distributions of particles. Protons projected by neutron impacts from the disk of paraffin in front of the chamber produce a distribution of proton deflections much like Fig. 2b, while oxygen and nitrogen nuclei projected from the air in the chamber produce another distribution in size of deflections. Those deflections which are above the maximum size possible for a proton, as shown in 2b, are clearly due to the large, highly ionizing projected nuclei from the air in the chamber.

Because of the small fluctuations near the base-line due to gamma-radiation, the relative numbers of neutrons entering the chamber during an experiment are determined by first picking as a new base-line some horizontal line definitely above any gamma-ray disturbance, and then counting only those deflections which are greater than that height. These deflections are then clearly due to nuclei projected by neutrons, and hence their number is proportional to the number of neutrons passing through chamber. This is quite satisfactory in practice, although in any case probably not more than 1 in 1000 to 3000 neutrons passing through a chamber of this type project nuclei whose ionization is detectable. The neutron detection efficiency is some function of the neutron energy which probably has a maximum in the region of 0.5 to 3.0 MEV, falling off at high energies, partly because of a small reduction in the neutron collision cross section, but largely because of the small ionization per cm of path by high energy protons, and on the other side, approaching zero as the neutron energy is reduced to the point where the projected protons no longer enter the chamber and produce appreciable ionization. The thickness of the paraffin further complicates this factor. As discussed in a later section, it appears that the collision cross section for neutrons with heavy nuclei probably does not vary with velocity a great deal over the range of velocities encountered, but the variation for protons is not clear as yet. If the probability of inelastic impacts of the neutrons with protons or other nuclei is some function of the neutron energy, this factor may also play some part. The presence of many particles giving small deflections, as shown on the oscillograph record, makes constant gain very important under these counting conditions, and in addition, the first or last tubes must not move appreciably from their normal operating points because of the gamma-radiation.

Thyratron circuits of both the single tube self-terminating type, and the two tube "scale of two" type[9] have been used to operate impulse counters with a resolution of about 1/150th of a second. The circuit is connected in parallel with the oscillograph, and is set to count only those pulses that are greater than some minimum amplitude which is definitely above any gamma-ray disturbance. By using W.E. 256A argon filled grid control tubes to avoid the high temperature coefficient of the mercury type, and a constant voltage power supply, these recorders proved fully as reliable as the oscillograph-camera system, and a great deal more convenient.

Neutron Emission

A study of the distribution-in-range of the protons projected from a disk of paraffin 2 mm thick placed 1.5 cm from the chamber has been made in order to throw some light on the problem of the energy spectrum of the neutrons emitted on bombardment of beryllium nuclei by alpha-particles from radon, Ra A, and Ra C′.[10, 11] In an elastic impact in which the proton is projected directly forward by the neutron, the neutron will communicate all of its energy to the proton, assuming that the masses are approximately equal. Under ideal conditions, with a parallel beam of neutrons, a negligibly thin layer of paraffin, and detection restricted to protons projected directly forward, a study of the distribution-in-energy of the protons would accurately indicate the distribution-in-energy of the neutrons, but unfortunately such studies must be made under severe limitations. This type of neutron source is sufficiently strong so that it may be placed 25 to 30 cm from the chamber, and a reasonably parallel beam of neutrons obtained, but the chief difficulty is that the number of projected protons must always be determined from the increase in the number recorded when the paraffin disk is placed in position, over the number recorded when the paraffin is removed, this comparatively large residual number representing nuclei projected from the air in the chamber or from the chamber walls. Hence the paraffin must be large enough, thick enough, and close enough to give a definitely measurable increase in the counts, thus making ideal conditions impossible. However, in spite of these limitations, and those arising from the variation of detection efficiency with neutron energy, it is possible to obtain a good deal of information from such investigations.

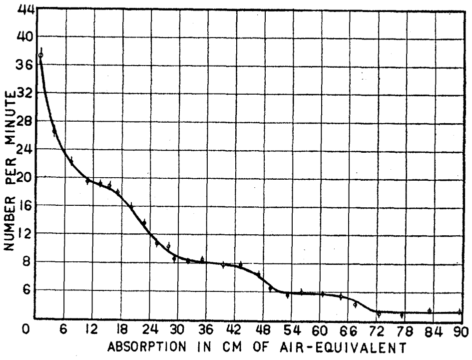

FIG. 3. Distribution in range of protons projected by Be-radon neutrons.

Fig. 3 shows how the number of protons recorded per minute varies with the air equivalent of the thickness of mica or copper introduced in the path. The number of protons per minute was obtained by subtracting the average number of deflections per minute, due largely to projected oxygen and nitrogen nuclei, which were recorded when the paraffin was not present. The points are plotted from readings each of which contain 1000 to 3000 counts, and the vertical lines indicate an estimated probable error. Since a proton causing ionization less than a certain amount is not counted, as explained before, and since a proton produces more ionization near the end of its range, the results in Fig. 3 are weighted in favor of protons near the end of their range, thus making what might be called a "semi-differential" curve, tending somewhat to convert a continuous distribution of neutron energies into a "plateau," and probably emphasizing the end of a velocity group.

While the probable error of the points plotted is such that no very close analysis is justified, any smooth curve drawn through the points indicates clearly a number of groups. There appears to be a broad group containing a large

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[9] Wynn-Williams, Proc. Roy. Soc. **A136**, 312 (1933).

[10] Dunning and Pegram, Phys. Rev. **45**, 295A (1934).

[11] Darrow, Rev. Sci. Inst. **5**, 66 (1934).

number of protons with a maximum range of about 30 cm, corresponding to neutrons with about 4.8 MEV maximum energy. A group of about 50 cm range also appears to be present corresponding to neutrons of about 6.5 MEV maximum energy, and also one with a maximum range of about 70 to 75 cm corresponding to about 8 MEV neutrons. In addition, low energy groups of the order of 0.5 to 1.5 MEV are suggested by the form of the curve.

In extending the curve to the upper limit, on account of the small number of projected protons present, it was necessary to enlarge and thicken the paraffin, sacrificing the angle conditions somewhat, and also to place lead around the source to increase the total recorded number of neutrons by scattering. A long series of readings covering more than 200 hours was necessary to get sufficient precision to be at all significant. The results are shown in Fig. 4, which indicates both the background without paraffin, and the additional protons recorded with the paraffin in position.

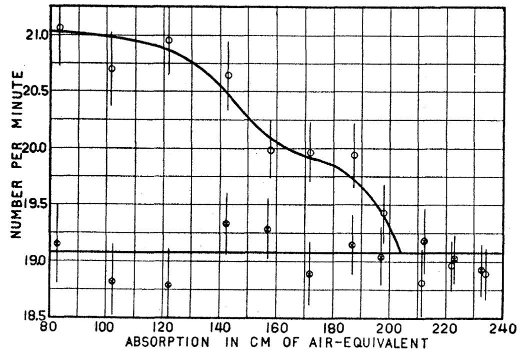

FIG. 4. High energy protons projected by Be-radon neutrons.

From the measurements as plotted, it seems probable that there is a definite decrease in the number of protons beyond 160 cm range, corresponding to about 12.5 MEV neutrons, and that some neutrons are capable of projecting protons a little more than 2 meters through the air, which corresponds to about 14.2 MEV neutrons. There is no indication that the additional secondary beta-radiation from the paraffin when it is placed in position is producing appreciable disturbance.

If we assume the reaction:

$$ {}_4\mathrm{Be}^9 + {}_2\mathrm{He}^4 + T_\alpha \rightarrow {}_6\mathrm{C}^{12} + T_{\mathrm{C}^{12}} + n + T_n $$

on the basis of $O_{16} = 16$, taking the energy of the alpha-particle corresponding to Ra C′ (7.68 MEV), making allowance for $T_{\mathrm{C}^{12}}$, the kinetic energy of the recoiling C^{12} nucleus, and using the mass values for He^4, C^{12}, and Be^9 given by Aston,[12] and Bainbridge,[13] then the neutron mass indicated by the protons with a maximum energy of about 14.2 MEV is approximately 1.0068, fairly close to the original value suggested by Chadwick. However, on account of the uncertainties in the mass values as estimated by Aston and Bainbridge, and also the uncertainty in the maximum energy of the neutrons from Fig. 4, the neutron mass on this basis might be in error by as much as ±0.0010, making possible a neutron mass as large as that of the proton, or considerably less.

No higher energy protons could be found in a long search, and this would indicate that the neutron mass is not lower than that estimated above, although admittedly such higher energy protons would not have been discovered had they been very few in number. There might be some question as to the effect on such measurements of a possible increasing probability of inelastic impacts with protons at very high neutron energies. It is also true that the above result only sets an upper limit to the mass of the neutron in this reaction, since it assumes that no energy is given off in some other form, such as gamma-radiation, but when these results on beryllium, those of Chadwick on boron,[1, 2] and those of Rutherford, Oliphant and Kinsey on lithium,[14, 15] appear to be consistent with a neutron mass very close to the same value, it seems a little difficult to reconcile this value with the very high value of about 1.012 suggested by Curie-Joliot,[16] or the very low value of about 1.0002 suggested by Livingston, Henderson, and

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[12] Aston, *Mass-Spectra and Isotopes.*

[13] Bainbridge, Phys. Rev. **43**, 36 (1933).

[14] Rutherford and Oliphant, Proc. Roy. Soc. **A141**, 259 (1933).

[15] Rutherford, Oliphant and Kinsey, Proc. Roy. Soc. **A141**, 722 (1933).

[16] Curie-Joliot, Comptes Rendus **197**, 237 (1933).

Lawrence,[17, 17a, 18] although more recently not supported by them. While the complete picture of what is happening in all of these cases is not entirely clear, the question arises as to whether the mass of the neutron may appear to have two or more different values in different reactions, and also as to the possibility of the "neutrino" playing some part in the process.

The emission of neutrons from such a Be-radon source is complicated by two major factors. The thickness of the beryllium results effectively in there being three distributions of alpha-particle energies: radon 0 to 5.44 MEV, Ra A 0 to 5.97 MEV, and Ra C′ 0 to 7.68 MEV. Thus in comparison with the Po-Be case studied by Chadwick,[2] Curie-Joliot[3, 4] and others, since radon and Ra A give approximately the same energy, we have, roughly speaking, a double group of alpha-particles with an energy slightly greater than Po (5.25 MEV), and a single group with about 2.4 MEV more energy than Po. Furthermore, since the alpha-particles have every possible direction, we have the complete range from "forward" to "backward" emission. This might be expected to leave the maximum "forward" energy of a group unchanged, and if there is the same probability of emission in all directions, should result in an energy difference between the upper and lower limits of a group dependent on conservation of momentum and energy considerations, and upon the nature of the emission process.

The work of Rasetti,[19] Bernardini,[20] and Chadwick[2] on the "excitation function" of Be^9 has suggested that at least one, and possibly two resonance levels are present, of the order of 1.4 and 2.5 MEV, and that so-called penetration over the potential barrier begins at about 3.5 MEV.[21] The work of Becker and Bothe[22] on the gamma-ray emission has seemed to indicate that this is a parallel process, but that the energy of the hard gamma-ray is independent of alpha-particle energy. The energy of the gamma-radiation is uncertain, but their measurements suggest that it is of the order of 5 MEV or more. Chadwick has suggested that this energy may be about 7 MEV.

Complete pictures of the nature of nuclear processes are of course quite impossible at the present time, but from the material available, it is possible to make a tentative diagram for the Be-radon case[10] which probably has some value, since it appears to offer some correlation of the energy relations shown in Figs. 3 and 4, even though it must lean heavily on a questionable model involving resonance levels and potential barriers.

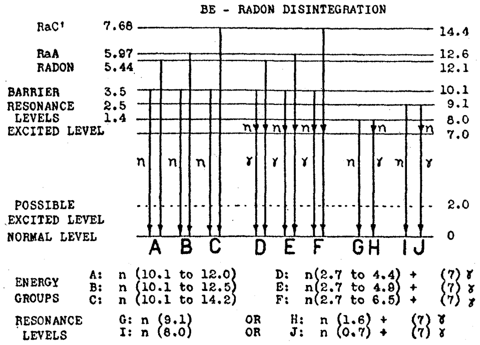

FIG. 5. Possible energy relations for Be-radon reaction.

With a so-called potential barrier height of about 3.5 MEV, alpha-particles from radon with energies of 3.5 to 5.44 MEV, from Ra A with energies of 3.5 to 5.97 MEV, and from Ra C′ with energies of 3.5 to 7.68 MEV may enter the nucleus. The new system may then return to its "normal" level by emitting a neutron with a kinetic energy appropriate to the mass-energy-momentum relations involved. The values shown on the diagram are for total energies with "forward" emission, and a correction must be subtracted for the energy of the recoiling C^{12} nucleus. Group *A*, from radon, would thus result in neutrons with energies ranging from about 10.1 to 12.0 MEV, Group *B*, from Ra A: 10.1 to 12.5 MEV neutrons, and Group *C*, from Ra C′: 10.1 to 14.2 MEV neutrons. Groups *A* and *B* may correspond to the broad group of protons which seems to have a maximum range of around 165 cm in Fig. 4, while Group *C* corresponds well

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[17] Livingston, Henderson and Lawrence, Phys. Rev. **44**, 781 (1933).

[17a] Lawrence and Livingston, Phys. Rev. **45**, 220 (1934).

[18] Lewis, Livingston, Henderson and Lawrence, Phys. Rev. **45**, 497 (1934).

[19] Rasetti, Zeits. f. Physik **78**, 165 (1932).

[20] Bernardini, Zeits. f. Physik **85**, 555 (1933).

[21] Kirsch and Slonek, Naturwiss. **21**, 62 (1933).

[22] Becker and Bothe, Naturwiss. **20**, 349 (1932); **20**, 757 (1932).

with the protons of about 200 to 210 cm range. On account of the small difference in energy, the neutron groups due to radon and Ra A alpha-particles would hardly be resolved under the experimental conditions.

The presence of the high energy gamma-radiation of quality independent of the α-particle energy noted by Becker and Bothe suggests the existence of a common excited gamma-ray level, which to fit this case should have a total energy of about 7 MEV. We may then expect an alternative process to that in Groups *A*, *B*, and *C*, which (making allowance for the rather considerable recoil energy of the C^{12} nucleus) gives transitions in which the system, after emitting a neutron, with part of the available energy, is left in an excited state, and then returns to normal by emitting a gamma-ray of the proper energy. This would result in transitions of the type shown in the second series: Group *D:* 2.7 to 4.4 MEV neutron+7 MEV γ from radon, Group *E*: 2.7 to 4.9 MEV neutron+7 MEV γ from Ra A, and Group *F:* 2.7 to 6.5 MEV neutrons+7 MEV γ from Ra C′. Groups *D* and *E*, which would be unresolved, correspond quite well to the broad 30 cm group of protons in Fig. 3, while Group *F* fits the 50 cm group reasonably well. These transitions are probably similar to those occurring in Be-Po which results in protons with a range of the order of 23 to 24 cm, as shown by the results of Chadwick,[2] the energy difference being about what one might expect from the higher energy alpha-particles.

In the case of the resonance levels, the same processes might be expected to occur. Alpha-particles entering the nucleus through the first level might result in Group *G:* 7.8 MEV neutron, and Group *H:* 0.7 MEV neutrons+7 MEV γ, while the second resonance level might result in Group *I:* 9.1 MEV neutrons, and Group *J:* 1.5 MEV neutrons+7 MEV γ. Group *G* corresponds fairly well to the 70–75 cm group of protons, while Groups *H* and *J* may account for the low energy groups suggested by the form of the curve in Fig. 3. Low energy neutron groups are also suggested by the cloud-chamber results of Feather with Be-Po.[23] While Group *I* does not show up definitely, it may be simply obscured on account of the low precision in that region, or it may indicate that only one resonance level is actually present. Group *G* also fits well with a 70–75 cm group of protons noted by Curie-Joliot, and which Chadwick also suggests, from Be-Po. This might be expected if this group is due to a resonance level.

While the variation in the efficiency of detection with neutron energy probably distorts somewhat the relative numbers apparently present in the groups, reducing the apparent number present in the upper energy groups, and also in the low energy groups, it appears that the probability of transitions involving both neutron and gamma-ray emission is considerably higher than those in which all the energy goes into the neutron. The reason for this is not apparent at present. It is possible that there may be two excited gamma-levels, which would make possible lower energy gamma-ray emission. The picture presented is probably very incomplete, although it does have rather good qualitative agreement with the curves in Figs. 3 and 4. Undoubtedly some of the gamma-radiation might be expected to be internally converted into electron-positron pairs, of the type suggested by Blackett,[24] and Oppenheimer,[25, 26] but the probability of internal conversion could hardly be large. The emission of nuclear positrons from Be does not seem to have been completely established, but it can hardly be of the same order of magnitude as the neutron emission. It is also conceivable that there may be other modes of disintegration possible, such as processes involving non-capture of the alpha-particle, or a complete break-up into two alpha-particles and a neutron, as there is considerable available energy in the latter process.

In the transformations studied so far involving supposed "capture" of the impinging particle, the assumption has usually been made that the break-up of the resultant excited and unstable system occurs almost instantaneously, all of the kinetic energy (due to the momentum imparted by the alpha-particle) associated with the center of mass of the system being divided between

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[23] Feather, Proc. Roy. Soc. **A142**, 3 (1933).

[24] Blackett, Nature **132**, 917 (1933).

[25] Oppenheimer and Plesset, Phys. Rev. **44**, 53 (1933).

[26] Oppenheimer and Nedelsky, Phys. Rev. **44**, 948 (1933).

ejected fragment and the resultant nucleus, with mass-energy-momentum relations being completely conserved over-all. While some of the cases studied show energy differences between "forward" and "backward" emission which seems to substantiate this point of view, it should be pointed out that as long as the mean life time of the intermediate excited state is less than around 10^{-16} seconds, this picture is justified, but if it is in some cases longer than about 10^{-10} seconds, then the kinetic energy associated with the centroid would be dissipated, the final disintegration taking place from a system at rest, and hence the forward energy of the ejected particle would be less than in the previous case. Intermediate mean life times would result in an intermediate distribution in energies. In such cases where the kinetic energy associated with the centroid before disintegration is appreciable, if the mean life times are longer than 10^{-10} seconds, there may thus be considerable error in mass-energy-momentum calculations if we assume complete over-all conservation, without taking into account that some or all of this kinetic energy may be lost. The recent work of Curie-Joliot[27] showing the unexpectedly long life times associated with nuclear positron emission suggests that there may be considerable justification for this point of view, and that other disintegration results should be considered carefully in this light.

The picture suggested for the Be-radon case assumed practically instantaneous conversion, and some interesting results which seem to substantiate this are obtained by studying the angular distribution of the neutrons emitted when beryllium is bombarded with alpha-particles from one direction only.[28] The source consisted of a 1 mm diameter beryllium plug sealed in the end of a cylindrical bulb containing radon, and Fig. 6 shows the recorded number of neutrons for various angles, as the source was rotated about the beryllium as a center, with two different thicknesses of lead present.

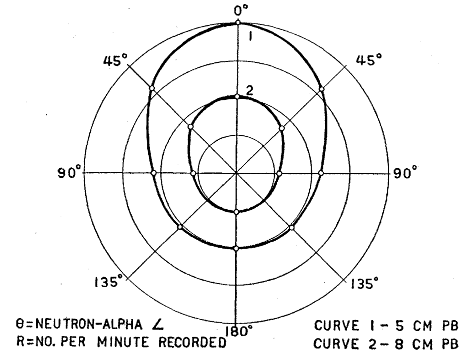

FIG. 6. Angular distribution of recorded neutrons.

The number of recorded neutrons emitted in the forward direction is at least twice as great as in the backward direction considering the angle conditions, while the scattering of the neutrons does not appear to be markedly different. On this basis, with the centroid having an appreciable velocity, and disintegration occurring within an extremely short interval, energy and momentum considerations would cause the neutrons from the resonance levels which have energies of the order of 0.5 to 1.5 MEV in the forward direction, to have their energies so much reduced in the backward direction that detection would be highly improbable. The same processes might also sufficiently reduce the energy of the neutrons due to alpha-particles just penetrating over the potential barrier so that their efficiency of detection in the backward direction might be appreciably reduced. This seems to imply that there are a large number of neutrons in the low energy groups, and this is not entirely inconsistent with the results in Fig. 3, since the low detection efficiency in this region, and the air path always present between the paraffin and the chamber may account for the difference. It may also be that some other type of disintegration process involving preferential forward emission is responsible for part of the effect. While the accuracy is possibly not much better than ±5 percent, Fig. 6 also suggests very strongly that the collision cross section for neutrons with heavy nuclei does not vary greatly with neutron velocity, since the fraction transmitted through the second thickness of lead is practically constant, although the energies must be markedly different in the forward and backward directions.[29]

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[27] Curie-Joliot, Comptes Rendus **198**, 254 (1934); **198**, 559 (1934).

[28] Dunning and Pegram, Phys. Rev. **44**, 317 (1933).

[29] Bonner, Phys. Rev. **44**, 235 (1933); **43**, 871 (1933).

Kirsch and Matzner[30] have reported a large neutron emission from Zn-radon, of the order of 50 times that from Be-Po, as determined by counting the relative numbers of scintillations caused by protons projected from paraffin. Table I shows the results of comparative tests in which Be-radon gave about 2050 neutrons per hour, and the glass bulb alone (which had a high boron content) gave about 16.4 counts per hour over a period of 5 hours, while technical grade zinc which undoubtedly contained many impurities, gave only about 15.9 counts per hour over the same period. The natural count of the amplifier was extremely low, of the order of 1 to 2 counts per hour. While the detection efficiency undoubtedly falls off below 1 MEV, it probably suffers no more than the scintillation method, and it seems that it must be concluded that the number of neutrons from Zn-radon, of energy greater than 0.5 to 1 MEV, if any, is less than 1/100 the number from Be-radon.

TABLE I. *Neutron emission from various materials.*

Source	Be-radon	Glass-radon	Zinc-radon	$H_2{}^2O$-radon
Number of neutrons per hour	2050	16.4	15.9	10.7

The disintegration of deuterium has been studied[31] by enclosing about 70 percent concentrated "heavy water," which was supplied by Professor Urey, in a small glass bulb containing radon. Allowance must be made for the boron in the glass, the partial shielding of the glass by the water, and the presence of oxygen in the water, but it appears that the number of neutrons, if any, is probably less than 1 percent of the number from Be-radon. Only a very small fraction of the "direct hits" can possibly be producing disintegration with the emission of a neutron with measurable energy. A similar result has since been published by Rutherford and Kempton for the bombardment of deuterium by Po alpha-particles.[32] While the relative energy, due to the low mass of both particles is not high, it is considerably greater for the Ra C′ alpha-particles than for Po alpha-particles, with no apparent difference in the results, and it seems that it must be concluded that the deuterium nucleus is comparatively stable under bombardment of alpha-particles of these energies, at least to the extent that its probability of disintegration seems to be not more than 1 in 10^7 alpha-particles. The experimental conditions are such that these studies are not definitely in contradiction to the experiments of Lawrence and his co-workers[17, 18] on the apparent break-up of the deuterium nucleus when it is projected against heavy nuclei, since the minimum observable disintegration may have been about the same order as the effects observed by Lawrence. The comparison with the case of the bombardment of deuterium by protons[33] is not entirely obvious, since the real nature of the processes does not seem clear at this time.

Attempts to show any natural radioactivity of deuterium involving the emission of gamma-rays, electrons, protons, or neutrons, by use of both a Geiger point counter and the linear amplifier have failed to indicate any measurable effect when observed over long periods, as has also been shown with a Geiger point counter by Ladenburg.[34] This also suggests that the mean life time of the deuterium nucleus must be of the same order as that of other stable nuclei. Tests for possible emission of neutrons from the feebly radioactive element potassium have likewise shown no evidence for any such parallel process.

THE SCATTERING OF NEUTRONS

The interaction of high energy neutrons with other particles is markedly different from other known types of radiation.[1, 3, 35, 36] On passing through matter, unlike protons, alpha-particles, beta-particles, or gamma-rays, neutrons interact very little with electrons,[37, 38, 39] but largely with atomic nuclei, and most of the observed phe-

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[30] Kirsch, Naturwiss. **21**, 640 (1933).

[31] Dunning and Pegram, Phys. Rev. **45**, 295A (1934).

[32] Rutherford and Kempton, Proc. Roy. Soc. **A143**, 724 (1934).

[33] Lewis, Livingston, Henderson and Lawrence, Phys. Rev. **45**, 242 (1933).

[34] Ladenburg, Phys. Rev. **45**, 224 (1934).

[35] Curie-Joliot, J. de Physique **4**, 21 (1933); **4**, 278 (1933).

[36] Dunning and Pegram, Phys. Rev. **43**, 775 (1933).

[37] Dee, Proc. Roy. Soc. **A136**, 727 (1932).

[38] Auger, Comptes Rendus **194**, 877 (1932).

[39] Meitner and Phillip, Naturwiss. **21**, 286 (1933).

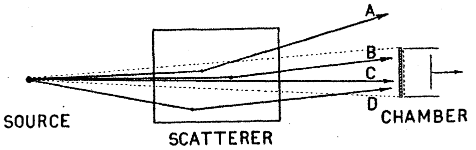

FIG. 7. Typical neutron paths when a block of scattering material is interposed between source and chamber.

nomena of "absorption" and scattering are explainable on the assumption that most of the collisions are approximately elastic.[40] Without making a definite hypothesis about the law of force between neutrons and nuclei, it may be expected that in a collision of this type, with one particle "uncharged," the interaction is negligible until the approach is very close, which approximates elastic sphere collisions.

If the neutron has a sharply limited force field, the "size" of the neutron should have more definite meaning than the size of charged particles, and likewise nuclei might be expected to exhibit more definite "sizes" in collisions with neutrons than with other types of particles. From a classical standpoint, in which the elastic sphere collision picture is used, the observed scattering of neutrons through nuclear impacts should depend simply on the neutron cross section, the nuclear cross section, the number of nuclei present, and the geometrical conditions, with uniform scattering at all angles for heavy nuclei.

However, since the wave-length of the incident neutron is of the same order of magnitude as the nuclear radii, the classical elastic sphere treatment cannot be more than approximate in its prediction either of collision areas, or of uniform angular distribution of scattering, and a wave-mechanics treatment is called for. Experimental scattering data may give values for "sizes" of particles and collision areas on a classical elastic sphere basis quite different from the values obtained from a wave interpretation.

Observation on the scattering of neutrons may be made by observing the reduction in the number of neutrons recorded when a block of matter is interposed between source and detecting chamber as in Fig. 7. In general, if λ is the mean free path of the neutron between collisions in which the neutron is deflected more than some assumed lower limit, then the fraction transmitted through a thickness "x" of some material without scattering will be:

$$p=e^{-x/\lambda} \quad \text{where} \quad \lambda=1/N\pi a^2$$

in which N is the number of nuclei per cm^3, and πa^2 is to be interpreted as the collision cross section. If N_0 is the number of recorded neutrons in the direct beam to the chamber within the dotted line of Fig. 7, and N_1 is the number of neutrons actually recorded in the chamber when the scatterer is present, then:

$N_1=N_0e^{-x/\lambda}$ (the number traversing the block without being scattered, as along C)

$+$ the number scattered by nuclei through some small angle, but not out of the chamber, as along B

$+$ the number scattered back into the chamber by nuclei outside of the geometrical path, as along D

$+$ the usually small number due to corrections for multiple scattering, etc.

The second term on the right will depend greatly on the scattering theory applicable, and is particularly important if the scattering is considered on a wave basis, where large small-angle scattering is usually predicted. The third term may involve very serious errors in some cases unless taken into account. For example the number of neutrons apparently scattered out of the direct beam to the chamber by a cylinder of lead 4 cm long and 2.5 cm in diameter is almost twice as large as the number apparently scattered out by a large plate of lead of the same thickness. This factor is complicated by the non-uniform angular distribution of recorded neutrons around some types of sources, but it may be reduced in any case by making the scatterer just large enough to fill the geometrical beam. Multiple scattering becomes increasingly important as the thickness of the specimen approaches or becomes greater than the mean free path of the neutron in that substance. It is obvious that scattering results must be interpreted in terms of all of these factors for anything more than qualitative significance.

In all experiments with neutrons, the scattering of the neutrons back into the ionization chamber or cloud chamber by adjacent matter,

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[40] Dunning and Pegram, Phys. Rev. **43**, 497 (1933).

the walls of the chamber, nearby apparatus, walls, floors, etc., is usually important, and may often be as high as 10 percent or more. This results in a serious uncertainty in the actual paths of the neutrons which seems to have been seldom considered, but it should certainly be minimized, or at least taken into account. The large amount of scattering material normally present in the walls, piston, etc., of a cloud chamber makes caution in interpreting results imperative.

The amount of actual absorption or stoppage of neutrons seems to be small, since the energy communicated to all except the lightest nuclei is quite small, while the probability of an inelastic impact resulting in capture (or non-capture) and possible transformation of the struck nucleus, of the type studied by Harkins, Gans and Newson,[41] Feather,[42] and Kurie[43] seems to be rather small in general, although Lea[44] suggests that as high as 25 percent of the impacts may possibly involve some interaction of this type in the case of neutron collisions with hydrogen nuclei.

The general arrangement of the apparatus for the measurement of the scattering from cylindrical specimens is shown in Fig. 8.

The Be-radon source was usually encased in a small platinum or lead container *N*, with a wall thickness of 5 or 7 mm, respectively, and was supported on a long thin rod. The neutrons normally traversed a cylinder of lead *G* 3 cm long and 2.5 cm in diameter to reduce the gamma-radiation, and the scattering cylinders *S* were likewise all 2.5 cm in diameter. The chamber *C* had a diameter of 2 cm, and adjacent matter was reduced to the minimum.

Fig. 9 shows the number of neutrons recorded per minute as various thicknesses of lead were introduced in the path. Distance *a* to the chamber was 27 cm, and *c* to the center of the lead scattering cylinders was always 14 cm, no additional gamma-ray absorber at *G* being used in this case. The transmission curve departs from the exponential, and appears to approach a constant value which is probably due to neutrons scattered back from the walls of the room, etc. However, the beam is non-parallel (almost radial), and the angle conditions change with increasing thickness of lead so that neutrons which have been scattered through larger angles can reach the chamber, while multiple scattering becomes more and more important. Hence such a flattening out, departing from an exponential curve, would be expected, even if the scattering were independent of neutron energy. Such an independence is suggested by Fig. 6, but the quantitative calculations from Fig. 9, in terms of all these factors and possible angle scattering functions are so involved that it is difficult to conclude whether or not complete independence is indicated.

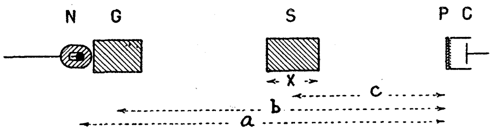

FIG. 8. Arrangement of apparatus for measurement of the scattering from cylinders of various materials.

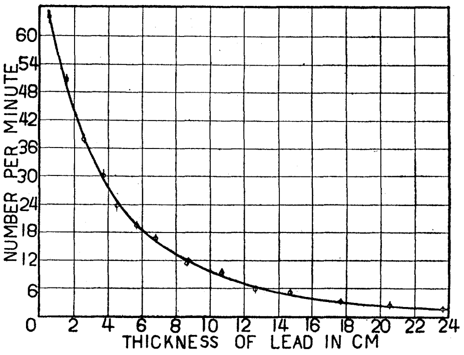

FIG. 9. Transmission of neutrons through lead.

Fig. 10 shows a series of comparative transmission curves for carbon, aluminum, lead, paraffin, and copper, together with a series of transmission values for 4 cm thicknesses of various substances. The 3 cm lead gamma-ray absorber was always present in this series, and was placed in contact with the cylinders of material under test, distance *c* to the center of the total length of material being 13 cm and

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[41] Harkins, Gans and Newson, Phys. Rev. **43**, 208 (1933); **44**, 529 (1933); **44**, 945 (1933).

[42] Feather, Proc. Roy. Soc. **A136**, 709 (1932); **141**, 194 (1933); **142**, 3 (1933).

[43] Kurie, Phys. Rev. **43**, 771 (1933).

[44] Lea, Nature **133**, 24 (1934).

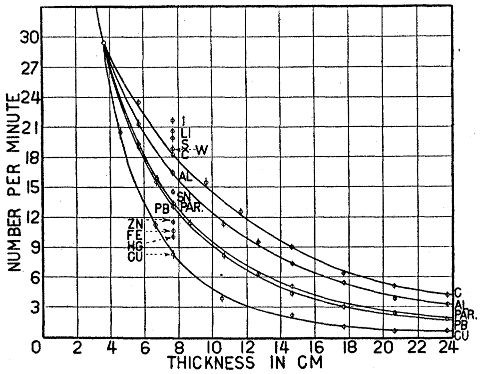

FIG. 10. Neutron transmission by various materials.

distance a to the chamber being 26 cm. The curves in Fig. 10 show the same trend as the curve in Fig. 9, but the relative transmission by various substances is very different from what is normally encountered with charged particles or gamma-radiation.

On account of the difficulty in taking account of all the factors mentioned previously, in order to arrive at values for collision areas, as a first approximation it is interesting to consider these apparently anomalous results in Fig. 10 on a classical elastic sphere basis, defining a scattering collision as an impact in which the neutron is scattered out of the chamber, thus neglecting the second term in the expression for the total number recorded since this correction is small on this basis, and also neglecting the third term in the expression, since the cylinders are very little larger than the geometrical beam. The fourth term, for multiple scattering, is likewise small. Under these circumstances, we have:

$$N_1/N_0 = e^{-x/\lambda}, \quad \text{where} \quad \lambda = 1/N\pi a^2,$$

the symbols having the same significance as before.

Table II shows a series of more accurate results obtained under better conditions than those in Fig. 10, and with a more nearly parallel beam of neutrons. The distance a to the chamber was 23.4 cm, b to the center of the gamma-ray absorber was 21 cm, and c to the center of the cylinder under test was 9.5 cm. The lengths (x) of the various cylinders were adjusted to have approximately the same transmission in order to secure more uniformity in the correction. Under these conditions, while the fraction transmitted and the mean free path vary widely, the collision areas, as is shown in Fig. 11 when plotted from the values in column 7 of Table II, show a slow variation over the complete range of elements, falling rather regularly down to nitrogen and carbon, but in this region the mass of the neutron

TABLE II. *New measurements of neutron transmission. The 6th and 7th columns show the results of calculations (approximate) on the classical elastic sphere basis of the mean free path of the neutrons, and the collision areas with various nuclei. The wave basis figures are those of Mr. Clark and Dr. Rabi.**

							Wave basis		
Material	Atomic weight	Length in cm	N Number nuclei per cc $\times 10^{-23}$	Amount transmitted	Exper. m.f.p. cm	Class. collision area $\times 10^{24}$ cm^{-2}	k.a.	Nuclear radii $\times 10^{13}$ cm	Neutron radii $\times 10^{13}$ cm
Paraffin		3.0	1.20	0.557	5.1	1.6			
Li	6.940	4.0	0.460	0.751	15.5	1.6	1.54	2.52	1.65
C	12.004	4.0	0.790	0.604	7.4	1.7	1.56	3.01	1.22
N	14.008	3.9	0.340	0.782	16.0	1.8	1.70	3.18	1.43
Al	26.97	4.0	0.637	0.575	6.5	2.4	1.85	3.96	1.05
S	32.06	4.0	0.358	0.699	10.3	2.7	1.98	4.19	1.18
Fe	55.84	2.5	0.847	0.521	3.9	3.0	2.23	5.04	1.00
Cu	63.57	2.0	0.849	0.575	3.7	3.2	2.30	5.26	0.98
Zn	65.38	2.5	0.660	0.579	4.6	3.3	2.35	5.31	1.06
Sn	118.7	3.0	0.370	0.618	6.3	4.3	2.79	6.48	1.08
I	126.9	4.0	0.181	0.725	12.0	4.6	2.82	6.62	1.02
W	184.0	4.0	0.241	0.594	7.8	5.3	3.22	7.50	1.23
Hg	200.6	2.0	0.411	0.625	4.2	5.8	3.25	7.72	1.09
Pb	207.2	3.0	0.333	0.563	5.3	5.7	3.27	7.80	1.06

* A series of later measurements on the scattering of neutrons by $H_2{}^1O$, $H_2{}^2O$, paraffin, Li, B and C, which will be reported fully in a later paper, indicate that the classical collision areas for these materials have practically the same values, around 1.6 to 1.7×10^{-24} cm^2.

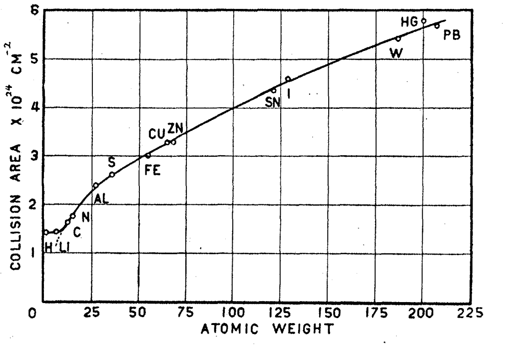

FIG. 11. Variation of collision area with atomic weight, approximate calculations on classical elastic sphere basis.

and nucleus approach the same order, the actual energy loss becomes more appreciable, and the type of scattering may well be expected to change, resulting in a larger experimental cross section for protons. The collision area for protons was obtained by subtracting the effect of the carbon in the paraffin, and while probably not as accurate as the other measurements, shows the general trend. The presence of occasional inelastic impacts in some cases, such as nitrogen, and probably in the case of protons, as mentioned before, may have some influence on the results, but this would not be expected to be very important, since the removal of a neutron from the direct beam by elastic scattering, or inelastic collision and possible capture, is probably very difficult to distinguish between under these conditions. Earlier results with a less parallel beam of neutrons[28] showed the same trend as in Fig. 11, but with a slightly lower value of collision area, as would be expected from the geometry. The neutron scattering theories developed by Massey,[45] Destouches,[46] and others, some of which predict collision areas varying as Z or Z^2, are seriously out of agreement with the observed collision areas which vary about as (atomic weight)$^{2/3}$.

On the classical elastic sphere basis, the total collision radius a, the sum of the neutron radius and the nuclear radius, obtained from the values for collision areas πa^2 shown in column 7 of Table II, ranges from about 6.7×10^{-13} cm for lithium to about 13.6×10^{-13} cm for lead. If we take values for the nuclear radii of the order to be expected from the Gamow theory or alpha-particle scattering measurements, starting with lead as 7.8×10^{-13} cm, and varying as the (atomic weight)$^{1/3}$, as shown in the 9th column, then the neutron "size" obtained by subtracting the nuclear radii from the total collision radii is of the order of 4.2 to 5.7×10^{-13} cm. Conversely, if one calculates about what the nuclear sizes must be in order to give an approximately constant value for the neutron size, the values arrived at are very nearly the same. The classical collision cross section values shown in column 9 are approximations which neglect the corrections mentioned previously, but these corrections will act to increase the estimates of collision areas, and hence of the neutron "size." While this simple elastic sphere theory gives approximately constant values for the neutron size over the complete range, the size indicated is much too large to permit the neutron to fit into atomic nuclei, and the results are therefore in accord with the view that the classical elastic sphere picture is inadequate to describe neutron collisions. Such results are logically what might be expected, since quantum cross section values are in general always larger than the classical cross section values.

Professor I. I. Rabi[47] has made some calculations from the earlier data in Fig. 10 on the basis of the wave scattering theory developed by the late Dr. Gronwall and elaborated by Dr. Rabi, which treats idealized hard-sphere collisions on a wave-mechanics basis, considering the neutron as a plane wave scattered by a nucleus of definite size. This theory predicts a large small-angle scattering which broadens and decreases with decreasing atomic weight, while the large-angle scattering is practically uniform, although larger in amount than would be expected on a classical basis. After making corrections along the lines mentioned previously, including the large small-angle scattering for high atomic weights, these earlier calculations of the neutron size from the quantum collision cross section indicated, gave an average of slightly less than 1.3×10^{-13} cm for the neutron radius, and with a fairly constant value over the entire range of

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[45] Massey, Proc. Roy. Soc. **A138**, 460 (1932).

[46] Destouches, Comptes Rendus **190**, 9 (1932).

[47] Rabi, Phys. Rev. **43**, 838 (1933).

atomic weight values. The computations were made by using an average energy for the neutrons of about 4.5 MEV, and this average value should not lead to serious error, since the theory predicts that the cross section for collisions with heavy nuclei under these circumstances should not show much variation over the range of velocities encountered with the greater part of the neutrons from Be-radon. As pointed out before, Fig. 6 strongly suggests this from an experimental standpoint. Further calculations have been very kindly furnished in advance of publication by Mr. Clark and Dr. Rabi based on the new data in Table II, with better corrections for the geometrical conditions, the small-angle scattering, and other factors, and also with correction for the small variation in cross section with neutron velocity, weighting the factor $k=(2\pi/h)\times(2mE)^{\frac{1}{2}}$ on the basis of the neutron energy distribution in Fig. 3, as $3.69\times10^{+12}$ cm^{-1}. The corrected values for ka, where a represents the collision radius, the sum of the neutron radius and the nuclear radius, are shown in column 8 of Table II.

On the wave basis, if the nuclear radii are taken as:

$$r=[7.8\times10^{-13}\,(\text{atomic weight})^{\frac{1}{3}}/207.2]\ \text{cm}$$

in the manner mentioned previously, then the values for the neutron radii are approximately constant throughout the entire range, as shown in the last column, with an average value of about 1.16×10^{-13} cm. The results also test the consistency of this assumption as to the variation of the effective nuclear radius with atomic weight, for the function must be of approximately this form to give a reasonably constant value for the neutron radius. It is interesting that this range of values for the nuclear radii must be fairly close to the Gamow values at the upper limit, in order to be reasonably consistent.

The increase in the apparent neutron radius for Li on the wave basis, and the approximately constant collision cross section for elements of low atomic weight up to carbon on the classical basis, are probably to be expected, since the packing of the particles in the light nuclei would hardly be the same as that in the tightly packed heavy nuclei. There may be some effect from the reduction in detection efficiency on account of the increased loss of energy by the neutron in collisions with nuclei of comparable mass, but this effect is probably small. The results seem to indicate that the neutron-proton interaction is large, and probably that the neutron-neutron interaction is small, but the effects of superposition of such particles in building up complex nuclei are not quantitatively clear as yet. It may perhaps be considered significant that the departures from the elastic scattering theory are not greater, since no account can yet be taken of inelastic collisions resulting in capture and transformation, or excitation of the struck nucleus.

The high intensity neutron sources available also make it possible to perform scattering experiments with the arrangement shown in Fig. 12.

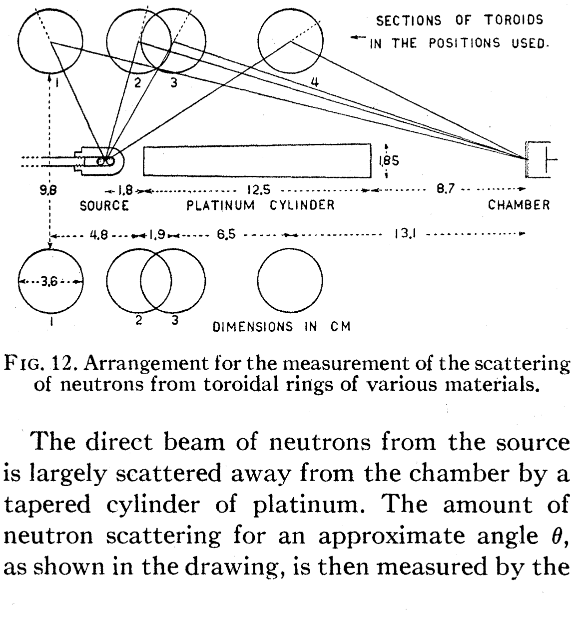

FIG. 12. Arrangement for the measurement of the scattering of neutrons from toroidal rings of various materials.

The direct beam of neutrons from the source is largely scattered away from the chamber by a tapered cylinder of platinum. The amount of neutron scattering for an approximate angle θ, as shown in the drawing, is then measured by the

TABLE III.*

Material	Approximate Scattering Angles							
	59° ±15°		77° ±20°		95° ±20°		132° ±13°	
	Number record.	Rel. amount	Number record.	Rel. amount	Number record.	Rel. amount	Number record.	Rel. amount
Paraffin	4.35	16.0	2.2	5.6	2.05	5.1	1.23	5.7
Carbon	4.45	16.3	4.4	11.4	4.4	11.0	2.82	12.0
Copper	4.41	16.2	—	—	5.5	13.7	3.3	14.0
Lead	3.62	13.3	—	—	4.8	12.0	3.1	13.2

* The results for the scattering by a given material at the various angles are probably more accurate than the comparative scattering by the different materials.

increase in the number of neutrons recorded when the toroidal rings are placed in the various positions shown. The large nuclear cross section and the large number of nuclei per cm^3 make platinum one of the most effective of all possible neutron scattering materials, and we are very much indebted to the American Platinum Company for both the tapered cylinder and the platinum source container, on account of the greatly improved experimental conditions which they make possible. The earlier scattering measurements using square sectioned rings[40] involved such large corrections for the screening of the chamber and scatterer, and multiple scattering, that calculation of quantitative values was tedious and uncertain. The screening correction is practically negligible in these measurements.

The results in the first column under the sections for the four positions of the rings are the number of neutrons recorded per minute at that point, with a source emitting about 30,000 recorded neutrons per minute in all directions. The second column shows the values approximately corrected for the solid angles involved on a relative basis. The complete calculation for the probability of a neutron being scattered into some small solid angle $d\omega$ at the various positions involves some long and difficult calculations and corrections, in order to compare with the theory, and these are now in progress. From a qualitative standpoint, however, the results are very much what might be expected. The large forward scattering from the protons in the paraffin is very evident, while the scattering of the neutrons beyond 90° seems to be about what might be expected from the carbon present in the paraffin. The gamma-radiation observed by Lea[44] of course would not be detected with such a linear amplifier. The results with the carbon ring show that carbon seems to have a somewhat large, broad forward scattering component, although it is fairly uniform beyond 90°. The elements of high atomic weight seem to show approximately uniform scattering within these angles. This is also what one would expect if the scattering were of a wave-nature, since the large forward-scattering predicted for the high atomic weights would be chiefly at smaller angles than can be reached with the ring scattering system shown, while the broader small-angle scattering for low atomic weights apparently does show up.

The writer wishes particularly to express his appreciation to Professor George B. Pegram, whose suggestions and cooperation have largely made this work possible, to Dr. G. Failla and the Memorial Hospital for the large quantities of radon, to the American Platinum Company for its interest in making and lending the large pieces of platinum required, to Professor Rabi for his assistance in interpreting the results as well as to Mr. Clark for the results of his calculations on the later data, and to other members of the department whose ideas and assistance have been of great value in this work.

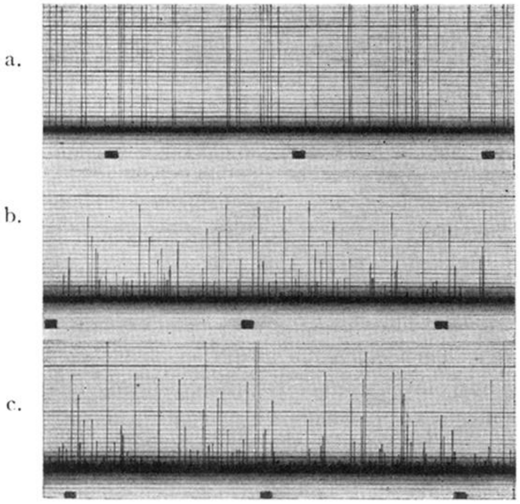

FIG. 2. Typical oscillograph records:
a. Alpha particles from polonium, reduced sensitivity.
b. Al-Po protons.
c. Be-radon neutrons.