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The Production of Collimated Beams of Monochromatic Neutrons in the Temperature Range 300°–10°K

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An electrical velocity selector is described, which allows the production and use of highly collimated beams of pure thermal neutrons. The mean temperature of the neutrons may be varied from 300°K to an undetermined lower limit, probably less than 10°K, without the use of refrigerants. The temperature width of the neutron "line" is also adjustable. Fast neutron effects are completely eliminated. Qualitative verification of the $1/v$ law for Boron has been extended to 30°K. The intensity of neutrons available from the cyclotron allows counting rates of 1000 per minute to be obtained at 30°K, with a source-detector distance of 4 meters, and an angular spread of 1°.

INTRODUCTION

IN 1934, Fermi and his collaborators[1] found that neutrons could be slowed to thermal velocities, by collisions with protons in various hydrogenous materials. This discovery has proved to be one of the most fruitful in recent years. Bohr[2] proposed his "liquid drop" model of the nucleus to explain the resonance capture of slow neutrons in the range from 0–100 volts. Schwinger and Teller[3] have shown that a determination of the scattering cross sections of ortho- and parahydrogen for slow neutrons can yield much information about the spin dependence and range of nuclear forces. Bloch's[4] suggestion that slow neutron beams could be polarized by passing through magnetized plates of iron has opened several valuable fields of investigation. For example, it should make possible the determination of the magnetic moment of the neutron,[5] and also give information on fundamental problems of magnetism. Interesting questions relating to the nature of the chemical bonds of hydrogen in organic molecules may also be attacked for the first time by the application of slow neutron technique.

It is indeed remarkable that so much good work has been done in this field, when one remembers that in all these experiments, the slow neutron effects were superposed on a background due to fast neutrons. It can be shown on quite simple grounds that it is impossible to obtain a pure slow neutron beam by absorption methods. The absorption coefficients of fast neutrons are less than or equal to those of slow neutrons, so the latter can exist only in partial equilibrium with their fast parents. Chalmers[6] found that it was possible to lead slow neutrons around corners through a tunnel in a block of paraffin. Since the scattering coefficient of slow neutrons on paraffin is much greater than that for fast neutrons, the emergent beam was relatively more rich in thermal neutrons than the original beam. But since the reflection coefficient of thermal neutrons on paraffin is only 0.83, it may easily be seen that this method cannot be very successful in yielding a slow neutron beam free from faster ones. The method which has been used in most thermal neutron work thus far consists in taking a series of measurements with and without cadmium sheets interposed in the neutron beam. The difference between the two sets of data is due to the thermal neutrons. It has thus been impossible to perform slow neutron scattering or absorption experiments with "good geometry," because if one restricts the solid angle of slow neutrons by cadmium slits, the ratio of fast neutron to slow neutron effects becomes too high.

For many purposes, it is desirable to work with neutrons having energies corresponding to temperatures of less than 300°K. The attempts to cool neutrons[7] have been rather disappointing, for although liquid hydrogen is available in

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[1] Amaldi, D'Agostino, Fermi, Pontecorvo, Rasetti, and Segrè, Proc. Roy. Soc. **149**, 522 (1935).

[2] Bohr, Nature **137**, 344 (1936).

[3] Schwinger and Teller, Phys. Rev. **51**, 775 (1937).

[4] Bloch, Phys. Rev. **50**, 259 (1936).

[5] Frisch, von Halban and Koch, Phys. Rev. **53**, 719 (1938).

[6] Chalmers, Brit. J. Radiology, **8**, 163 (1935).

[7] Libby and Long, Phys. Rev. **52**, 592 (1937).

several laboratories, it has been found impossible to obtain neutrons with a temperature of much less than 60°K. The explanation is probably that at temperatures lower than the Debye temperature of paraffin, the neutrons interact elastically only with the lattice, and therefore rebound with most of their incident energy. They cannot lose energy by inelastic collisions, as they have insufficient energy to excite the lowest rotational state of the cold paraffin molecules.

A method[8] has recently been developed, which allows the production of intense, highly collimated beams of pure, monochromatized thermal neutrons from 300° to an undetermined lower limit (probably $<10°K$). The energy of the neutrons may be changed at will without the use of refrigerants, and the background is determined only by the natural background of the detector—fast neutron effects are completely eliminated.

THEORY OF THE METHOD

Soon after the discovery of slow neutrons, several of the members of the Radiation Laboratory staff suggested that it would be possible to measure the velocity of the neutrons by "keying" the radiofrequency oscillators which drive the cyclotron, i.e., turning them off suddenly, and then observing on an oscillograph, the interval of time elapsing before the slow neutrons were detected near the control panel, a distance of about 15 meters. The idea was abandoned when the results of the rotating wheel method of velocity measurement were announced.[9] But the fact that slow neutrons take an appreciable time to travel distances of the order of meters is the basic principle of the method to be described.

In this method, the deuteron beam from the cyclotron is modulated at 120 cycles per second, so that fast neutrons are generated in a beryllium target about half of the time. A BF_3-filled ionization chamber is placed 8 meters from the Be target, and the linear amplifier to which it is connected is arranged to be sensitive only when the cyclotron is off. Since fast neutrons have a mean life of less than 10^{-5} second, it is impossible for them to be detected with this arrangement. But since it takes a thermal neutron 1/240 second to travel 8 meters, the amplifier will record those neutrons which were slowed to thermal velocities by a paraffin block near the Be target. The mean life of a slow neutron in paraffin is about 10^{-4} sec., which is small compared to the 4×10^{-3} sec. it takes to reach the counter. The BF_3 chamber and the paraffin block are placed at opposite ends of a cadmium-lined tube, so that no neutrons except those which travel in a straight line between the two may be counted. This latter feature assures that the beam is highly collimated. One might at first think that the tube is responsible for the collimation, but the beam would be just as well collimated if the cadmium tube had a diameter ten times as great; it merely serves to isolate a volume in which no slow neutrons may be produced or reflected.

While it is obvious that this method does not actually produce a pure thermal neutron beam, the effect on the recording instruments is exactly the same as though it did. On the operational viewpoint, therefore, one is justified in asserting that the beam is composed solely of thermal neutrons.

A feature of the method which increases its usefulness considerably is that the velocity of the recorded neutrons can be changed merely by altering either the modulation frequency or the source-detector distance. There are always neutrons of low energy present in a piece of neutron-irradiated paraffin, and it is possible to use the modulated beam method as a Maxwellian demon to sort out these slow ones. If the distribution of neutron velocities in paraffin is of Maxwellian form, the number of recorded neutrons will fall off about linearly with distance as one moves the counter toward the source, and the temperature will fall with the square of the distance. The Maxwell distribution is given by the relation[10]

$$N_{dv}=(4N/\alpha^3\pi^{\frac{1}{2}})(v^2\exp -v^2/\alpha^2)dv \qquad (1)$$

or for velocities less than the most probable, α,

$$N_{dv}\approx v^2dv. \qquad (2)$$

The distribution of velocities in a molecular beam is well known to have an additional velocity dependence due to the increased probability of

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[8] Alvarez, Phys. Rev. **54**, 235 (1938).

[9] Rasetti, Segrè, Fink, Dunning, Pegram, and Mitchell, Phys. Rev. **49**, 104, 777 (1936).

[10] Loeb, *Kinetic Theory of Gases* (McGraw-Hill, 1927), p. 78.

fast molecules hitting the exit slit. The same argument will apply to neutron beams, so

$$N_{dv} \approx v^3 dv. \tag{3}$$

If one uses the same modulation scheme with the chamber at different distances, d, from the source, the velocity spread of counted neutrons will be a constant percentage of the velocity, so dv will be proportional to v. Then neglecting the exponential term

$$N \sim v^4. \tag{4}$$

As one moves the detector toward the source, v decreases linearly with d (for constant frequency). But the solid angle subtended by the detector at the source increases as $1/v^2$, and the detection efficiency of a (thin) BF_3 chamber increases as $1/v$. The effects of the exponential term in (1) and the deep boron chamber are small, and of opposite sign, so

$$N \sim v \sim d. \tag{5}$$

While there are several reasons why the number of very slow neutrons will be less than that required by the Maxwell law, it is evident that if the method is successful for 300°K neutrons, there is a good possibility that beams of considerably colder neutrons may be realized.

Beam Modulation

Initial rough calculations of the intensity available indicated that it would be desirable to work 2 meters from the source, which would require a modulation frequency of 500 per second. A 500-cycle generator was available in the laboratory, and the first attempts to modulate the beam were made with it. A special transformer was constructed, the secondary of which could be placed in the grid circuit of the final stage of the power amplifier which energizes the cyclotron dees. A few trials showed that considerably more power at 500 cycles would be needed, than was available from the 1 kw motor generator set. Attempts were next made at modulating the emission voltage on the cyclotron filament. A special filament assembly was made which had a closer grid spacing at ground potential. It was found possible with this arrangement to cut off the beam completely by raising the filament to a few hundred volts positive with respect to the grounded shield. (With the usual type of filament mounting, the R.F. fields are able to pull out enough electrons to give a measurable beam even when the filament is highly positive.) Two modulation circuits were tried with this arrangement, but the time constants could not be lowered sufficiently to allow modulation at a frequency of 500 cycles. The timing was done by a commutator driven by a d.c. motor, and the operation was satisfactory up to about 50 cycles per second. The cause of the large time constant was never cleared up, but it might have been due to the ionization of deuterium atoms by the relatively slow deuterons near the center of the cyclotron. This does not seem probable, but no high resistances or large capacities could be found in the circuit which would explain the oscillographic record of the beam obtained in this manner.

The method finally adopted was simple plate modulation of the last two stages of the power amplifier. When the cyclotron is in normal operation, the plate voltage for the amplifier is supplied by a three-phase, full wave rectifier, through an a.c. filtering choke. The output of such a rectifier system is essentially d.c. For modulation purposes, the three high-voltage transformers normally used are replaced by one single phase transformer of higher kva rating. The circuit is shown in Fig. 1. The change from one supply to the other can be made very rapidly, by throwing the appropriate switches. The modulation frequency with this arrangement is 120 cycles per second. If the plate leads to two of the rectifier tubes are broken, the beam is modulated at 60 cycles.

One might first suspect that the 120-cycle modulation would not be usable, since there is always voltage on the oscillator plates. The simple theory of the cyclotron shows that it is possible to obtain a beam with any voltage on the dees—the lower the voltage, the more times the ions have to circulate around to reach their final energy. But with the inhomogeneity of magnetic field needed for focusing purposes, it is necessary for the dee voltage to be greater than some sharply defined value, which in the case of the Berkeley cyclotron is about half of the maximum value. (For lower voltages, the ions get

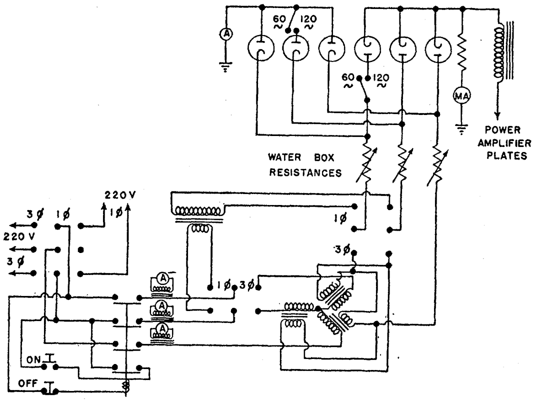

FIG. 1. Circuit for modulating neutron beam.

out of phase, and spiral back to the center with decreasing energy.) The result of this threshold is that there is an interval of time each cycle during which no beam reaches the edge of the cyclotron, and which is therefore devoid of neutrons. Oscillograph records of the beam current show that deuterons strike the target during about 50–60 percent of each cycle. At 60 cycles, the beam is on for 25–30 percent of the time.

AMPLIFIER MODULATION

The problem of modulating the amplifier sensitivity was easily solved when the beam modulation was controlled by a commutator. It was only necessary to short the output terminals of the amplifier with the same commutator. But the commutator could not be synchronized at 120 cycles, so the circuit shown in Fig. 2 was tried; it has proved to be entirely satisfactory. The essential feature of the scheme is the Rossi coincidence circuit, which has proved so useful in cosmic-ray researches. If the plates of two pentodes are connected in parallel through a resistance to a voltage supply, the potential of the plate will be insensitive to large changes in the grid voltage of either tube. If the potential of one grid is made negative enough to cut off all plate current through that tube, the current through the other will double, and therefore the *IR* drop across the resistance will be unaltered. But if both grids cut off at once, the *IR* drop will fall to zero, and the potential of the plate will rise to that of the *B* supply.

The pulses from a linear amplifier are fed through the 6C5, which inverts them to the negative sign required by the Rossi stage, sharpens them by distortion amplification, and eliminates the background noise level by the application of a high negative bias. The output of this tube is coupled to the grid circuit of one of the Rossi pentodes. The grid of the other pentode is maintained at a high positive value (about 300 volts), by means of a standard power pack, and a high resistance is placed in series with the grid to prevent large grid currents from flowing. The potential of the grid is then swung below the cut-off value once each cycle by the application of a high negative voltage from an unfiltered rectifier outfit in series with the steady positive supply. Pulses pass through this modulating stage only when the grid potential of the upper tube is below about -10 volts. The length of the sensitive time is easily altered by means of the potentiometer in the unfiltered supply. The bias voltages are made high so that little time is expended in passing from the conducting to the nonconducting state in the upper tube. The primary voltage for the unfiltered power pack is supplied from the secondary of a Selsyn transformer. The phase of the sensitive time of the amplifier may thus be altered through 360° merely by turning a knob on the control panel. The other controls on the panel are the potentiometer mentioned above, another potentiometer in the grid circuit of the 6C5, and a switch in the unfiltered power supply which makes it possible to change from 120 to 60 cycle modulation. The

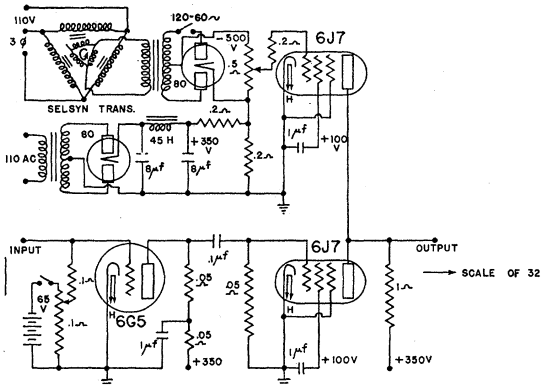

FIG. 2. Modulating unit for linear amplifier.

second potentiometer controls the size of pulses from the linear amplifier which will be recorded on the scale counter. As the bias is reduced, smaller kicks are effective, until finally the background noise gets through. The bias is increased to a point where microphonics due to persons walking in the room will no longer trip the counter. It was found necessary to place R.F. filters in each of the five power lines entering the modulation unit. If a Selsyn transformer were not available, there are several simple phase shifting networks which might be used in its place.

Ionization Chamber

The first tests on the method were made with a standard shallow ionization chamber of the Wynn-Williams type, fitted with a LiF lining. The intensity was just sufficient to show that the fast neutron background was indeed negligible. A BF_3 chamber of the type described by Schultz[11] was next tried, but the pulses from it were too long compared with the modulation time; if the voltage were increased, sparking occurred. It is quite certain that a chamber of this type could be made to work satisfactorily, and a modification of this one is at present under construction. A parallel plate BF_3 chamber was next constructed, and it has been used in most of the tests to be described below. The brass plates were $6\times18\times0.5$ cm, and were mounted on hard rubber insulators, 1 cm apart. In addition to the usual grounded guard ring, there was a high voltage guard ring half way down the insulator supporting the high voltage plate. With 800 volts across the chamber and a BF_3 pressure of 38 cm of Hg, the pulses were quite narrow and smooth. The defining slit of the chamber consisted of the two brass plates, so the beam as it entered the counter had a cross section of 1 cm$\times$6 cm.

Geometrical Features

The arrangement of the cyclotron room is shown in Fig. 3. The magnet is surrounded by water tanks 3 feet in thickness. The 6-inch pipe which passes through one of the tanks was arranged to allow fast neutrons from the ordinarily used target holder to pass into a pressure cloud chamber outside the water shield. The center of the paraffin block is about 6 inches from the old target position, so the cadmium tube is mounted diagonally through the large pipe, as shown in the figure. The BF_3 chamber is surrounded by cadmium and placed in a hole in the large paraffin block. This latter feature cuts down the number of fast neutron pulses in the off cycle of the counter, but it is probably not essential for the proper operation of the apparatus. Most of the data have been obtained with the chamber near the wall of the room, but some measurements have been made with it just outside the water tanks. Absorbers have always been placed half way between the source and detector, and the same applies for the Cd sheet used in determining the background count. The angular divergence of the beam is about 1°.

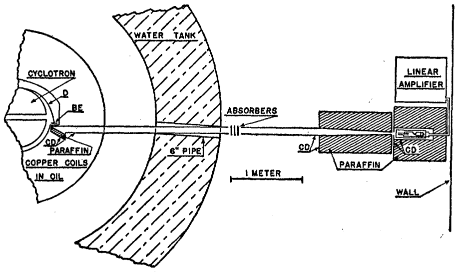

FIG. 3. Plan of cyclotron room.

Adjustment of the Apparatus

After the ionization chamber has been aligned on the axis of the cadmium tube, and the linear amplifier has been allowed to warm up, the modulation units must be "timed" with respect to each other. This adjustment is a very simple one; it is accomplished with the aid of a cathode-ray oscilloscope. Most of the work has been done at 120 cycles, so the timing procedure at this frequency will be described. As may be seen from the plan of the cyclotron room, it is impossible to place the chamber 8 meters from the paraffin source, as required for room temperature neutrons. If the chamber is placed near the wall, the neutrons should have a temperature of about 90°K.

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[11] Schultz, Phys. Rev. **53**, 622 (1938).

The oscilloscope sweep circuit is set for 120 cycles, and the synchronizing control is turned full on, to assure that the phase of the sweep will remain constant in time. It is necessary on the RCA outfit we have used, to employ an external source of 120 cycle a.c. for the synchronizing. If one uses the 60 cycle a.c. for this purpose, the two sweeps per cycle do not coincide on the screen, and it is therefore impossible to set the timing accurately.

The linear amplifier is connected directly to the oscilloscope, and the cyclotron is turned on. Pulses are then seen over most of the length of the sweep. But if a piece of cadmium is interposed in the beam, the number of pulses is diminished. and all of them occur in one-half of the cycle, The phase of the cyclotron modulation is then determined, and marks are made on the screen for future reference. The output of the amplifier modulation unit is then connected to the oscillograph plates, and the gain of the oscillograph amplifier is turned up. Under these conditions, the sensitive time of the linear amplifier modulation appears as a sharply defined trough in the normally straight sweep. It is a simple matter to vary the width of this trough, and to shift its center, by means of the controls mentioned above. It is only necessary to locate the trough completely in that part of the cycle during which no fast neutron pulses were observed. The marks on the screen allow this adjustment to be made with certainty. Now the modulation unit may be connected between the linear amplifier and the scale counter, and the apparatus is ready for use. A simple test will demonstrate that the fast neutron background is negligible. With the apparatus adjusted as described, the author has obtained counting rates of 300 and 1 per minute, with no absorber and a cadmium absorber, respectively. This background is the natural background of the chamber, and is less than 0.3 percent of the slow neutron count. With the paraffin source block removed, and no cadmium absorber in the beam, the background count of 1 per minute is also observed. This is perhaps the most striking demonstration of the method—although the cyclotron is surrounded by many tons of water, the removal of one pound of paraffin stops the beam completely.

Experimental Results

The data given above show that the collimation and purity of the thermal neutron beam is as good as one could possibly hope from the simple theory of the method. But as yet nothing has been proved about the homogeneity of the neutron energies. An obvious way to test this point is to measure the boron absorption coefficient for these neutrons. There are good theoretical reasons for believing that the absorption coefficient is inversely proportional to the neutron velocity over a large velocity range. The "$1/v$ law" has been checked in a small region on either side of 300°K, by the rotating wheel method,[9] and has been confirmed to about 100°K with neutrons cooled in paraffin by liquid air.[7] On the high velocity side, the law has been verified to some tens of volts, at which point the absorption coefficient becomes small with respect to the constant scattering coefficient. This verification[12] consists in establishing the energies of resonance neutrons by the boron absorption method, and finding that they agree with the values obtained from the spatial distribution of resonance neutrons in water surrounding a Rn-Be source. So there is every reason at present to believe that the absorption coefficient of slow neutrons in boron varies as $1/v$.

It is unfortunate that boron is one of the most difficult elements to prepare in the thin layers required for absorption of very slow neutrons. Pyrex plates are the most convenient form of thin homogeneous boron absorbers, but even then it is necessary to grind or etch them to the smallest size needed. Since the absorption coefficient of 300°K neutrons differs considerably in the reports of various workers, it seemed worth while to calibrate the Pyrex plates used in this work directly with room-temperature neutrons, with the same geometry as employed for the slower ones. The standard neutrons were obtained by operating the cyclotron on d.c., and removing the upper pentode in Fig. 2 from its socket. With this arrangement, the counting rates with and without cadmium absorbers were about 4000 and 1000 per minute, respectively. This high counting rate made the large background relatively unimportant, as the probable errors of the points

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[12] Amaldi and Fermi, Phys. Rev. **50**, 899 (1936).

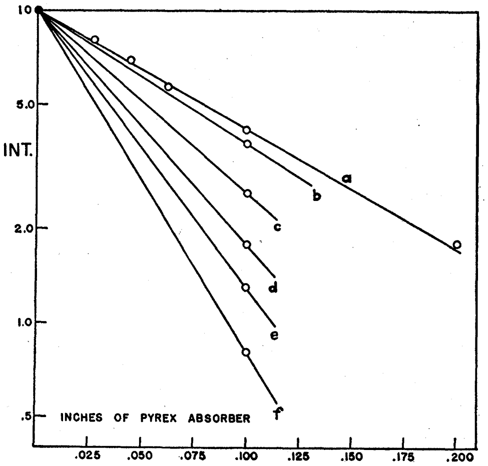

FIG. 4. Variation in boron absorption with timing scheme.

could be made very small in short periods of counting. The absorption curve of the 300°K neutrons is shown in Fig. 4(a).

With the modulation scheme as described under the section on adjustments, the absorption curve was again determined. From the simple theory, one would expect the absorption coefficient to be approximately twice that for room-temperature neutrons. Actually, the difference is quite small (Fig. 4(b)). But the reason for this discrepancy is quite obvious if one examines the modulation scheme, shown in Fig. 5(b). The time from the center of the beam pulse to the center of the amplifier sensitivity is that required by a 90° neutron to travel from the source to the detector. But a 300° neutron needs only half that time to travel the same distance. Consequently, all room-temperature neutrons which are formed in the latter half of the beam pulse will be recorded in the first half of the amplifier sensitive time. Since the number of these faster ones is so much greater than the number of 90° neutrons, most of the recorded counts will be due to the former. In order to obtain a low temperature beam, it is therefore necessary to have the amplifier insensitive for an appreciable fraction of each cycle after the deuteron beam has been turned off.

The result of shifting the amplifier sensitivity toward the end of the cycle (Fig. 5(c) and 5(d)) is to lower the effective neutron temperature, as shown in Fig. 4, (c) and (d). It may be seen that the neutron temperature with the latter timing arrangement is about what one would predict from the $1/v$ law. The apparatus in this adjustment is not as stable as one would desire—the counting rate with no absorber in the beam varies considerably more than one would expect from statistical considerations. The reason for this instability was found when the amplifier modulation "trough" was observed on the oscilloscope screen. The length of the sensitive time was found to vary erratically by about 20 percent. This instability is due to small changes in the opposing voltages on the grid of the modulating pentode. The effect is, of course, most pronounced when the amplifier sensitive time is short, but it could easily be cured if a peaking transformer were placed in the primary of the unfiltered power pack. Perhaps the most satisfactory solution would be to have the pulsating negative voltage on the pentode grid supplied by a relaxation oscillator, synchronized in the same manner as the sweep circuit of an oscillograph. With this arrangement, the modulating voltage wave would cut the horizontal axis at a steep angle, for all timing adjustments.

The detecting chamber was next moved to the outside edge of the water tank, where the temperature should have been about 20°, or the absorption coefficient in boron about four times that at room temperature. Fig. 4(e) shows that the temperature is somewhat lower than with the same adjustment near the wall of the room. The half thicknesses for absorption in boron as shown in Fig. 4 indicate temperatures greater than the average value for the beam, particularly for the steepest curves. This is due to the fact that these lower curves are drawn through only two experimentally determined points, 0 and 0.1″ of Pyrex. Since the spread in neutron energies must be about ±30 percent, the actual curves are due to the superposition of several exponentials. Therefore, the curves must be convex toward the origin, and start down with a greater slope than is indicated by the chord actually drawn.

Sixty-cycle modulation was next tried, and it proved to be the most satisfactory arrangement. The chamber was returned to the wall, and the timing was set as shown in Fig. 5(f). The long interval between the beam pulse and the amplifier sensitive time completely eliminates the possibility of counting room-temperature neu-

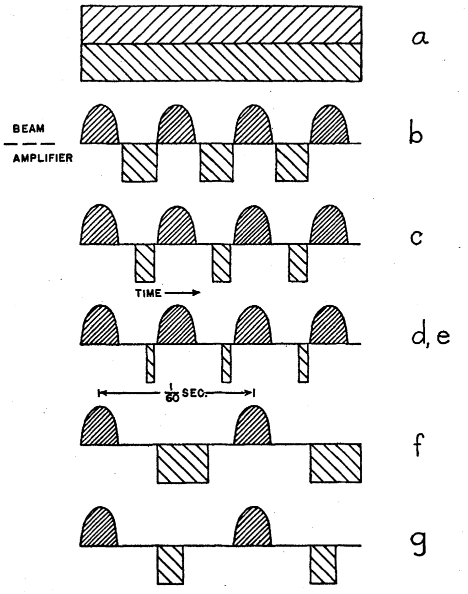

FIG. 5. Phase relations in modulation circuits.

trons. The absorption curve with this timing is shown in Fig. 4(f). The temperature given by the straight line is about 30°, but it is certain that considerably lower temperature neutrons contributed an important part to the counting rate at zero absorber thickness. The velocity of the neutrons obtained from the time interval and distance is consistent with the velocity deduced from the $1/v$ law. The timing was next changed to that shown in Fig. 4(g). As would be expected, the counting rate fell but little from that recorded with the previous timing. This shows that the number of neutrons in the second half of the amplifier sensitive period was small compared to that in the first half. But the background was cut in half, so the second timing scheme is to be preferred. The counting rate with this latter arrangement was 30 per minute, with a background of 1.2 per minute.

In the hope of obtaining more intensity, a cold piece of paraffin was used to slow the neutrons. The paraffin was reinforced with two concentric helical copper tubes, which helped to keep it from falling apart when cooled, and also speeded the attainment of thermal equilibrium at liquid-air temperature. Since no large soft glass Dewar flasks were available, the paraffin was placed in a large Pyrex Dewar filled with liquid air, for several hours. It was then substituted for the usual paraffin block, and the resulting counting rate was quickly measured. The initial rate was 75 per minute, but it fell slowly back to 30 per minute as the paraffin warmed up. So it does not seem at the present time to be worth while bothering with cooled sources. It is much easier to increase the intensity by improving the detecting chamber.

The chamber under construction at the present time will be operated at 4 atmospheres pressure of BF_3. This increase will give a factor of from 4–8 times in intensity, depending on the energy of the neutrons. The chamber will be of cylindrical form, with a diameter of about 10 cm, so the intensity will be increased several-fold due to the greater solid angle available. The new chamber should therefore allow data to be collected at counting rates in excess of 1000 per minute, for temperatures of the order of 30°K.

POSSIBILITIES AND LIMITATIONS OF THE METHOD

Up to the present time, the only measurements made with the apparatus have been on the absorption and scattering of ultraslow neutrons in boron, paraffin and iron. It seemed more important at first to explore the characteristics of the method, and to learn something of its reliability, etc. Considerable trouble was at first experienced in obtaining reproducible data. Some of the trouble was traced to faulty design of the modulation circuit. But with the arrangement shown in Fig. 2, it is possible to turn on in the morning and take reproducible data all day without touching any controls. The linearity of the counting circuits has been checked by taking absorption curves in iron at various beam intensities. The absorption coefficient is independent of the intensity. Counting intervals are usually 1 microampere hour, as measured on an integrating beam meter connected to the beryllium target. With 60-cycle modulation, the average deuteron currents are 5–10 microamperes, so the counting periods are about 8 minutes long. The steady currents obtainable with d.c. operation are 50–60 microamperes at 8 Mv. The number of counts per μ an hr. as measured on the integrator is not quite independent of the deuteron current, which is probably due to a slight nonlinearity of the integrator. But the beam is so steady under these conditions of light load that the integrator gives a reliable indication of the total number of slow neutrons produced in a given time interval.

Sixty-cycle modulation seems to be much more satisfactory than 120, so it will probably be used exclusively in the future. It is very convenient that the laboratory power is supplied at this frequency, although 120 cycles would quadruple the available solid angle for any temperature, and allow the method to be used in smaller rooms. The reason for preferring 60-cycle to 120 in actual practice is, of course, that the former is obtained by half-wave rectification, allowing more freedom in timing. It is planned for the future to mount the paraffin block in which the counter rests, on a truck, so that temperature changes can be made without the realigning now necessary. The truck will run on rails, which will pass several meters beyond the wall, on a platform to be constructed outside the building.

There does not seem to be any convenient way to take advantage of the larger solid angle offered by faster modulation. With the large pressure Van de Graaff machines which are now under construction, it would be quite convenient to modulate the source at about 200 cycles per sec. If one tried to use much higher frequencies, he would experience trouble in sharpening the amplifier pulses. Even if this factor did not enter, the mean life of slow neutrons in paraffin would soon become comparable with the time of transit, and the homogeneity of the beam would suffer on that account. With the distances used in the present work at 60-cycle modulation, considerable intensity is lost by neutron absorption in nitrogen. It will probably be worth while to place evacuated tubes between the source and detector, in the future. Since the tubes are already in place, it will merely be necessary to close the ends and connect them to a vacuum pump.

One source of trouble which was anticipated, but which fortunately did not materialize, was the possible formation of Li^8 in the reaction $\mathrm{B}^{11}+n\rightarrow\mathrm{Li}^8+\mathrm{He}^4$. Li^8 has a half-life of 0.8 sec. after which it disintegrates into an electron and two alpha-particles. If this reaction were more probable, fast neutrons could be recorded by alpha-particles expelled during the sensitive time of the amplifier, from Li^8 nuclei formed while the beam was on several cycles earlier. This reaction, if observable, may set the lower limit of attainable neutron temperatures.

One would, of course, hope that it would be possible to investigate the resonance neutrons with a velocity selector such as this. With the modulation limits discussed above, the distance from source to detector becomes prohibitively large, and therefore the intensities are too low. If the pulse breadth could be narrowed sufficiently, the source-modulated Van de Graaff machine could be used for this purpose. The trouble due to the mean life of thermal neutrons in paraffin is nonexistent in this case, as resonance neutrons are formed from fast ones in times of the order of 10^{-7} second, and are converted into thermal neutrons in about the same length of time.

The apparatus is then seen to be most useful in the range from 300° down. The lower limit is unpredictable, and depends largely on the neutron intensities available in future cyclotrons. It will be surprising if the new pressure chamber does not permit measurements to be made as low as 10°K. Theoretically there is no lower limit; single scattering can give rise to neutrons with zero velocity.

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