THE M. I. T. LINEAR ACCELERATOR
AS A PULSED NEUTRON SOURCE FOR A
TIME-OF-FLIGHT NEUTRON SPECTROMETER

by

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ABSTRACT

A pulsed beam of neutrons has been produced by bombardment of thick metal targets with high energy electrons from the linear accelerator and by the use of paraffin and lead collimation. The space and energy distribution of this beam has been investigated and the total neutron yields of several targets measured. Methods of detecting, timing, and counting the neutrons have been studied in an effort to determine the feasibility of constructing a neutron spectrometer for use with the linear accelerator.

ACKNOWLEDGMENT

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I. INTRODUCTION

Observations of the interactions of neutrons with nuclei furnish important information about the structure of matter. The neutron absorption spectrum of a given nucleus depends on the arrangement of energy levels in the associated compound nucleus, and nuclear size can often be calculated from neutron scattering data. Accordingly, determination of the energy dependence of neutron cross sections has been the object of many recent experiments, several different procedures having been developed for measuring this dependence. The present investigation is concerned with the possibility of employing the M. I. T. linear accelerator as a neutron source for use in a time-of-flight neutron spectrometer.

In the very low energy range, where the neutron wave length is comparable to interatomic distances in solids, spectrum measurements are usually made by utilization of Bragg reflection from crystals. High-intensity pile neutron beams are used as sources in these experiments, and mechanical velocity selectors are frequently employed in the same energy range. Fairly monoenergetic neutrons in the 100 Kev. region are obtained from nuclear reactions such as Li(p,n), using heavy particle accelerators. High energy γ-rays from radioisotopes give neutrons in the 10 Kev. to 1 Mev. region. The Columbia Cyclotron Group has achieved considerable success with a spectrometer whose neutron source is a paraffin-surrounded beryllium target in the cyclotron. The deuteron beam of the machine induces a Be(d,n) reaction in the target, and the variable length (5 - 160 μsec.), variable frequency (1000 - 10,000 μsec. period), cyclotron pulses produce neutron bursts with similar time characteristics, giving a system with reasonable resolution up to approximately 1 Kev.(1)

As is the case with all spectrum measurements, the major problems in neutron spectrometry have been those of intensity and resolution. Cockroft has suggested that an electron linear accelerator, because of its short, high-current pulses, could be used to furnish neutrons at fairly high fluxes with a maximum of resolution.(2) Preliminary experiments with the Harwell (England) accelerator have indicated that satisfactory intensities can be obtained at higher resolutions than have heretofore been possible. A comparison of the resolutions of three present systems is given in Table I.(3)

Table I. - Comparison of Neutron Spectrometers.

System	Energy (E)	Resolution (ΔE/E)
Columbia - Pulsed Cyclotron Beam	1 ev. 10 ev. 100 ev. 1 Kev.	1/16 1/8 1/3 1/1
Argonne - Mechanical Velocity Selector	1 ev. 10 ev. 100 ev. 1 Kev.	1/11 1/6 1/2.5 1
Harwell - Linear Accelerator	1 ev. 10 ev. 100 ev. 1 Kev.	1/9 1/7.5 1/5 1/2

The M. I. T. linear accelerator is well adapted to neutron pulse production because of its high energy and short pulse length (20 Mev. maximum and 1 μsec., as compared to Harwell's 3.2 Mev. and 2 μsec.). Heavier elements can be used as targets, taking advantage of (γ,n) resonances in the 15 - 20 Mev. region to give higher neutron fluxes, and the greater accuracy of time measurements permitted will lead to an increase in resolution over other current installations. Preliminary calculations by Prof. Feld, using bremsstrahlung X-rays from a monoenergetic 20 Mev. electron beam consisting of 100 ma., 1 μsec., 120 cycle pulses, showed that the thick target $Cu^{63}(\gamma,n)$ neutron production should be approximately 5×10^{10} neutrons/sec.[(4)] Since the uncertainty of time-of-flight measurements will be of the order of the pulse length (1 μsec.), the maximum theoretical resolution for 10 meter detector distance turns out to be $\Delta E/E = \frac{1}{2}$ at 30 Kev., so that good resolution can be expected over a considerably wider range than has previously been obtained.

In order to evaluate the prospects for a successful spectrometer installation in conjunction with the M. I. T. accelerator, total neutron yields from various targets were measured, the energy spectrum of the emitted neutrons was investigated, and various methods of timing and detection were studied.

II. APPARATUS

The present state of the linear accelerator is such that maximum design current and energy are not realized, the best values of these quantities obtained up to this time being 16 ma. pulse current at 16 Mev. (For a complete description and discussion of the M. I. T. linear accelerator, see reference 5.) The electron beam of the accelerator is brought nearly to a point at the target by magnetic focusing, so that the bremsstrahlung radiation is produced in a small region in the target. Heavy metal targets are placed directly in the beam where it emerges from the scattering chamber, and the emergent neutrons (produced by the (γ,n) reactions) are collimated by means of lead and paraffin shielding. Detection is ordinarily accomplished at a distance of two meters from the target, but provision has been made for moving as far back as ten meters. An overall plan view of the system is shown in Figure 1.

The choice and design of targets were influenced by several considerations. In order to determine the general effect of atomic weight on neutron yield, four targets were tested: Al, Cu, Pb, U. The dimensions of the targets were so chosen that nearly all of the γ-rays produced in them would be absorbed, either by pair production, Compton scattering, photoelectric effect, or nuclear excitation. Since the length of each target was made approximately five times the geometric path length of γ-rays in the material, and since neutrons are produced throughout the

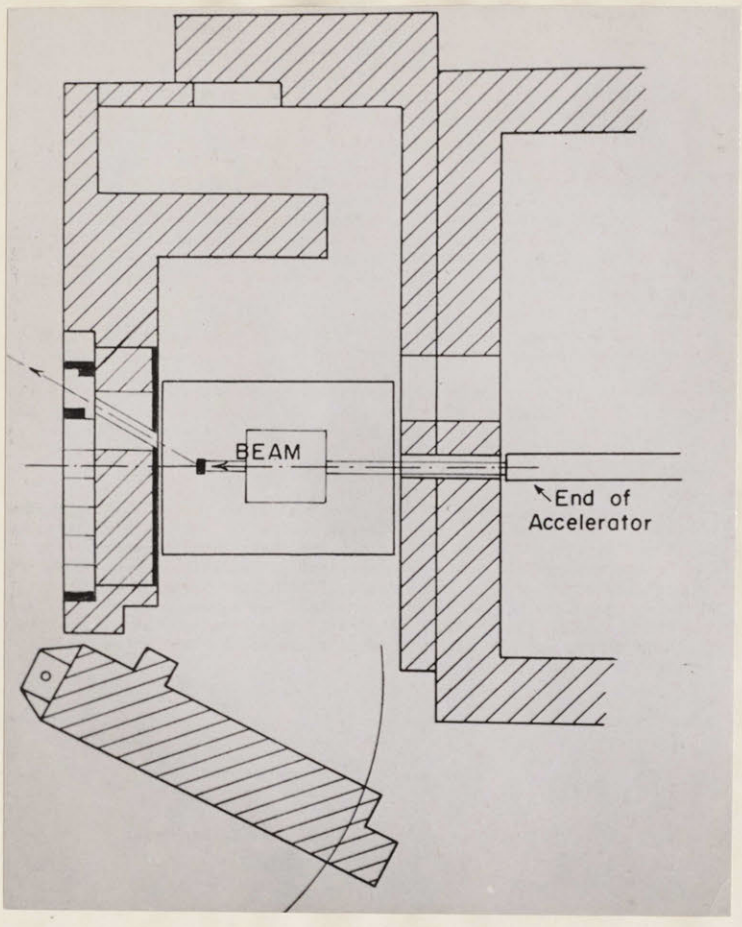

Figure 1. - Plan View of
Accelerator Target Room

The electron beam is shown striking a lead target, and the collimated neutron beam is indicated. The main body of the collimator is paraffin, while the solid black areas represent lead and the cross-hatched areas are concrete.

total extent of the target, only the uranium and lead targets can reasonably be considered point sources. The dimensions of the targets are given in Table II. Because of the scarcity of copper and uranium, it was necessary to use brass (approximately 70% copper) in place of the former and to encase the uranium cylinder in a lead housing. Interest in uranium derived from the possibility of obtaining additional neutrons from photofission.

Table II. - Target Dimensions

Material	Mass	Dimensions
Aluminum	2.33 Kg.	3" dia. x 10" long cylinder
Brass (approximately 70% Copper)	18.6 Kg.	6" dia. x 6" long cylinder
Lead	5.33 Kg.	$2\frac{1}{2}$" x 4" x 4" rectangular prism
Uranium	1.0 Kg.	1 3/8" dia. x 2" long cylinder

Collimation to produce a neutron beam is accomplished by allowing a small, carefully selected portion of the neutrons emitted by the target to escape from the target house, the rest being rejected by the thick concrete shielding surrounding the accelerator. A cast paraffin block with a $3\frac{1}{2}$" cylindrical hole passing through it replaces some of the concrete blocks ordinarily used to shield the target room, in such a way that a horizontal neutron beam is obtained at an angle of 35° with the forward direction of the electron beam in the accelerator. Two or three inches of lead shielding in front of the paraffin was found to improve the collimation greatly by slowing the incident neutrons to a velocity at which the paraffin cross section is large. The degree of collimation was measured with a neutron detector (to be described in the next paragraph) whose sensitivity is approximately constant over the energy range under consideration, and the results are plotted in Figure 2.

For the measurement of absolute neutron yields, a neutron counter is desired whose efficiency as a function of energy is essentially constant. A counter assembly with the desired characteristics, a cross-section view of which is shown in Figure 3, was constructed following the design proposed by Hanson and McKibben.(6) Figure 4. is a photograph of the completed counter. Since the central counting mechanism is a B^{10} enriched BF_3 proportional counter whose sensitivity varies inversely with the velocity of the incident neutrons, the large paraffin housing surrounding the counter tube, by slowing the higher energy neutrons, tends to make the overall counting sensitivity of the device more nearly constant over a considerable energy range. A full description of this "long counter" will be found in the Hanson and McKibben article, from which the sensitivity curve shown in Figure 5. is taken.

Because the long counter functions by slowing down fast neutrons, a considerable uncertainty in neutron arrival time is inherent in its operation, and this uncertainty renders the counter useless for time-of-flight measurements.

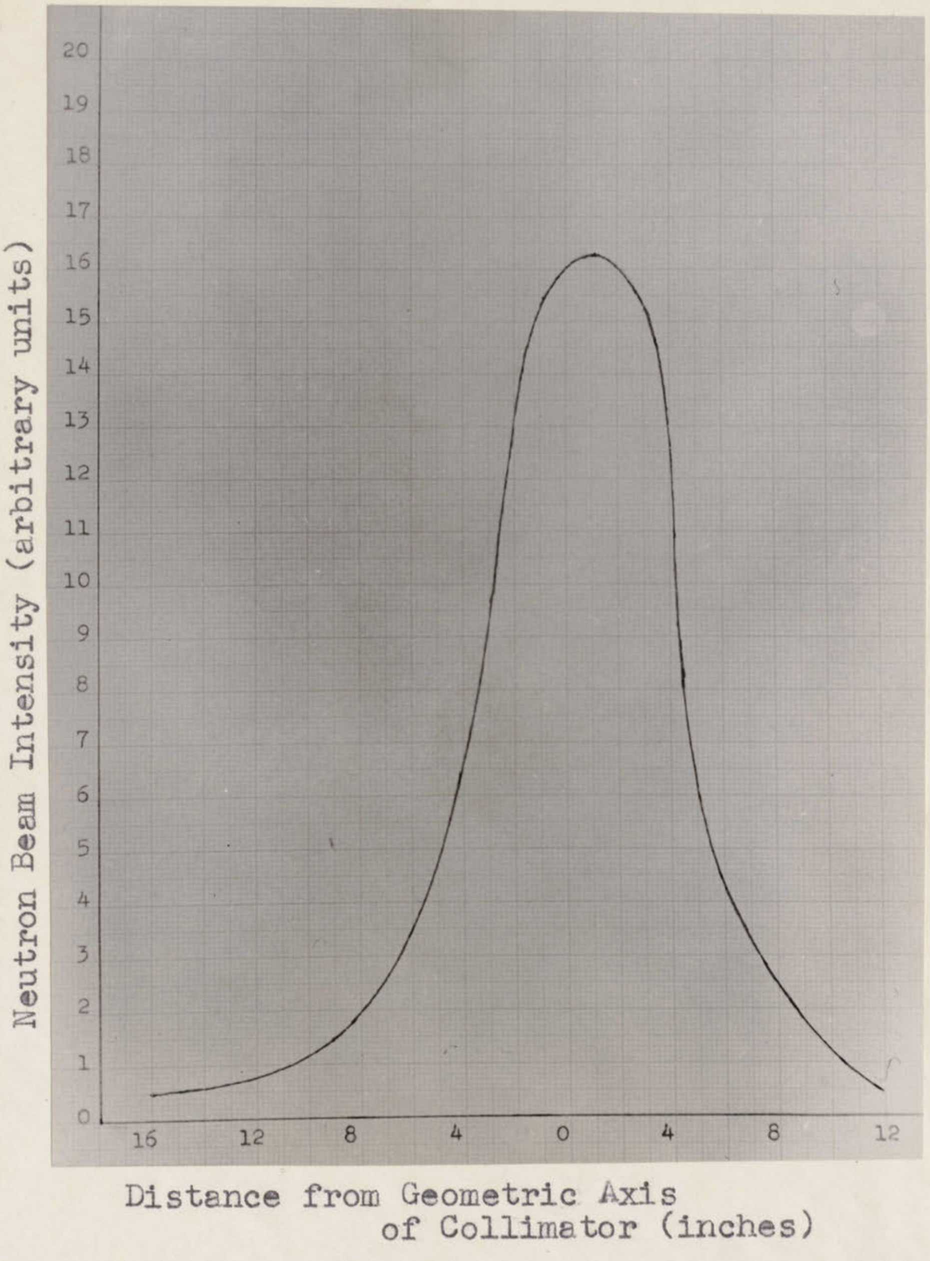

Figure 2. - Neutron Beam Collimation

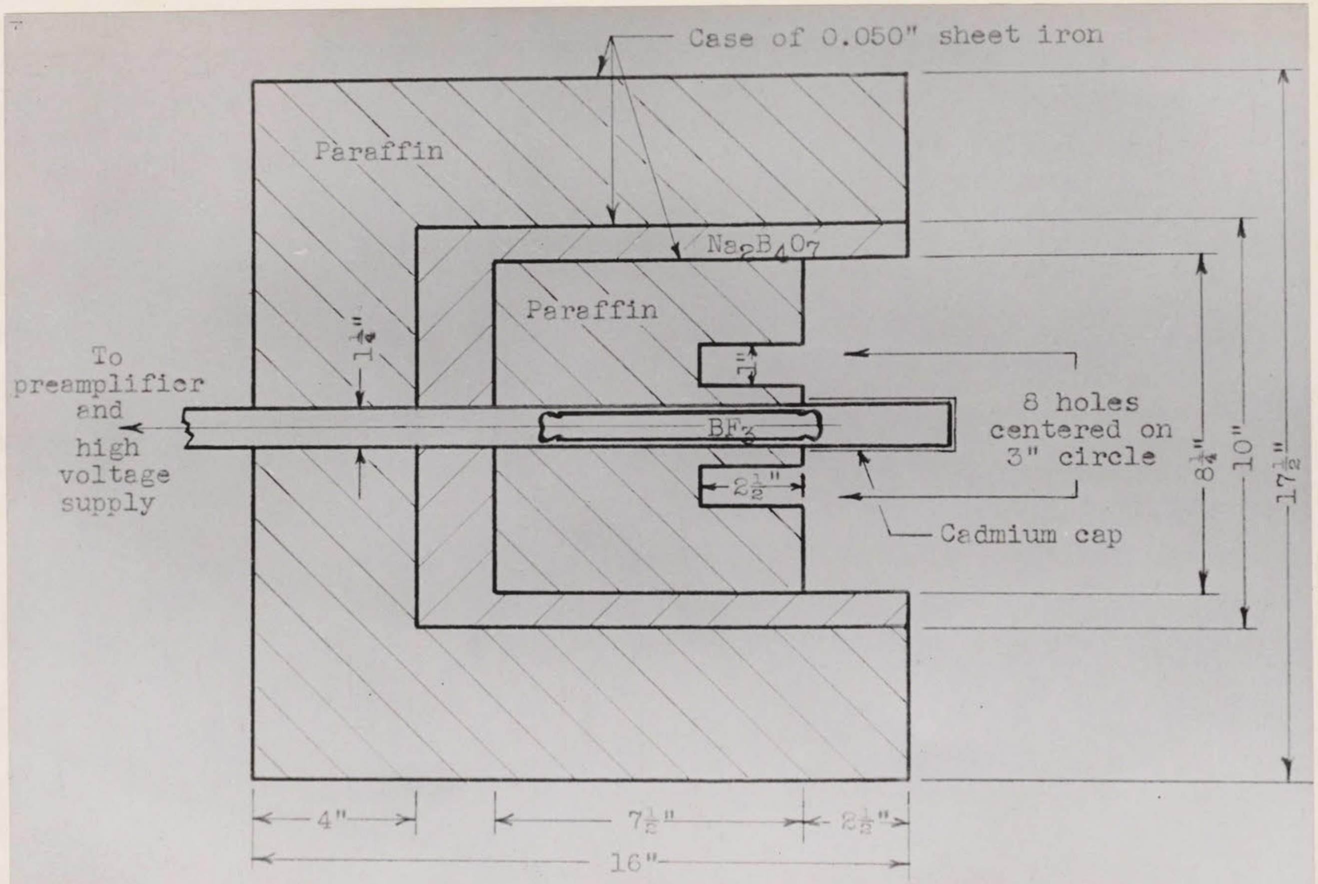

Figure 3. - Cross Section of Long Counter

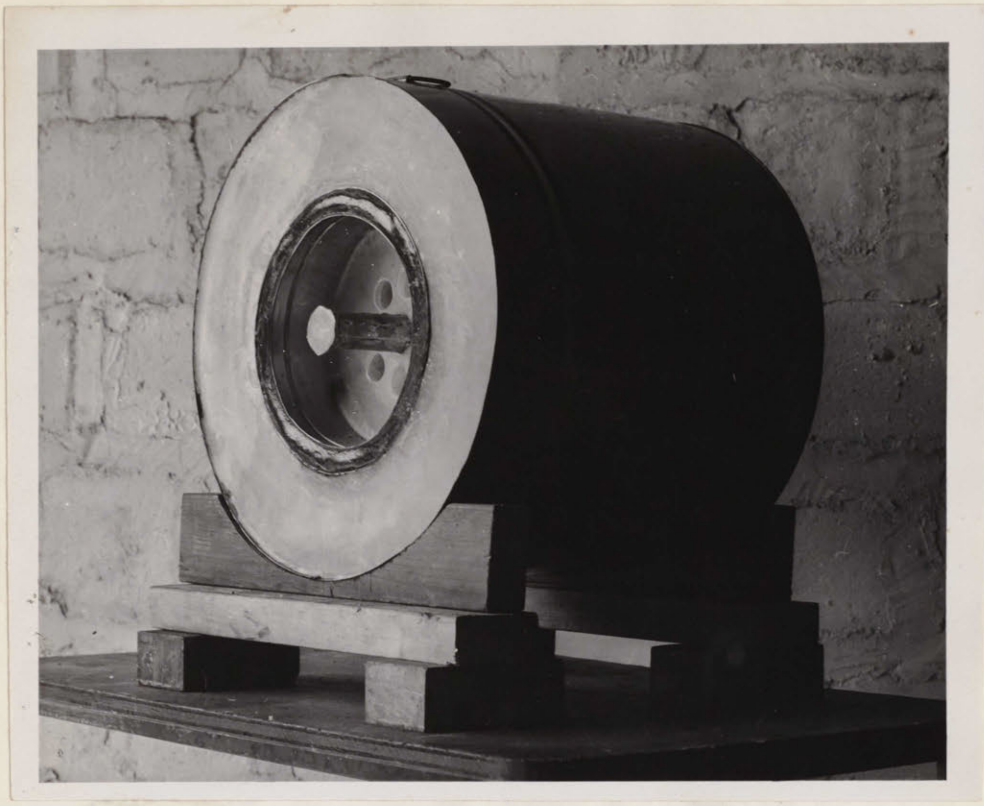

Figure 4. - Photograph of Long Counter

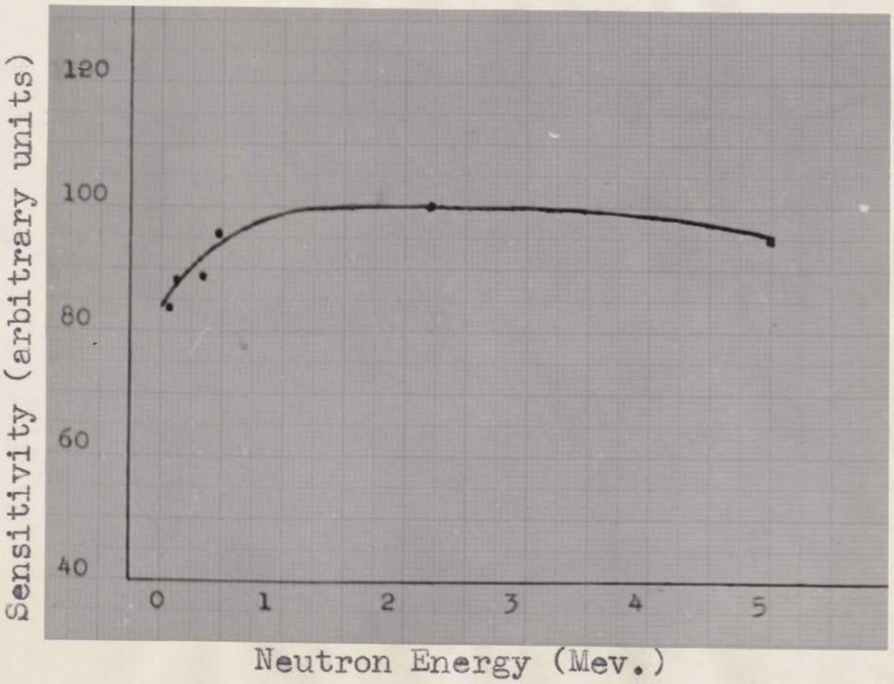

Figure 5. - Long Counter Sensitivity

Some type of "prompt" detector must be employed if good resolution is to be obtained in a spectrometer experiment. Accordingly, a bare BF_3 proportional counter, 6" long by 3/4" dia., filled to 30 cm. Hg pressure and operated at 2000 volts, was used in the investigations of neutron energy spectra reported later in this paper. As was mentioned before, the efficiency of such an instrument is inversely proportional to the square root of the neutron energy, the constant of proportionality for the stated conditions being of the order of 10^{-2} when energy is expressed in electron volts. It should be noted that the large neutron flux necessitated by so low an efficiency is a very important limitation on the source to counter distance in a spectrometer, and hence on the resolution, since the time required to obtain good counting statistics varies with the square of this distance.

Two phenomena associated with the particular experimental arrangement of the present investigation made it necessary to modify the usual amplifier-scaler counting procedure. The accelerator magnetrons, when firing, radiate sufficient RF energy to produce a pulse in the counting circuits. Also, a considerable number of γ-rays (from the target and from scattered electrons elsewhere in the target house) are incident upon the bare counter at the beginning of each cycle of the machine, and these γ-rays produce a pulse. Both of these disturbances occur once each cycle. Thus 120 spurious counts per second are introduced into the counting system, regardless of whether or not the electron beam is on, and in order to overcome this difficulty, an anti-coincidence device has been made an integral part of each scaler. This anti-coincidence modification, designed by M. Labitt, consists essentially of a provision for applying a negative blanking pulse to the screen of the phase inverter stage of the scaler, the blanking pulse being obtained directly from the trigger pulse which fires the magnetrons.

In order to measure neutron energies by the time-of-flight method, it is necessary to divide the time following emission of the neutron pulse from the source into short intervals for counting purposes. Of the several possible ways of accomplishing this division, the following method was chosen, chiefly because of availability of apparatus. A multivibrator circuit is used to provide a negative 300 volt square wave "gate", which is applied to the scaler in the same manner as the anti-coincidence pulse. The multivibrator is triggered by the anti-coincidence pulse, which occurs at the same time as the production of neutrons and hence acts as a reference time. The gate pulse itself can be varied continuously in width from one to ten thousand microseconds, and its beginning can be delayed to any time in the cycle after the end of the reference pulse. As is the case with the anti-coincidence, when the gating pulse is applied to the scaler no counts are registered, so that with this arrangement it is possible to prevent those neutrons from counting which arrive at the detector during the gating interval. By making measurements of neutron intensities with various gate widths and delays, the time-of-flight, and hence energy, spectrum of a neutron beam can be established. Neutron cross sections of nuclei can thus be determined by interposing samples in the neutron beam and measuring transmission spectra.

A synchroscope is incorporated as an integral part of the apparatus, being used both as a monitor for examining wave forms throughout the system and as a time measuring device. Gate widths and delay times are easily measured with an error of less than five per cent by observing the shape and position of the gate with reference to the anti-coincidence pulse. By observing pulse shapes of the input to the scaler, it is also possible to distinguish neutron-initiated pulses from those produced by γ-rays and spurious discharges, and thus to check on the proper operation of the counting system. An overall block diagram of the detection-scaling-monitoring apparatus is shown in Figure 6.

III. RESULTS

The measurement of the total neutron yields from the four targets mentioned previously required an absolute calibration of the long counter. Since its sensitivity is essentially constant for neutron energies up to a few million volts, a standard Ra-Be source was employed for the calibration. This source was placed at the position

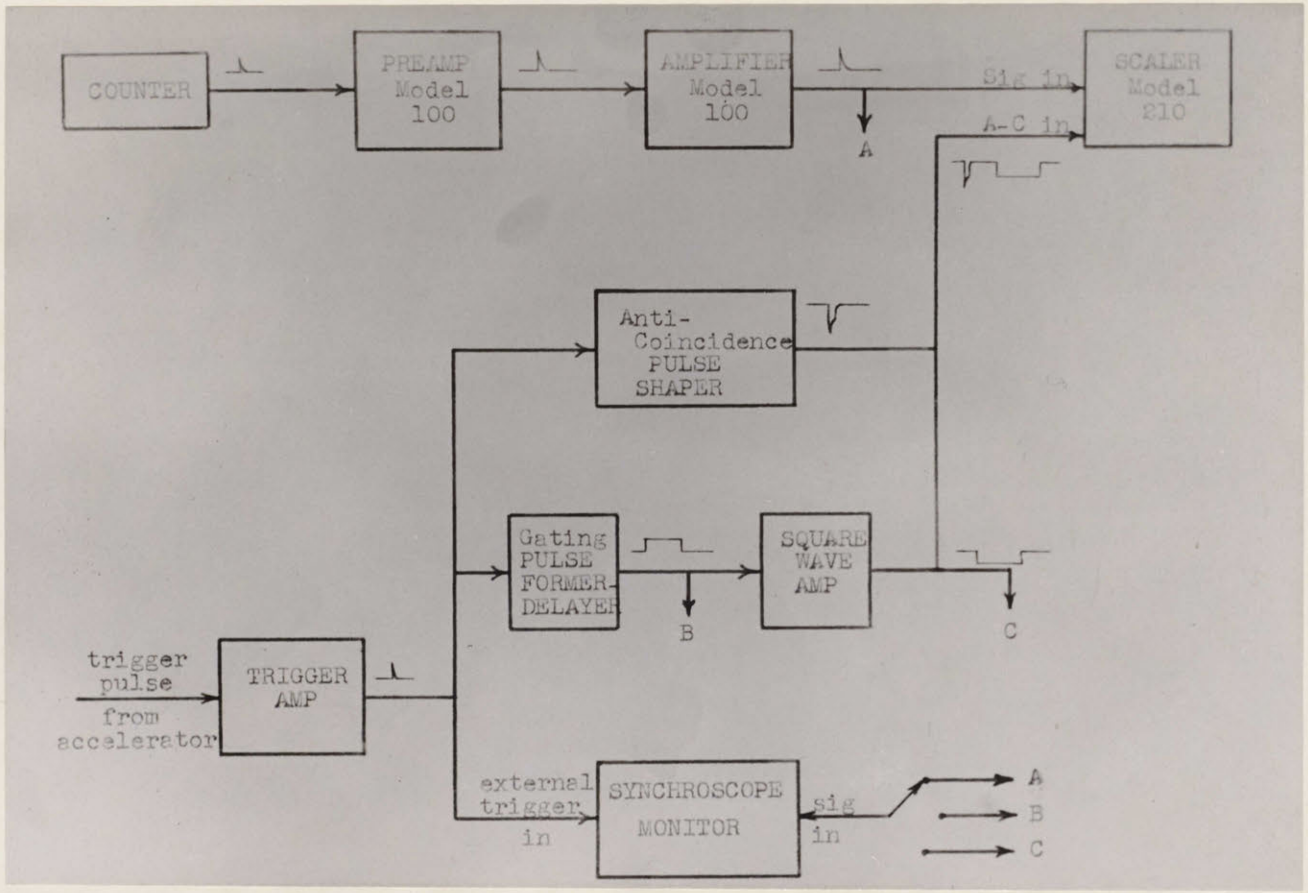

Figure 6. - Block Diagram of Detection Circuits

of the accelerator target, and the complete detection arrangement - counter position, amplifier gain, scaler discriminator setting, and counter operating voltage - was made identical to that used for yield measurements. The long counter was placed outside the target house, in the collimated neutron beam, at a distance of two meters from the source for all of this work. The total Ra-Be source strength was given by S. Levin of the M. I. T. Health Physics Group as 6.7×10^5 neutrons per second, and the energy was assumed to be centered about 5 Mev. Table III shows the results of the total yield measurements, which were based on the above calibration data.

Table III. - Neutron Yields.

Target	Total Yield (neutrons/sec.)	Relative Yield (neutrons/electron)
Aluminum	7.61×10^6	4.87×10^{-6}
Brass	8.53×10^7	5.48×10^{-5}
Lead	1.39×10^8	8.88×10^{-5}
Uranium	2.44×10^8	1.56×10^{-4}

Total neutron yields are given for a beam current of 0.25 μamp. at 16 Mev. Estimated error from all sources: ±10%.

An approximate calculation of the neutron yield per incident electron for copper is given in Appendix I. For 16 Mev. bremsstrahlung, this relative yield comes out to be 1.3×10^{-4} neutrons per electron, which is in reasonably good agreement with the measured value. It should be noted that because of the large size of the brass target, the long counter "sees" only approximately half of the target volume, so that the measured yield can be expected to be correspondingly smaller than the true value.

Determination of the energy spectrum of the neutron beam presented greater difficulties than did the yield measurements. It was found that the counting rate with the bare counter in the beam was lower than that with the long counter in the same position by several orders of magnitude, and hence, even considering the difference in counting efficiency, it is apparent that a significant portion of the neutrons in the direct beam have energies of the order of millions of electron volts. Since the maximum available γ-ray energy is 16 Mev. and the binding energy of a neutron is of the order of 8 Mev., it would be expected that some neutrons would be emitted with energies as high as 8 Mev. However, most of the neutrons probably boil off with energies nearer 1 Mev., leaving the residual nuclei in excited states, to decay by means other than neutron emission. As has been pointed out earlier, both resolution and detection efficiency become progressively poorer with increasing neutron energy, and it has been found that with the present detectors and timing circuits, significant measurements in the 1 Mev. range are impracticable. Accordingly, it was decided to introduce a thin paraffin slab, or "window", to shift the energy spectrum of the neutrons downward. The window was 3.5 cm. thick, and it was placed between the source and the collimator, approximately 40 cm. from the source. Besides shifting the total neutron spectrum, such a window will both delay the neutrons slightly (a few microseconds) and introduce a small dispersion, but these effects are more than compensated for by the increased detection efficiency and resolution.

It is to be expected that a significant portion of the neutrons emitted from the window will have made several collisions with the nuclei of the paraffin, enough so that they will have nearly attained thermal equilibrium with the molecules of the paraffin. (Approximately fifteen collisions with hydrogen are required to thermalize a 1 Mev. neutron.) These neutrons will then emerge with energies corresponding to a Maxwellian distribution in the neighborhood of room temperature. If the paraffin were of infinite extent, the distribution would be roughly Maxwellian, at roughly room temperature, but because of the finite size of the window, neutrons with appreciable velocities, still in the process of "cascading", will also escape.

Since the mean free path of 1 Mev. neutrons in paraffin is approximately 3 cm., it would also be expected that of the order of 1/3 of the incident neutrons will pass through the window without making even one collision, so that the transmitted beam will also contain large numbers of neutrons with their original energies. Thus the complete energy spectrum of the paraffin-modified beam will consist of two widely separated peaks, one near 1 Mev. and the other near thermal energies (0.025 ev.), between which are distributed those neutrons that escaped from the window after making only a few collisions. Measurements with the gated bare counter using cadmium and boron shielding, showed that there were indeed components of quite low energy in the beam from the window, components which are not present when the window is removed.

Boron absorption measurements with the long counter indicated that there is also a sizeable fraction of the neutrons with energies considerably above the electron volt region, for the average boron absorption cross section came out to be 25 barns, which corresponds to a neutron energy of 25 electron volts. A more detailed examination of the neutron beam spectrum could not be made because of low counter efficiency and scattering of neutrons in the collimator.

IV. CONCLUSIONS.

The M. I. T. Linear Accelerator now operates at 16 Mev. maximum energy and 2 μ amp. average current. The machine was designed for a peak energy of 20 Mev. and current of 12 μ amp. If the design energy could be realized, calculations by Feld indicate that copper should be expected to have a yield of 0.7×10^{-3} neutrons per electron, a factor of 5.2 better than the value calculated in Appendix I for 16 Mev. Noting that the measured yields given in Table III are for an average current of 0.25 μamp., a 12 μamp. current would represent an additional factor of 48 in the total neutron yield. Thus the total neutron yield at the optimum conditions should be 250 times the measured yield for copper. Assuming the energy dependence of the relative yield for lead to be about the same as that for copper, a total neutron yield of approximately 3.5×10^{10} neutrons per second would then be expected for lead, and this value compares favorably with the reported Harwell flux of approximately 10^9 neutrons per second.(3) Neutron fluxes of the order of 10^{10} to 10^{11} per second should enable time-of-flight measurements to be made over greater distances than have been employed in this investigation, with corresponding increases in the resolution of the system.

There are several possible improvements which might be made to increase the accuracy and resolution of the spectrometer. One primary consideration is the inefficiency of the detection apparatus, especially at high energies. Bigger BF_3 counter tubes, larger in diameter and filled to a higher pressure than the ones now in use, would have greater efficiency and more nearly uniform energy response. They should not be made much longer than the present six inch tubes, because longer counters introduce a greater error in distance-of-flight measurement and hence reduce resolution. Several small, high pressure tubes could be operated in parallel, or larger single tubes could be built. To keep high voltage requirements within reason, the parallel arrangement seems the more practical, although larger tubes might employ multiple electrodes and operate at normal voltages. In any case, the counter array should have approximately the same diameter as the neutron beam.

Other possible detection schemes include the use of B^{10} scintillation counters and/or photographic recording of amplified proportional counter pulses on a synchroscope. The scintillation method, suggested by Duckworth, Merrison, and Whittaker,(7) makes use of the 480 Kev. γ-ray emitted from a Li^7 excited state produced in 93% of the reactions, $B^{10}(n,\gamma)Li^7$. Adequate γ-ray shielding is important here because of the sensitivity of the scintillation crystal to stray radiation. The synchroscope could be used by triggering it with the anti-coincidence pulse and photographically recording the time distribution of the amplified neutron pulses. A time-of-flight neutron spectrum can then be obtained directly from the photographic emulsion by photometric analysis. By this latter method, a continuous spectrum will be produced, whereas the other procedures yield intensities at discrete points only.

For the most accurate time-of-flight determinations, revision of the timing and scaling devices along the lines of those now in use at Columbia and Harwell should be considered.(8,3) Both systems employ crystal oscillator timing standards and thirty-two channel scaling circuits, which permit the timing interval to be split into as many contiguous sub-intervals, each of which is counted on a separate scaler. By this method, more accurate measurements are achieved and several experimental points are determined simultaneously, since the procedure is equivalent to thirty-two separate measurements with a single scaler.

Improved collimation which will absorb rather than reflect neutrons incident upon the walls of the collimator would improve the accuracy of the measurements in the low energy region. The ordinary method is to use a boron-lined collimator tube and adequate boron shielding around the absorbing sample and the detectors. The present collimator, which has no absorbing lining, reflects a sufficient number of slow neutrons to obscure the true, unreflected, low energy component of the neutron beam, as was shown by experiments using cadmium shielding and the gated bare counter.

With the present equipment, it has been found that reasonably accurate measurements of neutron cross sections can be made in the low energy range using a paraffin window. If more refined measurements are to be made in this range, or if any measurements are to be made at energies greater than 10 electron volts, some improvements of the sort outlined above will have to be made in the system.

APPENDIX I.

Calculation of the Thick Target Relative Neutron Yield.

Assuming that a fast electron loses energy by two processes, radiation and inelastic collisions with atoms resulting in ionization, we can estimate the bremsstrahlung spectrum and, subsequently, the thick target neutron yield by the following theory.

We assume the loss of energy due to ionization to be a constant. That is,

$$\left(-\frac{dE}{dx}\right)_I = \text{constant} = b.$$

The radiation loss per unit distance can be assumed to be proportional to the energy of the electron:

$$\left(-\frac{dE}{dx}\right)_R = a\,E_x \quad ,$$

$$\left(-\frac{dE}{dx}\right)_{TOTAL} = \left(-\frac{dE}{dx}\right)_I + \left(-\frac{dE}{dx}\right)_R = aE_x + b.$$

Integrating the above expression:

$$x = \frac{1}{a}\ln\left(\frac{aE_0+b}{aE_x+b}\right) = x(E_x).$$

Since the electron radiates as it loses energy, we will assume that the number of quanta of a given energy will be inversely proportional to the energy of the emitted quanta. That is to say, that in a slab dx thick,

$$\frac{dN}{dE_\gamma} = \frac{c}{E_\gamma}\,.$$

But the total energy radiated in dx must be given by

$$\int_0^{E_x} E_\gamma\,dN = a\,E_x = \int_0^{E_x} E_\gamma\left(\frac{c}{E_\gamma}\right)dE_\gamma = c\,E_x\,,$$

and therefore: $c = a, \quad \frac{d}{dx}\left(\frac{dN}{dE_\gamma}\right) = \frac{a}{E_\gamma}$.

Now for the total spectrum from a thick source:

$$\frac{dN}{dE_\gamma} = \int_0^{x(E_\gamma)} \frac{a}{E_\gamma}\,dx = \frac{a}{E_\gamma}\,x(E_\gamma) = \frac{1}{E_\gamma}\ln\left(\frac{aE_0+b}{aE_\gamma+b}\right).$$

Thus, the total thick target bremsstrahlung spectrum is given by: $\frac{dN}{dE_\gamma} = \frac{1}{E_\gamma}\ln\left(\frac{aE_0+b}{aE_\gamma+b}\right) = \frac{1}{E_\gamma}\ln\left(\frac{E_0+k}{E_\gamma+k}\right)$

where $k = b/a = f(Z) \cong 814/Z$, as given by Feld.[4]

The cross section for the production of neutrons by electrons is

$$\sigma(e,n) = \int_0^{E_{max}} \sigma(\gamma,n)\,\frac{dN}{dE_\gamma}\,dE_\gamma .$$

From the known (γ,n) cross section plotted in Figure 7, for copper, the product $\sigma(\gamma,n)\frac{dN}{dE_\gamma}$ may be computed.[9]

E_γ	E_0+k	$E_\gamma+k$	$\ln\left(\frac{E_0+k}{E_\gamma+k}\right)$	$\frac{1}{E_\gamma}\ln\left(\frac{E_0+k}{E_\gamma+k}\right)$	$\sigma(\gamma,n)$	$\sigma(\gamma,n)\frac{dN}{dE_\gamma}$
11.0	44	39	0.120	.0109	----	------------
11.5		39.5	.108	.0034	.009	0.345 x 10^{-4}
12.0		40	.095	.0079	.014	1.106
12.5		40.5	.082	.00656	.019	1.247
13		41	.070	.0054	.025	1.350
13.5		41.5	.058	.0043	.033	1.420
14		42	.047	.00335	.042	1.407
14.5		42.5	.034	.00224	.051	1.14
15		43	.020	.00133	.061	0.810
15.5		43.5	.010	.00065	.071	0.460
16		44	.000	0	.080	0

When the product of $\sigma(\gamma,n)$ and $\frac{1}{E_\gamma}\ln\left(\frac{E_0+k}{E_\gamma+k}\right)$ are integrated over all energies E_γ from the copper threshold

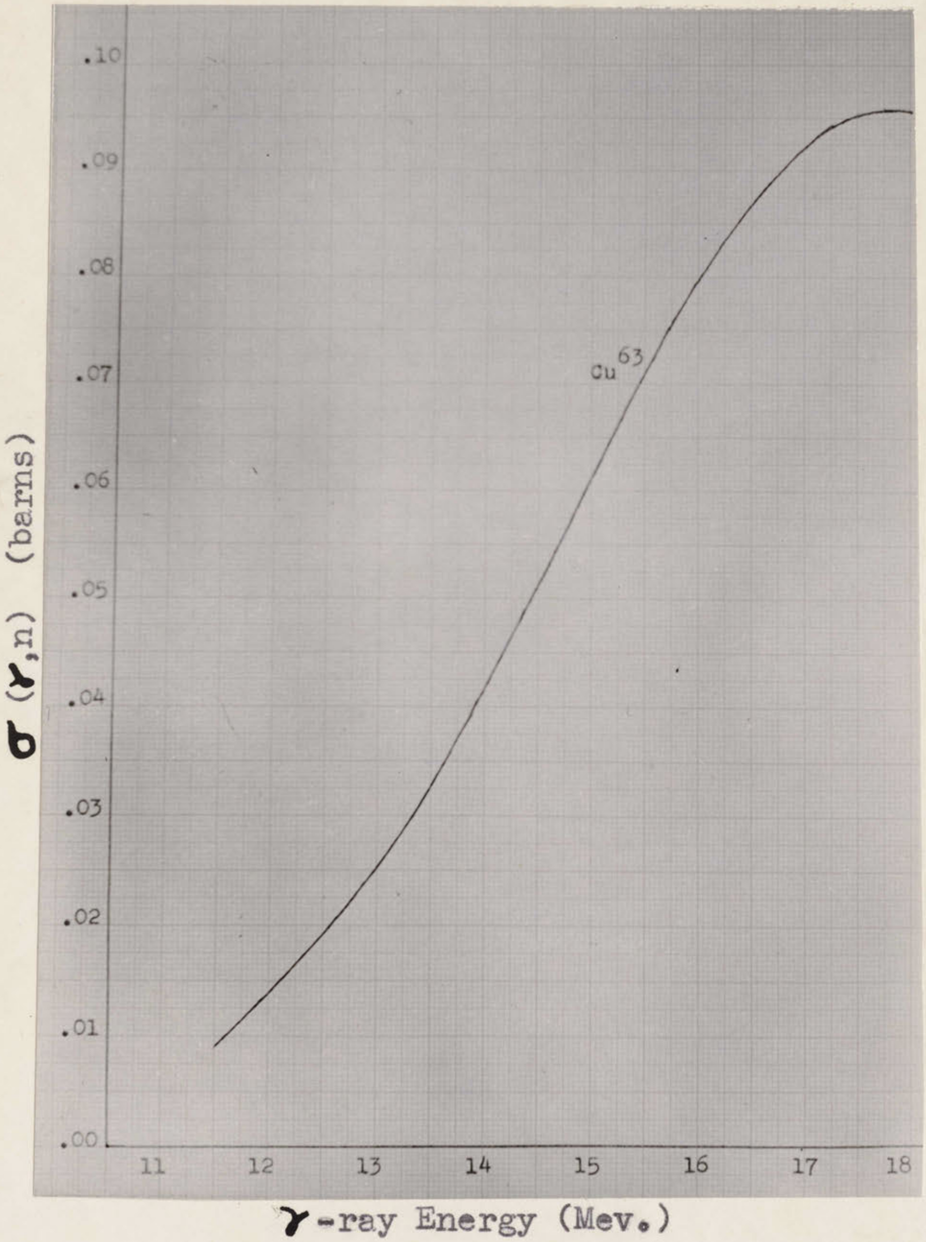

Figure 7. - Photo-neutron Cross Section for Cu^{63}

(11.5 Mev.) to the maximum available energy for electrons (16 Mev.), we find that

$$\sigma(e,n) = \int_0^{16\,Mev} \sigma(\gamma,n)\frac{dN}{dE_\gamma}\,dE_\gamma = 4.7 \times 10^{-4}\text{ barns} = 4.7\times 10^{-28}\text{ cm}^2.$$

Since the chance that an electron will interact with matter in any given manner is just proportional to the cross section for the interaction, the thick target neutron yield is given by the ratio of the cross sections, $\sigma(e,n)/\overline{\sigma_a}$ where $\overline{\sigma_a}$ is the cross section for the degradation of the bremsstrahlung by means other than nuclear excitation (i.e., Compton collisions, pair production, and photo-electric effect). It is assumed that a quantum will die by one of these means, or by a nuclear interaction, and that $\sigma(e,n)$ is small compared to $\overline{\sigma_a}$. For copper $\overline{\sigma_a}$ is about 3.5 barns.

Thus, we have the relative neutron yield:

$$Y = \frac{\sigma(e,n)}{\overline{\sigma_a}} = \frac{4.7\times 10^{-4}}{3.5} = 1.34\times 10^{-4}\ \frac{\text{neutrons}}{\text{electron}}.$$

APPENDIX II

Data

Note: All counting rates except yield measurements are corrected for variations in electron beam strength by comparing with a standard, ungated, cadmium shielded, bare BF_3 counter located in the accelerator target room. Yield measurements assume constant beam strength because no method of monitoring was available. Estimated electron beam strength: 0.25 μamp. (time average) at 16 Mev. Target - counter distance: 2 meters. Paraffin thickness: 3.5 cm. Boron absorber: Pyrex with 0.0586 gm./cm.^{2} boron.

Target	Counter	Paraffin window in	Boron absorber in	Counting time (μsec.)	Counting rate (counts/min.)	Comments
Pb	Bare BF_3	No	No	0-8000	550	Many Scattered
"	"	"	Yes	"	128	
"	"	Yes	No	"	1010	
"	"	"	Yes	"	157	
Pb	Bare BF_3	No	No	0-200	---	Nil
"	"	Yes	"	"	22.9	Very poor
"	"	"	"	0-250	22.6	statistics
"	"	"	Yes	0-200	11.3	
Pb	Long	Yes	No	0-8000	5600	Used for average
"	"	"	Yes	0-8000	5150	σ Boron
Pb	Long	No	No	0-8000	7900	
U	"	"	"	"	13900	Yields
Al	"	"	"	"	434	
Cu	"	"	"	"	4870	

Calibration of long counter: Ra-Be source, 2 meters from long counter, no paraffin, no boron, no gate, gives 38.4 counts/min. Source strength: 134 neutrons/cm.^{2}-sec. at 20 cm.

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