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TECHNICAL STEERING COMMITTEE
ATOMIC ENERGY EXECUTIVE

The Neutron Project

1. Introduction

Within a few years fissile material will become available in relatively large quantities permitting the construction of various multiplying assemblies. We shall have to find out, for instance, if reactors designed to operate in the intermediate region from 20-20000 ev neutron energy offer particular advantages as compared to the thermal or fast energy region. To obtain information about the neutron economy (e.g. breeding), the neutron spectrum in the system contemplated must be known and the nuclear data of the fissile nuclei interacting with this neutron spectrum must be available.

One way to study these problems is to perform intermediate energy exponential experiments and to build zero energy reactors. Such a method is certainly very costly, slow and gives the partial answers only. The other complementary approach lies in the measurement of the nuclear constants and the study of neutron spectra from suitable assemblies.

Therefore, a proposal is outlined below of the type of nuclear equipment which it is anticipated will be required for certain measurements in about two years time, the reasons why these instruments are necessary and why this particular type has been chosen.

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Nuclear measurements with neutrons are at present fairly easy at energies of about 50 kev to a few million electron volts where high voltage equipment can be used, and below about 10 ev down to thermal energies (pile neutrons). The region between 50 kev and 10 ev has to be covered by time-of-flight methods exclusively. Here the resolution, with reasonable counting times, is acceptable for transmission measurements in the region 10-1000 ev if large samples are available. Experiments, however, which use thin foils of the specimen (or a restricted beam diameter) because e.g. small amounts only of the material investigated are available, lead quickly to most uneconomical counting times if one is not satisfied with short flight paths and consequent low resolution. Unfortunately this difficulty is particularly encountered in fission and capture cross-section measurements which form the basis of the considerable mathematical efforts connected with reactor calculations. This is true to a high degree for the transuranium elements formed in second and higher order reactions in high flux piles (nuclear species such as plutonium of mass 240, 241, 242 and the trans-plutonium series). The lack of intensity also leads to great difficulties when the number of secondary neutrons emitted on neutron capture in fissile materials as a function of energy has to be found, or the neutron yield per fission in its dependence on energy has to be determined (see table in Appendix). It cannot be stated too strongly that the present equipment often allows only measurements with uncertainties which are too large to justify the considerable effort of high class mathematicians. This is particularly true of the medium energy region of importance for intermediate reactors with slight energy moderation of the neutrons.

Light nuclei. Large range

Heavy nuclei [illegible] [illegible] the [illegible] [illegible].

$\eta(E)$.

The continuous demands for nuclear data in the U.S.A. has led the Argonne, Oak Ridge, Idaho and the Brookhaven National Laboratories to invest considerable funds and manpower in the time-of-flight method. The devices which they are going to set up are different from ours; their merits will be summed up below. We, however, believe that we have good hope of achieving in many, though not all, respects, at least equal and in some cases superior performances. In addition our instrument, if completed according to plan, will show some revolutionary novel features.

Fission cross sections
thin targets
Nuclear [illegible]

M.T.R

Neutron spectrum, reactors

2. The New Proposal

If one wishes to overcome the previously stated inadequacies, one must, besides other factors, increase the distance between source and detector to lengthen the flight time t and cut down the pulse length τ_s of the source and the duration of the acceptance of the gates of the detector τ_d since the energy resolution $E/\Delta E$ is proportional to $t/(\tau_s + \tau_d)$. Both improvements require an increase in intensity of neutron emission during the pulse if the channel counting rate has to be constant. This increase in neutron production will be achieved in two steps:

(a) High current linear electron accelerator

The experience in linear accelerator design at A.E.R.E. and of firms such as Metropolitan Vickers and Mullards and the availability of klystrons will permit an increase in the electron current by a factor 20 over the present value and step up the electron energy by a factor 2.0 (see technical notes below). Owing to the particular variation of the cross-section of the nuclear photo-effect with gamma energy, an increase of 50 - 200 in neutron production rate over the present one has been estimated by Mr. Lawson. This would bring the neutron production rate to $0.5 - 2.10^{16}$ n/sec. in the pulse or with a duty cycle of 10^{-3} (500 pulses of $2\,\mu$ s) to a mean of $0.5\text{-}2.10^{13}$ n/sec.

(b) Neutron booster

The neutron production rate can be further increased by surrounding the electron target of uranium with a multiplying mass of fissile material placed inside a uranium reflector. From the calculations of Dr. Tait one finds that a useful multiplication by a factor 30-100 can be achieved.

The new neutron source (linear accelerator + booster) therefore leads to an increase of the neutron production rate from 10^{14} to $10^{17}\text{-}10^{18}$ neutrons per second in the pulse or about $10^{14}\text{-}10^{15}$ mean neutron emission/sec. It does not seem feasible at present to make a closer estimate of this factor since the data required are not available, but the estimate is certainly realistic and the lower limit very conservative. The neutron booster in this form is a completely new and original development of considerable use for other purposes (see below).

Dr. M.J. Poole has made a careful appreciation, A.E.R.E./N/R.1418, of the problems which confront us in the design of the electron target and the neutron booster and a possible design has been drawn up and discussed with the Engineers. As a consequence of these investigations we feel now quite confident that no fundamental difficulties will arise. However, we expect to learn a great deal from the booster about the behaviour of a pulsed reactor, which will be very valuable in itself.

We have in the past considered plutonium as the multiplying material, but now prefer uranium-235, partly because it is cheaper, less toxic and leads to smaller heat production per kg. due to the larger critical mass. (For a multiplication of 50 and 1 μ second pulse length, the fission heat amounts to 7.5 kW.). The latter is estimated to be about 25 kg. of 90 p.c. material.

3. Before proposing this new instrument, we have been looking into alternative methods towards improving the time-of-flight performance.

(a) At the moment, the Brookhaven National Laboratory is building or has in operation two cyclotrons (60" and 18") exclusively for time-of-flight operation, besides two neutron choppers associated with the pile. The former have been designed on the basis of several years cyclotron design studies to achieve the highest charged particle currents. The advantage of a neutron source based on a cyclotron lies in the short pulse length possible (10^{-8} sec.) and the high neutron production during the pulse. The high background is its weakness, and the inaccessibility of the target inside the vacuum box makes it difficult to surround the target with suitable moderating material to obtain the neutron spectrum desired. If the beam is brought out of the cyclotron, considerable losses partly eliminate the merit of the high current. As an example we can consider the small high current cyclotron at Brookhaven. Its internal current in the pulse is stated as 20 mA, but it is hoped to increase it to 100 mA. The pulse duration is about 3×10^{-8} secs., the number of pulses is 10^{6}/sec., as only every 10th pulse (by deflecting it into the target) is used to avoid overlap of neutrons from neighbouring pulses. This yields a mean current of $100 \times 10^{6} \times 3 \times 10^{-8}$ mA = 3 mA equal to 1.8×10^{16} charged particles per second. For an external beam one has to reduce the mean current by about a factor 4 to 4.5×10^{15} p/sec. If the charged particles are deuterons, $10^{11} - 10^{12}$ neutrons can be expected at the energy considered (1.5 - 2.5 Mev), but during the "off" period a strong background is present from the circulating beam. To avoid this, a p-n reaction can be used with a low threshold. In this case the efficiency of neutron production is greatly reduced (e.g. Li or Be). The main problem, however, a detector which is satisfactory for these short times of 3×10^{-8} secs., has still to be solved.

In consultation with Dr. Pickavance, we have come to the conclusion that the cyclotron presents no advantage, even if the particle energy were increased. It would certainly cost at least as much as the high current linear accelerator and the development effort for a high current cyclotron would be very large in time and manpower. In contrast to the linear accelerator it could hardly be contracted out to a firm.

(b) Nuclear reactor as neutron source

It is possible to chop the neutron beam emerging from a reactor into pulses of satisfactory duration. The intensity in the thermal and epithermal region is quite good if a flux of 10^{14} n/sec./cm^{2} is available, but it is deficient in high energy neutrons. A fast reactor, such as the one being designed by D.A.E. would certainly merit consideration as one alternative. However, there will be no facilities available for such work and this possibility is therefore ruled out. The reactor-based time-of-flight equipment suffers generally from considerable background, since the reactor is running during the "off" periods. If a small medium energy, high power reactor were available in the near future, some problems for which the new equipment is meant could be solved. The versatility of such a machine is certainly smaller.

4. Research Work Planned for the New Equipment

(a) In the introduction it was already stated that the high intensity will very much improve the resolving power of cross-section measurements. (See table in appendix showing improvement of 10^{14} to 10^{18} production rate). It is expected that part of the information will be particularly useful for calculations concerning intermediate reactors. It will now be possible to measure fission cross-sections of materials which are available only in small quantities, such as specimens of the transuranium class obtained in the mass separator which is under construction at the moment.

As an example of the importance of obtaining more intense pulsed neutron sources, we consider the problem of measuring the fission cross-section of an isotope which is itself radioactive (α, β or spontaneous fission) or cannot be separated from other isotopes which are radioactive. The isotopes Pu^{239} and Pu^{241} are examples of this kind, and samples of them would contain Pu^{240} and Pu^{242} which have high spontaneous fission rates. If the specimen investigated shows spontaneous fission, it is obviously necessary that the number of neutron induced fissions is larger than the former. The present neutron strengths are mostly quite inadequate for measurements of such nuclei (which are very frequent among the transuranium elements).

~ 2 x 10^{-8} sec., yet there is a significant probability that the build-up of α or β disintegrations during this time is sufficient to produce pulses as large as fission pulses, and in number about equal to the number of fissions per energy interval obtained with existing spectrometers. (This is true for the resolutions shown in the table and the effect would be worse if the resolution were improved).

It is therefore clear that in order to improve the signal to background ratio, and to improve the resolution of these fission cross-sections it is essential to obtain much more intense neutron sources.

(b) Velocity selector

The above method sorts the events observed by the detector according to the time-of-flight of the neutrons, but uses in fact, energetically heterogeneous neutron beams. If a pulsed neutron source is combined with a mechanically actuated gate (chopper) one obtains a true velocity selector arrangement selecting neutrons of a definite flight time and therefore energy. This possibility has not been put into operation, because very great intensities are required. A velocity selector will permit the measurement of absorption cross-sections by induced radioactivity in the sample and the study of this effect as a function of neutron velocity.

(c) The velocity selector will in the low energy region offer a wide field for the study of the interaction of neutrons with a crystal lattice. In particular it will permit, because of the large intensity, the analysis of neutrons scattered by the atoms of the lattice. The energy distribution of the neutrons is connected with the spectrum of the proper vibrations of the lattice. Excepting the case of the optically active vibrations (infra red spectra etc.) no direct method exists which permits such an investigation. The theoretical side of this field is still in its infancy.

(d) Neutron spectrum in reactors

The neutron spectrum in a reactor is a quantity of greatest interest, particularly in the energy region where the relevant cross-sections vary strongly. The spectrum has been measured in a graphite reactor (Taylor, A.E.R.E./N/R.1005) and can be determined in the high energy region (above a few 100 kv) by new methods developed at A.E.R.E. In the region below 200,000 ev and above, say 50 ev, the time-of-flight method offers considerable possibilities:

(i) An aperture through the tamper of the booster will allow the timing of the flight of the neutrons emitted by the core and determination particularly of the lower end of the neutron spectrum of the critical assembly. It will also allow the measurement of the energy distribution of the neutrons emerging from the tamper. The value of such information for fast reactors is evident and up till now no-one has brought into operation a satisfactory alternative method. The urgency of finding a solution to this problem suggests that the project should be pressed forward with as much initiative as possible.

(ii) The great sensitivity of the intermediate and slightly epithermal reactors to the neutron spectrum is caused by the very strong variation of the fission and capture cross-sections of the fissile and structural material contained in it. This has recently been supported by an outstanding representative of the A.E.C.

It is intended to build up small assemblies and to inject neutron bursts into them. The time-of-flight study of the neutrons emitted from various parts of the system will yield information about the neutron spectrum. (See below under d(iii).)

It is quite likely that large amounts of money and time will be saved, since the only other alternative is the building of a great many zero energy assemblies. Dr. Dunworth informs me that the sums spent by the A.E.C. on such assemblies are very large.

(iii) An important factor in the feasibility of a <u>thermal reactor</u> is the fraction of neutrons which are absorbed in low lying resonance levels in the fuel, structural materials, fission products etc. For a given system this factor is calculated from the neutron cross-sections and the incalculable neutron spectrum in the system. In order to compare the behaviour of various systems it is then necessary to determine the neutron spectrum in each experimentally. Heretofore direct spectrum measurements have been only just feasible because of the low intensities available. With the new equipment we shall be in a position to perform a proper study of various systems. The neutron source will be placed in the centre of the assembly and the detector will view the regions of the system where one wishes to know the energy distribution of the neutrons. The measurement of the neutron spectrum at any point in the system is therefore possible by measuring the time-of-flight of the neutrons from this point to the detector about 20 m. away. Calculation by Dr. J.H. Tait of the pulse width obtained when neutrons from this source are moderated by water have shown that detector on-times of about 500 μ sec. are required, so that reasonable resolution is obtained at 20 m.

Tables showing the resolution for the various experimental problems as a function of the neutron source strength are appended.

5. Time Scale

It is a property of most research equipment that its use is of greatest value when no-one else has an instrument of similar performance. At the moment there is a powerful upsurge of effort and expenditure being made by the American Atomic Energy Commission to bring into operation instruments which serve to investigate problems similar to our own. These are mostly advanced designs of mechanical neutron shutters used in conjunction with high flux piles such as the materials testing reactor of Arco, Idaho. We have also to be prepared that they will acquire equipment similar to the type proposed in this report. In view of the American resources, we must urge that the time scale be kept to a maximum of two years, if we wish to keep the lead which we now have in some parts of this field.

6. Cost Estimate

(a) Primary neutron source

As seen from §2, a linear electron accelerator is considered, which will supply electron pulses of 1-2 μs. duration and a repetition frequency of 500. The current in the pulse is expected to be in the region of 600 mA and the energy should be of the order of 30 Mev. Discussions with Mullards and Metropolitan Vickers have revealed that they are willing to accept such a task. Detailed specifications have been drawn up and both firms have now been asked to submit a design study. The preliminary estimates of the complete electron accelerator from the two firms were £120-180000.

(b) Buildings

The new device cannot be placed in Hangar 8 and a suitable building has to be obtained. This will include facilities for ordinary time-of-flight work extending over six flight paths of length up to 500 m. The accelerator will require space for its four klystron tables, four modulators, a power unit, and controls. Two "target" rooms will be required. The first will contain the usual electron target as it is in use with the present machine. Ample space will have to be provided here to permit the setting up of assemblies such as discussed under d(ii) or d(iii). A set of flight paths will start from this point (6 paths with up to 500 m. flight distance). A second room is necessary in which the booster will be located. The electrons will travel in an evacuated pipe from the end of the accelerator to the target in the booster room. The two rooms are separated by enough shielding to permit work in the first target room when the booster is not in operation.

The detecting equipment at the end of the flight paths would be placed in very simple small huts with all cables running to the central building. We would like to achieve widest flexibility so as to be able to modify our flight arrangements according to the particular problem to be investigated. There will be no services required except A.C. at the detector stations.

After many modifications we have arrived at a simple building for which the Ministry of Works has offered a token estimate of £90,000.

(c) Electronics

The gating circuits and auxiliary equipment, apart from standard electronic units such as amplifiers, has cost us about £20,000 for the present machine. If the new machine is to be used efficiently more electronics will be involved. We have at present considered £50,000 a realistic figure. It should be noted that we are desporately short of gates now when 132 are in use.

(d) Booster and target

An estimate of the likely cost of the booster as mentioned under 2b has been made by Dr. Poole and Mr. R.F. Jackson. It is stated here in a rough break down:

1) Core and tamper assembly, including electron and bremsstrahlung targets, tamper and core supports, control block guides, beam tube, He filled containing tank.		£3,600
2) Cooling circuits for core, target, and beam window. Calculated on the assumption of heavy water cooling for the core and mercury cooling for the target. Excluding special coolant materials.		£4,200
3) Control and instrumentation, including electronics.		£9,000
4) Special materials:		
a) uranium for tamper	£2,000	
b) 10 gallons of D_2O (for fuel element cooling)	£3,500	
c) 1 cu.ft. Hg (for target cooling)	£ 500	
	£6,000	£6,000
5) Drawing Office.		£4,500
6) Installation.		£2,000
7) Handling and storage facilities for hot core.		£5,000
		£34,300

The fissile material (U^{235}) is not included as it will presumably be on loan.

The total cost estimate therefore looks as follows:

Accelerator:	Mullard (Development Contract)	£120,000	
	Metropolitan Vickers (Dev. Con.)	£170,000	
	" "(Fixed Price)	£180,000	
M.O.W. (Buildings) (token estimate)			£90,000
Electronics (time sorting, pulse analysers etc.)			£50,000
Booster			£34,000
Total			£354,000

The 5 klystrons are not included (possible cost £1000 each).

7. Personnel

When the new machine is in operation we expect that the present 15 Mev accelerator will be sold, as it will still be a valuable instrument for pure research. The staff (4 scientific officers, 5 experimental officers, 1 scientific assistant) would be transferred to the new machine with some strengthening in the scientific officer staff. The new machine would also be used by the present thermal neutron research group and by members of the Reactor Physics Division, as is our present equipment.

Special consideration must be given to the detection and associated electronic equipment. It has been our experience in the past that far too many breakdowns of components interfere with experiments. It will be necessary to improve the circuits and guard against overload of circuit elements. Any effort in this direction will be well spent. This work has started.

8. Conclusion

We think that the present proposal will keep us in the front line of this field. It contains, particularly through the use of a neutron multiplicative system, a new and bold idea of which the Establishment can be proud. The results which can be obtained will be scientifically and practically very valuable. In cost it compares favourably with any novel device of comparable complexity and promise.

E. Bretscher

A.E.R.E. Harwell

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APPENDIX

These tables present a comparison between the attainable resolution widths* ($E/\Delta E$) with 10^{14}, 10^{16} and 10^{18} (neutrons/sec, peak rate) sources for those measurements which are difficult with a 10^{14} source. The figures are intended to be representative rather than exact.

There are, of course, other measurements (e.g. σ_t, σ_s, σ_a with large samples) in which the resolution obtained with a 10^{16} source (i.e. accelerator without a booster) would be adequate.

Case 1 σ_t, σ_s, σ_a with 30 mgm. sample.

Neutron energy (ev) ——>	10	10^3	10^5
10^{14} source	7	2	-
10^{16} "	28	7	2
10^{18} "	1000	40	8

Case 2 σ_f with few mgm. sample.

Neutron energy (ev) ——>	10	10^3	10^5
10^{14} Source	9	1.4	-
10^{16} "	36	5.4	1
10^{18} "	180	27	2.8

Case 3 Activation cross-section with 2 gm. sample.
(see case 4b: velocity selector)

Neutron energy (ev) ——>	10	10^3	10^5
10^{14} source	2	-	-
10^{16} "	13	4	-
10^{18} "	60	18	4

Case 4 Measurement of η as a function of energy in the intermediate region using large (~ 200 gms.) quantities of fissile material. (Assuming a fast neutron counter efficiency of 10^{-4}).

Neutron energy (ev) ——>	10	10^3	10^5
10^{14} source	3	1	-
10^{16} "	8	3.2	-
10^{18} "	38	15	3

Case 5 Measurement of spectra from intermediate energy region assemblies.
(see case 4d)

Neutron energy (ev)	10	10^3	10^5
10^{14} source	3	1	-
10^{16} "	13	5	1
10^{18} "	50	20	4

* The width is taken to be the base width of the resolution function.

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