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GA-2510

NEUTRON THERMALIZATION MEASUREMENTS USING
AN ELECTRON LINEAR ACCELERATOR

by

J. R. Beyster

U.S. Atomic Energy Commission
Contract AT(04-3)-167
Project Agreement No. 2

April 10, 1962

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DIVISION OF
GENERAL DYNAMICS

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FOREWORD

The experiments discussed in this report were performed using the General Atomic 32-Mev S-band electron linear accelerator, which had been in operation since September, 1958. This accelerator was subsequently replaced, in July, 1961, by a 45-Mev L-band electron linear accelerator (described in detail in General Atomic Report GA-1855 (Rev.)). The new accelerator provides a greater degree of flexibility and capability in performing experiments.

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INTRODUCTION

This report discusses reactor physics measurements that were made at General Atomic using the General Atomic 32-Mev S-band electron linear accelerator.

Before discussing this experimental program, conducted during the period from the spring of 1959 to the summer of 1961, it would be helpful to consider why integral measurements are made. With a high-intensity machine, two alternatives are available: to use the machine to add to the supply of fundamental information by measuring total and partial cross sections with already available techniques or to perform integral experiments.

In present-day reactor analysis, the systems that are considered are becoming increasingly complicated, and the basic data going into the analysis comprise many thousands of pieces of information. Some of this input information is very well understood; some, however, must be estimated. In addition to the approximations in the analysis input data, there is the problem of the calculational procedures employed; usually, reactor performance cannot be calculated exactly from the Boltzmann equation but certain approximations to the exact solutions (i. e., diffusion theory) must be made. Thus, there are approximations both in the method of analysis and in the basic input data.

The role of the integral experiment, therefore, should be to provide definitive measurements on clean systems; such measurements should involve the same methods of calculation and the same nuclear input information as actual reactor applications. For the experiment, one should not try to test everything at the same time, but try to test separately the parts of the theory or the parts of a method of calculation.

One of the research areas in which very little experimental information is available is the field of reactor spectrum measurements. A linear accelerator is ideally suited for neutron spectrum measurements because data may be obtained rapidly and changes in experimental arrangements can be made easily owing to the great flexibility of the facility. The spectrum can be measured under conditions in which there are essentially no spatial effects on the spectrum, and then the geometry may be altered in such a way as to introduce a gradient change (buckling), a linear variation of the spatial distribution of the flux, or a temperature discontinuity. The linear accelerator, as a pulsed source, allows a high degree of flexibility, provided that accurate methods of measurements--especially techniques for time-dependent measurements--are developed.

In the experimental program, one starts with the simplest possible system and proceeds to more complicated situations. Because it is very easy in integral work to obtain fortuitous agreement between theory and experiment, a sufficient number of measurements should be performed. Also, in the analysis of the experiments, the simple theoretical methods should be attempted first before proceeding to more complicated schemes.

Integral experiments on water and graphite systems are primarily discussed in this report, although work on other moderators, such as polyethylene, zirconium hydride, and beryllium oxide, has been performed at General Atomic, and some shielding measurements using lithium hydride have been obtained from work with the Oak Ridge group. The analysis of the measurements in water is based principally on the scattering law proposed by Nelkin.⁽¹⁾ The measurements in graphite are compared with a theoretical scattering law which has been developed by D. E. Parks.⁽²⁾ Die-away experiments in water are also discussed briefly.

FACILITIES

The linear accelerator facility is shown in Fig. 1 and the underground facilities are shown in Fig. 2. The accelerator used for the experimental program was a two-section S-band accelerator powered by 5-Mw klystrons. During most of its life, it was run at an energy of about 25 Mev and a peak beam current of 80 to 100 ma. A beam tube from the accelerator, which is located at one end of the 100-ft-long building, is coupled with critical assemblies in two other buildings. In addition to the photonuclear facility shown in Fig. 2, the targets of interest for this discussion are

1. The facility for making lifetime measurements.
2. The Poole-type facility for measuring spectra based on machine pulsing and time-of-flight techniques.⁽³⁾
3. The chopper facility.

The first is a boron carbide shielded box in which an assembly for lifetime (die-away) measurements is placed. The second, the Poole facility, is shown diagrammatically in Fig. 3. During the period when the experiments discussed here were performed, this facility was large enough to accommodate a 3-ft cube. (It has since been enlarged to accommodate a 6-ft assembly.) Two flight paths--16 meters and 50 meters long--look into the neutron cave. The source can be located almost anywhere in the neutron cave. In the Poole-type experiments, the assembly lifetime is short enough that it does not impair energy resolution. The third, the chopper facility, is used for spectrum measurements on assemblies which have long neutron lifetimes. The main features of the chopper facility are shown in Fig. 4. This facility was used for graphite experiments. The

Fig. 1--Plan view of accelerator and associated critical assembly facilities

Fig. 2--Underground experimental facilities for linear accelerator

Fig. 3--Poole facility--geometry for pulsed spectrum measurements

Fig. 4--Slow chopper spectrum-measuring facility

graphite stack could be heated and split in half for interface experiments. A collimator running on railroad tracks was installed so that the spectrum could be measured in any part of the assembly. The chopper, which is similar in design to that in use by Slovacek and Stone⁽⁴⁾ at Knolls Atomic Power Laboratory, has a flight path of about 4 meters.

The geometry used for age experiments is shown in Fig. 5; the experiment shown is an age measurement in beryllium oxide. The target was equivalent to a reactor of about 300 w. It is fairly difficult to perform an experiment of this type with an electron accelerator: because of the (γ, n) reactions in beryllium, the geometry must be extremely accurate. With careful, adequate shielding, the gamma-ray-induced neutron background was kept very low. The age measured in this experiment was 94 cm^2 , which agrees with the theoretical value of Goodjohn, et al.⁽⁵⁾

DIE-AWAY EXPERIMENTS

When the experimental program was started, it was felt that it would be worth while to make some very simple measurements of known quantities. Initially, some total cross-section studies and also some measurements of neutron lifetimes were made. For the latter measurements, water was used in the early program, because a considerable amount of information was available from the work done with pulsing water systems. Of course, the same problem found by other investigators was encountered in these experiments; that is, the decay constant measured in a water tank depends on the position of the measurement. Normally, the neutron density is assumed to decay exponentially, with a decay constant, λ , given by the following equation:

$$\lambda = \sum_A v + DB^2 - CB^4. \quad (1)$$

This was not found to be the case, and it was necessary to analyze the experiments by assuming that the thermal neutron flux density decayed according to the following relation:

$$N(x, T) = \sum_{m=1}^{\infty} A_m \sin \frac{m\pi x}{a} \exp(-\lambda_m T). \quad (2)$$

In other words, a simple modal analysis was used, where the coefficients A_m are determined by the initial thermal distribution that is established in the tank and each mode has a given decay constant, λ_m .

The type of data obtained from such die-away experiments is

Fig. 5--Geometry for performing age measurements

illustrated in Fig. 6. The object of the experiment was to try to obtain the decay of each of the modes; that is, a very small detector was used to measure neutron decay at many points in the assembly and a Fourier analysis was used to fit the data.

Fig. 6--Die-away curves for various harmonics in excited water tank

The fundamental decay is not shown in the figure, but the second, third, fourth, and fifth harmonics are shown. Although there is some uncertainty about the higher harmonics, it is clear that the fundamental decay can be determined quite exactly, and probably that of the second and third harmonics can also be determined. These experiments, if it is not desired to do a modal analysis, help to determine how long it takes for the higher modes to die out. In a pure-water system, the waiting time was found to be quite long--about five mean lifetimes. This means that in pure water a period of from 800 to 1,000 μ sec elapses before a pure fundamental mode is established. Many experiments in the past have not been performed in this way, and possibly some of them may have suffered from effects which could easily have changed the decay constant by several per cent. This experiment is capable of 1% precision.

The decay constant, λ , as determined for the fundamental mode is plotted versus the B^2 curve in Fig. 7. The decay constants for the higher modes should lie along the same general curve. (6) After λ for the higher modes is determined, the buckling is a better-defined quantity, since in a large tank the extrapolation length uncertainties are not as important as in a small tank.

Fig. 7--Inverse mean lifetime measured in water versus geometric buckling

In summary, one must be very careful of modal effects in die-away experiments. Attempts to obtain decay constants by using the decay of the higher harmonics have not been particularly successful. The next harmonic appears to lie approximately on the λ versus B^2 curve obtained from fundamental-mode studies. For the higher harmonics, it seems that something is happening that is not understood. Possibly, the quantity

C in Eq. (1) is inadequately defined. These experiments must be performed very precisely, and even then there may be some ambiguity in interpretation.

INFINITE-MEDIUM SPECTRUM MEASUREMENTS

The next series of measurements performed with the electron linear accelerator were infinite-medium spectrum studies. In equation form, if one tries to calculate the spectrum in a system, the very simplest equation that can be used is

$$-D\nabla^2 \phi(E) + \Sigma_T(E) \phi(E) = \int_0^{E_m} \phi(E') \Sigma(E' \rightarrow E) dE' + S(E), \quad (3)$$

where the first term is the leakage from a cubic centimeter, $\Sigma_T(E) \phi(E)$ is the total scattering plus absorptions in a cubic centimeter, the integral represents the neutrons transferred by scattering into the energy group around E, and S(E) is a source term. The upper energy limit chosen for use with this kernel normally involves a considerable number of physical considerations, including that of the molecular binding. The source term usually takes into account the neutrons transferred into the low-energy group by free-atom collisions above E_m , so the model is presumably very simple above this point. For infinite-medium experiments, an attempt was made, by poisoning the assemblies, to minimize the size of the leakage term by making the absorption term quite large. Results obtained by the Poole technique⁽³⁾ for poisoned water (various poisons, including cadmium, boron, samarium, and erbium, were used) are shown in Fig. 8. The upper curve in each case was calculated with the free-hydrogen kernel; the lower curve was calculated using Nelkin's kernel. In general, the agreement was found to be much better for the Nelkin kernel, which takes into account in a simple manner the vibrations and rotations of the water molecule.

The neutron spectra in an erbium-poisoned solution, one almost saturated with erbium, are shown in Fig. 9. This element has two resonances at low energies, one of which is very near that of plutonium, a material of great importance in reactors. This study was made to see whether the spectrum could be calculated with such a resonance present. Again, the bound-hydrogen kernel worked better than the free-atom kernel.

The neutron spectra in water poisoned with samarium are shown in Fig. 10. In this case, poor agreement was found in fitting the data. Although it may not be apparent from the graph that the disagreement was any worse, neutron conservation, which served as an over-all check on the adequacy of the measurements, indicated that it was. In other words, when the

Fig. 8--Infinite-medium spectra measured in boric acid and in cadmium sulfate solutions

total thermal absorption was calculated using the measured spectra and this quantity was compared with the slowing-down of the neutrons, there seemed to be a failure of about 10% for the samarium data. This may have been due either to a mistake in the total cross section or to some difficulty with the chemical analysis of the systems. These measurements were repeated many times; the total cross-section information used to evaluate the data were most probably at fault.

Some small disagreements for other spectra also exist. In general, the disagreements occur near the 0.1- to 0.3-ev energy region, the magnitudes of the disagreements between measured results and calculations with Nelkin's kernel⁽¹⁾ being from 5% to 10%. In attempts to pinpoint the experimental difficulties, the detector banks were oriented in several ways, the energy sensitivity of the detectors was recalibrated and different neutron flight paths were used. Further, the resolution corrections were made more accurately, the effect of the re-entrant tube in the assembly was investigated, the spectrum was measured in various places in the assembly, and the effect of leakage (even though it should introduce only a small error) was considered. All these investigations failed to reveal any experimental error.

Fig. 9--Infinite-medium spectra measured in water system poisoned with erbium

Fig. 10--Neutron spectra in water poisoned with samarium

Fortunately, from the standpoint of reactor calculations, the significance of the disagreement may be small; nevertheless, it is worrisome in regard to averaging cross sections over the spectrum. In most reactor calculations, thermal neutron energies are taken into account as a single group, although many neutron energy groups may be considered above 0.3 ev. In the thermal group, lumped constants are used; an average of all the fundamental cross sections over the thermal spectrum must be obtained. Therefore, a good method of calculating this spectrum is obviously important.

Even after changes were made in the theoretical model, no better success in trying to fit the data was achieved--the experimental results were always above the theoretical values. Apparently, a better definition of the water kernel is needed. Nelkin⁽¹⁾ has already taken into account various degrees of freedom of the water molecule, including the vibrational levels at about 0.2 and 0.47 ev, a rotational level at 0.06 ev, and translational degrees of freedom at lower energies. It seems, however, that the kernel should be improved. Perhaps the experimental scattering-law data that are available should be examined closely and Nelkin's model should be changed on the basis of this rather than on the basis of trying to fit the integral data.

SPATIALLY DEPENDENT SPECTRUM MEASUREMENTS

The geometry used for the spatially dependent measurements is shown in Fig. 11. The agreement between theory and experiment in the previous work was considered close enough for many practical applications; therefore, the program proceeded to one-dimensional spatial problems. One advantage of a pulsed linear accelerator neutron source is that the small source size makes possible various orientations of the assembly and detectors. When the experiment is performed with the re-entrant tube, essentially, the angularly dependent flux is obtained; unless the position is chosen carefully, the energy spectrum of the scalar flux is not determined. In many reactor calculations, all that is needed are the integral over-all angles of the spectrum, not the directional components. Therefore, the method used by the Swedish workers⁽⁷⁾ in this field, and referred to General Atomic by Henry Honeck⁽⁸⁾ of Brookhaven National Laboratory, was tried. This method utilizes a small scatterer in the hole to perform the angular integration automatically. Zirconium has been used successfully for this purpose; the data have been checked against re-entrant tube measurements.

In another experiment, the spectrum was measured in boric acid which had a 1-in. water channel, using the previous technique to measure the scalar flux. In an experiment of this type, it is very convenient to

Fig. 11--Geometry for measuring spatially dependent spectra

measure the scalar flux as a function of position simply by moving the scatterer. Sheets of cadmium, boron, etc., have been inserted in one-dimensional geometries, and the spectrum incident on these control elements have been measured.

A one-dimensional transport theory which will explain the spectra is, of course, desired; only fair success was achieved. A spatial distribution of epithermal neutrons in a 4-in. -wide slab of water and boric acid is shown in Fig. 12. This was the source distribution--it peaked at about 3 cm and decayed in a fairly linear manner. By measuring the spectrum at this point, there is no first derivative but only a leakage correction.

In the analysis, the shape of the flux is very important and therefore should be measured carefully, with many experimental points. The difficulty is that it is desirable to have the spatial dependence completely determined by the control rod, or the water channel, or whatever is inserted in the system, and not by the neutron source which is exciting the assembly.

Fig. 12--Flux plot of cadmium-covered indium in boric acid

Calculation of the neutron spectrum when there is only a buckling correction is illustrated in Fig. 13. This type of correction can be made quite easily, with Eq. (3), simply by putting an appropriate energy-dependent absorption term into the analysis. (Note that D is energy-dependent.) Although this is an easy calculation, when the attempt is made to calculate the spectra in the presence of a gradient, using the diffusion approximation, difficulties are encountered.

The failure of simple diffusion theory is illustrated in Fig. 14, which shows the measured spectrum and an infinite-medium and diffusion-theory calculation of the current. It is possible, however, to get agreement. The results of a calculation by Honeck,⁽⁸⁾ who used a transport-theory approximation to calculate the leakage spectrum from a 4-in. tank, are plotted in Fig. 15. It must be acknowledged that the best theoretical approximation to make in all cases is not known. This is particularly true when there is a gradient which affects the spectrum strongly.

SPECTRUM MEASUREMENTS FOR GRAPHITE SYSTEMS

A small hot box was built to measure the spectra of graphite systems (see Fig. 16). Such an assembly can be set up with boron poison strips, using about a 2-ft graphite cube. In other experiments, graphite cubes of

Fig. 13--Spectrum in boric acid at 3 cm from edge of tank

Fig. 14--Leakage neutron spectrum from a 4-in. poisoned-water assembly

Fig. 15--Leakage neutron spectrum for a 4-in. slab of pure water

Fig. 16--Cut-away view of 3-ft heated graphite assembly

up to 4 ft on a side were used, with the graphite poisoned to about 0.4 barn per carbon atom. The 2-ft assembly, which was heated to about 1000°F, had re-entrant holes. Provision was made for mapping the spatial distribution of neutrons in order to perform a modal analysis, calculate the spectrum appropriate for each mode, and add the spectra together.

Some additional information needed in the analysis of the graphite system is shown in Fig. 17. One has to be able to calculate the mean time spent by a neutron in the graphite block, because even though the graphite is very highly poisoned, the mean emission time may be as much as 300 μ sec. D. E. Parks⁽⁹⁾ has found a very simple way to calculate the corrections for this lifetime. The curves shown in Fig. 17 represent the various spatial modes present in the graphite block. The mean emission time was then calculated as a function of energy for each mode, and combined with appropriate weighting factors. Thus, a time correction to be subtracted from the flight time for each channel was obtained. This correction is not large, no more than 300 μ sec, compared with flight times of the order of 5 msec.

Fig. 17--Mean emission time of 2-ft cube of borated graphite

A spectrum for carbon at the highest temperature--about 800°K--is shown in Fig. 18. The theoretical (solid line) curve is calculated on the basis of the free-gas model. It is clear that at these temperatures the agreement is fairly good. It should be noted that this is a very hardened spectrum. The theoretical curve shown in Fig. 19 for a room-temperature

Fig. 18--Neutron spectrum in poisoned graphite at 810°K

Fig. 19--Neutron spectrum in poisoned graphite at 323°K

spectrum does not agree very well with experiment. Parks⁽⁹⁾ has been able to obtain very good agreement with these room-temperature spectra using a different frequency spectrum. He uses that proposed by Yoshimori and Kitano⁽¹⁰⁾ several years ago. The surprising thing is that one can construct a realistic frequency spectrum without any reference to nuclear data whatsoever. Yoshimori and Kitano calculated it on the basis of a knowledge of the crystalline structure of the graphite lattice and whether, for example, nearest neighbors affected each other strongly or weakly, along with considerations of the specific heat of graphite as a function of temperature. Although it is dangerous to be too optimistic, and other temperatures remain to be tried along with other poison concentrations, the analysis certainly appears hopeful. In fact, the graphite fits that Parks has obtained may be better than those obtained for spectra in water.

Figure 20 indicates what can be done by phasing the neutron chopper with the accelerator for graphite measurements. The data shown were obtained with boron-poisoned graphite. Steady-state graphite measurements both with the chopper and by the Poole technique have been made and they seem to agree quite well. The simplest method is to pulse the accelerator and then open the chopper at some predetermined time after the accelerator burst, measuring the spectrum as a function of the time after the accelerator is pulsed.

Fig. 20--Time-dependent neutron spectrum measured with phased neutron chopper

It was very difficult to make the experimental setup. In spite of the many experimental problems, the background was kept very low compared with the signal. The chopper opening time was around 1 msec after the accelerator pulse. After making a burst of fast neutrons, low-energy neutrons were often detected whether the chopper was open or not. This was one of the experimental problems and, in fact, it was found that the chopper was not poisoned enough and was itself acting as a large secondary source of thermal neutrons. It appears that this kind of measurement is indeed practical and is now fairly easy.

SUBCRITICAL ASSEMBLY PROGRAM

In trying to work with one-dimensional geometry, one of the disadvantages in not using the multiplying system is that the source injects effects which are not of particular interest. In a reactor, there is a cosine distribution or a normal-mode flux distribution, and the perturbations in the energy spectrum of the neutrons are caused by localized effects of absorber or water channels, etc.; it is desirable to concentrate on these rather than on the effects due to the external neutron source. The hope is that source effects will not be significant in a multiplying medium.

The assembly developed for measuring spectra in multiplying systems is shown in Figs. 21, 22, and 23. As may be seen in Fig. 23, the small lattice used for this program consists of closely spaced plates containing uranium and aluminum. The electron beam comes in from the left and hits the target, which has a hole through it in such a way that the detector bank which is at the end of the flight path on the side behind the assembly does not see the gamma flash. Thus, there is a small "glory hole" through the entire system that can be used for extracting the neutron beam. The system can be run as a reflected or as a bare assembly--plates can be removed to open up various channels, and the spectra in these channels can be measured to obtain data on flux peaking.

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Fig. 21--Side-view photograph of multiplying assembly

Fig. 22--Photograph of multiplying assembly showing safety rods and fuel spacing

Fig. 23--Top-view diagram of multiplying assembly tank

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