Rensselaer Polytechnic Institute

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FINAL REPORT

AEC Contract AT(30-3)-328

and

AEC Contract AT(11-1)-3058

November, 1958 - June 30, 1974

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SECTION I

SECTION I - INTRODUCTION

The work carried out under this contract was made possible by an electron linear accelerator design based on the use of high power L-band klystrons which were just coming into service in the late fifties. The RPI conceptual design for this system was exceedingly well implemented by Applied Radiation Corporation of Walnut Creek, California and led to the construction of several outstanding accelerators. The RPI research program subsequently carried out around this facility earned international recognition, as had the preceding work by some members of this team formerly engaged in neutron cross section studies at the General Electric Company in Schenectady.

The research completed during the 16 years of this contract was reviewed in an invited paper presented by one of us (M. L. Yeater) at the New Orleans meeting of the American Nuclear Society in June, 1975, as a memorial to Dr. Erwin R. Gaerttner. This paper, with a few additions, constitutes the "Summary of Work" given in Section II of this report. The remainder of the report contains a description of the facility, listings of research projects and publications, and identification of personnel involved.

It is our pleasure to acknowledge with deep gratitude the encouragement and support of the U. S. Atomic Energy Commission and its representatives. Although we cannot include a list of the many people in the Commission who were helpful in the administration of this work, we wish to pay special tribute to I. Zartman, P. Hemmig and W. Hannum for their technical understanding as well as administrative skill in helping to guide the program through its long and productive course.

SECTION II

SECTION II - SUMMARY OF WORK

The role of differential and integral measurements is a continuing one which today still poses challenges and problems fundamental to the design of efficient and economical reactors.

Some of the nuclear data measurements run like a continuing thread through the fabric of reactor physics, interfacing the technologies of light water reactors and breeders. Measurements of neutron capture and fission at increasing energy and improving accuracy have been needed from the nineteen forties through the seventies. The change in the state of the art in differential measurements is illustrated by a comparison of a differential ^{235}U measurement which we made in 1955, with a resolution of about a tenth microsecond per meter, and our present resolution of the order of a tenth nanosecond per meter for equivalent measurements. This has been accompanied by equivalent progress in data analysis such as the multiple scattering correction code MSC of Bischoff at RPI and a similar Monte Carlo code based on the 05R code developed at Oak Ridge, and by convenient and powerful methods of cross section resonance analysis based on interactive graphics techniques, as well as advances in various computational methods and analysis of integral measurements.

Theoretical developments relating differential and integral measurements have provided a harsh testing ground for methods of reactor analysis. It is clear that one needs nuclear data and group cross sections to calculate spectra in critical assemblies and flux distributions and depletion in operating reactors. When these calculations fail to predict the integral results one begins to suspect that either the differential measurement is inaccurate, the integral experiment is clouded by too many variables, or the theoretical approximations are inappropriate.

The Overall Problem

The situation suggested by these introductory remarks is that sometimes astonishing comparisons of various integral parameters with measurements can lead to

better differential measurements
better theoretical approximations
better integral measurements

which ultimately may have beneficial effects such as reducing the ad hoc nature of data sets used in design codes, and alleviating the high price of (ultra conservative) design decisions and safety systems.

In order to see how some of these interactions have worked out, let us think about a few specific cases. Generally speaking, one is concerned with the effect of some form of cross section integral on a predicted system response.

Iron

First we consider the case of the iron cross section. This is obviously of general interest as a major component of reactors and is especially important as it will affect the breeding ratio in fast reactors. One of the characteristics of this cross section which turns out to be rather crucial is the appearance of deep minima from potential-resonance interference, of which the well-known one at 24 kiloelectron volts is the most striking. These minima provide windows which cause selective energy-dependent streaming and lead to calculational difficulties in predicting neutron spectra. These problems have been clarified through the spectrum measurements carried out at RPI. This was a measurement carried out with a cuve of iron 40 inches on a side; this lattice was pulsed with neutrons generated in an imbedded target by radiation from the LINAC, and spectra were measured for neutrons escaping from penetrations to various

positions in the assembly. The results are shown in Fig. 1. The agreement between the measured and calculated spectra actually looked fairly good, but it is just the modest deviations observed which led to significant insights which are important in reactor calculations. Some of these are --

1. One of the early results was a clear comparison of the ENDF/B-I and ENDF/B-II data files which showed that ENDF/B-I was deficient in its treatment of the 24 keV minimum but in other respects was somewhat better than ENDF/B-II which brought out more resonance structure but did not lead to improved calculations. (This and many other tests of the ENDF/B files have of course led to successive revisions and ENDF/B-V is now in preparation.)
2. The low energy spectrum is particularly sensitive to the capture cross section, so there has been from the beginning, an incentive to improve capture measurements.

The results of the spectra measurements having demonstrated the inadequacy of the total cross section data near the minima, an experiment was carried out to focus directly on these minima. A 14-inch thick Fe filter was placed in the neutron beam path to remove all but the neutrons transmitted through the minima, and a 6-inch thick Fe sample was cycled into the beam to determine the Fe cross section, resulting in the neutron counts vs. time of flight curves shown in Fig. 2. The data for the 24 keV minima are shown in Fig. 3 and clearly measured the minimum cross section to better than ~ 8% and showed the inadequacy of the ENDF/B-I and II data. Data for the higher energy minima also shed light upon the directions that future evaluated data would have to take to accurately reproduce the effects of these minima.

Our concern in measurements of this type supported by the AEC was particularly for LMFBR problems. Analysis by the Hanford group shows that below

a breeding ratio of about 1.3 (the present range) the doubling time is a sensitive function of specific power and breeding ratio (contours closely spaced) both of which are directly or indirectly dependent, from the design standpoint, on our knowledge of capture in a component as important as stainless steel. The first high resolution neutron capture measurements on Fe, Ni, Al and Na were made at RPI. Fig. 4 illustrates the data for capture in Fe. These measurements showed, for the first time, the extensive p-wave contribution as well as producing accurate radiation widths for the larger s-wave resonances. Further measurements were carried out on about all of the isotopes of Fe, Ni, Al and V covering the range from 20 eV to about 200 keV. These later experiments also showed a positive correlation between magnitudes of radiation widths and neutron widths for resonances in the Cr isotopes and ^{60}Ni . A major result of all these experiments was the determination of wide variations in the radiation widths from resonance to resonance in the same isotope.

Fission and Capture Cross Sections

We turn now from measurements relating to structural materials, of which iron was a significant example, to the area of fuels and fission products.

One of the most powerful techniques for capture cross section measurements, namely the detection of γ -rays in a large liquid scintillator surrounding the sample, lends itself to a variety of experiments including simultaneous fission and capture measurement in fissile materials, which is to say the measurement of the quantity α . These fundamental measurements are obviously crucial to the determination of reactor fuel performance, including breeding ratio in fast reactors. The quantity of particular interest is the number of neutrons emitted per neutrons absorbed, η . Many of the important measurements of this type have been carried out at RPI and Oak Ridge, often by cooperation between the two laboratories.

The first of these cooperative experiments carried out at RPI was the measurement of α in ^{235}U by the simultaneous determination of fission and absorption. In this experiment the gamma rays from capture came from fissile material in a fission chamber operating inside the liquid scintillation detector. These cooperative experiments later included ^{233}U and ^{239}Pu in particular. The ^{239}Pu experiments carried out in 1968 still stand as the most important alpha measurements for the LMFBR program; these results are shown in Fig. 5. These measurements have been repeated at ORNL, essentially confirming the 1968 data.

ETA Measurements

The number of neutrons produced per neutron absorbed in the fission process, the quantity called η , can in principle be measured either directly or derived from measurements such as those just described. On balance it is not clear that one is greatly superior to the other. The direct measurement has the advantage that one is less worried about the difference between $\bar{\alpha}$ and $\frac{\sigma_c}{\sigma_f}$, but the η value derived from an α measurement is less sensitive to experimental errors in a formal sense just because $\eta = \frac{\nu}{1+\alpha}$. One advantage of the α approach is that one can use the same equipment as was used for the capture measurements. An early eta experiment used plastic scintillators to count prompt fission neutrons. The result of this measurement, for ^{233}U , is shown in Fig. 6. Here again the general trend of the energy dependence is clearly brought out, but the experimental uncertainties make the result extremely tantalizing -- a low energy breeder doesn't seem attractive, yet the uncertainties are just enough to leave room for some doubt. There have been some subsequent measurements of η for ^{233}U at Oak Ridge. Depending on the final outcome of current evaluations (such as being carried out now by the Electric Power Research Institute), more work on alpha

and/or the cross section slopes of the three fissile isotopes may be needed. The importance of these data may be further enhanced by the Light Water Breeder Program.

"Nubar" Measurements

In the foregoing it was noted that an energy dependent α measurement leads to the determination of η as a function of neutron energy, which is certainly true if $\bar{\nu}$, the average number of neutrons emitted per fission is known. This quantity $\bar{\nu}$ is clearly a key factor, comparing the effect of various nuclear parameters on the breeding ratio of a fast reactor. In the light of these and other considerations, there have been measurements of $\bar{\nu}$ made at RPI on ^{239}Pu , ^{235}U and ^{233}U in the low eV and thermal regions. The results shown for ^{233}U and for ^{235}U in Figures 7 and 8 bear out the conjecture that $\bar{\nu}$ is not constant. Furthermore, there is not convincing evidence that $\bar{\nu}$ is simply correlated with the spin J. These measurements have been repeated in the resonance region by others who also observe real fluctuations in $\bar{\nu}$ and have postulated the (n, γ f) reaction as a possible mechanism.

Multiple Scattering Correction

One of the extremely important factors in nuclear data experiments is the effect of scattering on various absorption measurements. In most absorption measurements (either capture or fission) it is not practicable to use a sample so thin that a single collision interaction is guaranteed, and in some cases it is desirable to measure directly the penetration in thick slabs. It is now common practice to use a Monte Carlo code to calculate correction factors to account for absorption in second, third or even more collisions. Two of the widely used programs are the MSC code originated by Bischoff at RPI and the Sullivan-Warner code patterned after portions of the Oak Ridge 05R code. Jack Rush and Mal Kalos report that the MSC code or its derivative is used in Europe

as well as in this country, and recent reports tell of the use of the Sullivan-Warner code in Australia and Japan. The Sullivan-Warner code is standard at RPI for corrections to resonance and high energy measurements. As a result of these codes it is no longer necessary to be concerned about using fairly thick samples, although for many years such corrections were so unreliable that multiple scattering (or the poor statistics resulting from very thin samples used to minimize these corrections) was a major factor in the accuracy of differential measurements. The MSC code was developed specifically for the analysis of low energy neutron inelastic scattering measurements (that is, in the energy range of molecular rather than nuclear binding).

Low Energy Neutron Inelastic Scattering

In a cooperative research program between RPI and the Knolls Atomic Power Laboratory we carried out a series of double differential measurements using the pulsed beam from the RPI LINAC to generate neutron pulses, and by means of a rotating shutter and time-of-flight analysis were able to determine the energy of incident and scattered neutrons, including the dependence on scattering angle. Studies were made of energy changes caused by molecular energy levels in uranium carbide, in water and in various hydrides. Zirconium hydride has a simple structure and lends itself to an idealized experiment which is relatively easy to analyze, although any inelastic scattering measurement with the double energy measurement is experimentally very difficult. The main complication in the case of zirconium hydride is the variation of structure with differing hydrogen concentration. Niobium hydride is analytically somewhat more difficult to study, although it presents no additional experimental difficulties. This material may be of interest in possible fusion reactors, and Jack Rush and his collaborators at the Bureau of Standards are continuing to study this material. In any case,

the purpose of our measurements was to determine frequency distributions and force constants to provide input for calculations of neutron slowing down and thermalization.

Of more immediate importance to light water design and operation were the studies by Esch and his collaborators of the temperature dependence of inelastic scattering in water, as shown in Fig. 9. The scattering at room temperature for various angles, and at 270°C , for one of several incident neutron energies used in the range .04 to .6 electron volts was of special interest. The search was to determine the change in relative contributions from levels which in this type of measurement produce peaks that are very small compared to the elastic peak (scattered neutron has same energy as the incident neutrons). As in measurements discussed earlier, the results seem by inspection to be of limited accuracy because of experimental difficulties. However, this was a highly significant experiment which showed in a direct way the structure in the rotational band near 0.1 eV and the effect of increased temperature in broadening this and the bending and stretching mode levels at higher energy. This work led to an improved theoretical model of the role of water in neutron thermalization. In this as in other inelastic scattering experiments the multiple scattering corrections provided by Bischoff's MSC code were essential.

The levels for uranium carbide, another relatively simple compound, as seen in Fig. 10, showed up more clearly than for water. These results are fairly straightforward from the standpoint of thermalization analysis, and Lajeunesse showed that a satisfactory theoretical model could be based primarily on harmonic oscillator frequency distributions consisting of an acoustic-mode centered at .013 electron volts and an optical mode at .045 eV. A simple Einstein oscillator model was not adequate either for UC or the hydrides. The UC analysis was based on the Born Von Karmen model involving forces between

second and third as well as first nearest neighbor atoms, and required the use of all known thermodynamic constants as well as the neutron scattering data to determine the force constants.

Uranium 238

Another type of problem which provides a striking example of the role of differential and integral measurements in reactor design and operation concerns ^{238}U . Almost everything that we can learn about ^{238}U appears to be relevant to fuel loading and management in LSW's and to breeding ratio in LMFBR's. At RPI we have made both cross section measurements and spectrum measurements in a continuing program. First we looked at some cross section results and then some spectra and their interpretation.

^{238}U Cross Sections

One of the recent measurements by a combined team from RPI and the Knolls Atomic Power Laboratory is that of subthreshold fission in ^{238}U . These small but significant cross sections are extremely difficult to measure by conventional time of flight means, and were first studied at RPI in a lead slowing down spectrometer set up by a KAPL-RPI group under the leadership of Rudy Slovacek. The interaction of neutrons with an imbedded sample is determined as a function of time as they slow down after the system is pulsed with fast neutrons. The effect is an improvement of the order of 10^4 in counting rate because of improved geometry over the ordinary time of flight experiment. In this case the very small cross section had previously limited observation to an experiment using neutrons from a nuclear explosion (this was not an RPI experiment!) The fission widths measured in the slowing down spectrometer were determined to an accuracy of about 10 to 15 percent, and are in the range 10 to 60×10^{-9} eV. The cross section shown in Fig. 11, varies about 2.7 μb at thermal energy to average values of

20 μ b at thermal energy to average values of 20 μ b in the range 0-350 eV, 500 μ b from 350 to 1650 eV and 100 μ b from 1650 eV to 30 keV. The resonance fission integral from 0.4 eV to 40 keV is about $1.33 \pm .15$ millibarns. This is a direct measurement of a small but significant contribution to the reactivity of any reactor.

Spectra in a ^{238}U System and Capture Cross Sections of ^{238}U

A more critical and much more frustrating problem is that of the low energy capture cross section of ^{238}U . One of the examples of the discrepancies which make this a continuing problem is the result of spectrum measurements, as reported by Malaviya, Gaerttner, Becker and Kaushal, and illustrated in Fig. 12. The difference between the calculated and measured spectra suggest that either capture or inelastic scattering or both need further study. The analysis of Becker and his collaborators suggests that the capture cross sections in the unresolved region are too large as given in the ENDF/B data sets, as are the inelastic scattering data in the low MeV range. Thermal reactor integral benchmark tests also suggest that currently used capture data in the resonance and unresolved resonance region are high. Suggestions have been made, for example by Hardy, that since most cross section experiments employ fairly thin samples they tend to be most accurate in describing peak resonance values, whereas the integral experiments involve strongly self-shielded materials in which the resonance wings are important.

One of the ways to check this was to make shielded cross section measurements by the self indication technique. In that case capture in a thin sample of ^{238}U , for example, was measured as a result of irradiation by neutrons which have another ^{238}U sample which is thick. Block and Byoun used this method to study ^{238}U and Ta at several temperatures. During the course of this study a sensitivity analysis was made which shows that the self indication response is sensitive to the strength function.

Since all the white-source ^{238}U capture measurements over the past decade or so have resulted in a 10% - 15% discrepancy in the keV capture cross section, a "point" cross section measurement was undertaken. This measurement used an 8-inch-thick Fe filter to produce a low-background beam of neutrons near the 24 keV Fe minimum, and the key feature of this measurement is an accurate determination of the background near 24 keV. This technique has been used recently in Japan (Yamamuro et. al., 4th Nuclear Cross Section & Tech. Conference) and recently at RPI to extend the "point" measurements to energies corresponding to Fe minima up to ~ 200 keV. These "point" measurements served as accurate benchmarks to which the high resolution white-source measurements can be compared and normalized.

Theoretical Analysis and Interactive Graphics

As noted in the beginning, the differential integral measurement is a crucial test of theoretical methods as well as experimental results. In principle one should try different theoretical approaches as well as different data sets in trying to match the integral results such as spectra and reactivity, and as a matter of fact this was done. However, these calculations are laborious and one can always question whether enough theoretical approximations have been tested or whether the sensitivity analysis is really understood. Once a mathematical model has been selected, much of the analytical labor consists of computational iterations involving changes in parameters or functions. In order to reduce the time required for such iterations an interactive graphics system was developed at RPI. By means of a combination of light pen and push button controlled preselected programs, one can communicate with a computer to modify a calculation displayed graphically on a large CRT screen. The machine very kindly provides guidance for the user in a language that he can easily understand.

Fast Reactor Physics and Engineering

This task has as its principal objective, the measurement and analysis of integral fast reactor parameters to obtain checks of nuclear data for the LMFBR program. To this end, the Project carried out a series of investigations - both experimental and analytical - to explore the potential of integral experiments (with a pulsed neutron source) on clean, homogeneous assemblies for the evaluation of differential nuclear data and refinement of analytical procedures applicable to fast reactor systems. The project accomplished these general objectives and applied the techniques and methodology developed to specific materials and systems of direct relevance to the LMFBR designs. The results of these investigations have provided important guidelines in the planning and evaluation of fast reactor systems and improvement of data and methods leading to a more precise assessment of the safety, economics and performance characteristics of alternative fast reactor designs.

The over-all project can be broadly classified into five major areas of activity:

- I. Development of techniques, methodology and the basic tools and equipment: for example, the development of special targets designed to generate tailored energy and angle-dependent neutron distributions appropriate to fast integral measurements; development of fast and intermediate energy neutron detectors and the determination of detector efficiency as a function of energy; design of a fast neutron time-of-flight spectrometer and associated equipment and instrumentation; the development of procedures and codes for the processing of time-of-flight data; design of mock-up assemblies.
- II. Integral Time-of-Flight Measurements on Actual Systems: principally involving the measurement of position dependent fast and intermediate

energy angular flux spectra in large, homogeneous assemblies of simple geometry amenable to precise calculational treatment.

Assemblies of Iron, Depleted Uranium, Aluminum, Sodium and two-region systems (FE-Al) have been investigated. Measurements have spanned a wide energy range - from a few keV to about 10 MeV.

III. Development of Calculational Procedures and Codes for Analysis of Integral Experiments: several standard codes such as DTF-IV, SUPERTOG, etc. have been substantially modified and improved and made operational for the generation of calculated fast neutron distributions. The measurements have also stimulated new analytical approaches (such as Continuous Slowing Down Theory) which have been applied - in cooperation with the Theory Group - to the analysis and interpretation of experimental results.

IV. Evaluation of Nuclear Data: based on the comparison of measured and calculated integral fast reactor physics parameters. Several data files (ENDF/B) for such materials as Fe, ^{238}U , Al, Na, etc. have been investigated leading to important inputs into the data evaluation process and progressive revisions of differential nuclear data in several cases.

V. Miscellaneous Auxiliary Investigations: leading to results of general significance and interest such as improved understanding of the effect of reentrant hold perturbation, and sensitivity of fast reactor integral parameters to certain differential data.

Various journal publications and presentations of professional society meetings have resulted from the work of this project. These are listed among the publications in Section VI.

SUMMARY AND CONCLUSIONS

1. The interface between differential and integral measurements is a sensitive point at which to test experiments and theory to be sure that we have valid information for reactor design. I have given some examples which show how much effort is needed to reconcile the differences which show up in the two approaches; this provides a check and balance system which I think has worked very well.
2. Most of the emphasis to date has been on the attempt to reconcile differential and integral results either in simple homogeneous systems such as the RPI spectrum measurements or in critical assemblies at ANL, at Chalk River and other developmental laboratories. Up to this point it has been appropriate and perhaps necessary to maintain the simplest possible set of variables in the integral experiments. However, I think that data from operating reactors should be considered even in these seemingly physics oriented problems. Certainly these kinds of results are relevant to fuel management decisions and at least indirectly to operating experience.
3. Following the first principle of research, we conclude that more research is needed. Our plans include other key measurements in both the differential and integral areas, such as capture cross sections of stainless steel, capture cross sections of fission products, and actinide cross sections which with very small available samples require the extreme sensitivity of the slowing down spectrometers. In order to pursue the ^{238}U problem we believe that better measurements of both cross sections and spectra are needed. The plans of Block for self indication measurements have already been cited, and Malaviya is prepared to make detailed spectrum measurements down to energies in the eV range.

4. Finally, there is a general observation which I think is of the utmost importance. These differential and integral measurements, and what have been euphemistically called consistency studies at the interface, provide a classic example of the interplay between universities, industrial groups and government laboratories. I think that it is most appropriate to follow this same path in other problem areas such as structural dynamics, thermal hydraulic transients, corrosion chemistry and reliability.

FIGURE CAPTIONS

- Figure 1A Comparison of source-normalized measured and calculated (DTF-IV; ENDF/B-I) spectra in iron assembly: $R = 10$ in., $\mu = \pm 0.8$.
- Figure 1B Comparison of measured and calculated (DTF-IV; ENDF/B-I) spectra in iron assembly: $R = 10$ in., $\mu = 0$.
- Figure 2 Transmission experiment count spectra for the 14- and 20-in. iron samples.
- Figure 3 Comparison of other sources and our evaluation of the elemental iron total cross section about 24-keV minima.
- Figure 4 (Capture yield)/(sample thickness) from 25 to 200 keV for natural Fe for a 0.25 in. sample, 1.3-nsec/m resolution.
- Figure 5 Ratio of the average value of σ_c to the average value of σ_f for energy intervals between 0.1 and 40 keV.
- Figure 6 Eta for ^{233}U as a function of neutron energy.
- Figure 7 Nubar values for ^{233}U Resonances (5 to 40 eV).
- Figure 8 $\bar{\nu}(E)$ for ^{235}U , 0.01 to 10 eV.
- Figure 9 Neutron double differential cross section of water at 27°C .
- Figure 10 Double differential cross section for UC at incident neutron energy of 0.134 eV.
- Figure 11 ^{238}U fission cross section.
- Figure 12A Comparison of amplitude normalized experimental and calculated neutron spectra (at $R = 6$ in., $\mu = 0$; $R = 10$ in., $\mu = 0.7$) in depleted uranium, using DTF-IV code and ENDF/B-I data.
- Figure 12B Comparison of amplitude normalized experimental and calculated neutron spectra (at $R = 6$ in., $\mu = 0$; $R = 10$ in., $\mu = 0.8$; and $R = 14$ in., $\mu = 0.9$) in depleted uranium using DTF-IV code and ENDF/B-I data.

Fig. 1A

Fig. 1B

Fig. 2

Fig. 3

Fig. 4

²³⁹Pu CROSS SECTIONS

Fig. 5

Fig. 6
-25-

Fig. 7

PROMPT NEUTRONS/FISSION

Fig. 9

Fig. 10
-29-

Fig. 11

Fig. 12A

Fig. 12B

SECTION III

SECTION III - THE FACILITY

Accelerator

The Rensselaer Electron Linear Accelerator (LINAC) is a machine for accelerating electrons up to 100 million electron volts (MEV). Its major function, for which it was originally designed, is the production of brief, intense neutron bursts for time-of-flight experiments; as such it is still the only neutron facility of its kind in the world for on-campus research involving students. The maximum neutron production rate is developed at 50 MeV; however the selection of electron energy over the range 10 to 100 MeV makes other experiments possible, e.g., radiation damage by electrons and X-rays and various photonuclear reactions.

A broad selection of electron and neutron burst widths ranging from nanoseconds (10^{-9}) to microseconds (10^{-6}) can be generated with ample intensity for many kinds of experiments in atomic, nuclear and reactor physics. For the short burst mode of operation, approximately 10^{10} neutrons are available in a single 10 nanosecond burst. For long bursts the maximum time-average neutron yield is about 2×10^{14} neutrons per second with a neutron energy distribution which is the same as the primary fission source in a nuclear reactor when uranium is used as a target. The accelerator has been continuously upgraded since it began operation, and it has more than tripled its original peak electron current during short pulses. The specifications of the LINAC (today) are presented in Table I.

In the Rensselaer LINAC, the electrons traverse a path length of 27 ft in a series of 9 copper waveguides, each 3 ft in length, at a velocity very near the velocity of light. A cutaway drawing of the accelerator is shown in Fig. 13. Electrons are injected initially at 150 kilovolts into an electron

"buncher" which produces bursts of short time duration for injection into the first of the series of waveguides (for acceleration to 100 MeV). They are accelerated to high energy by an electromagnetic wave traveling with a phase velocity equal to the velocity of the electrons. To establish the electromagnetic wave, radio frequency power is supplied in each waveguide by a powerful klystron amplifier; 9 klystrons are so phased that the electrons are continuously accelerated throughout the combined lengths of the waveguide sections.

Experimental Arrangement

Since many nuclear experiments involve the measurement of neutron energy by time-of-flight, the facility includes many neutron drift tubes ranging in length from 3 meters to 260 meters. The experimental arrangement is shown in Fig. 14. The combination of the longest flight path and the shortest burst gives the maximum neutron energy resolution. Because of the high X-ray and neutron intensity, a concrete and earth radiation shield of 15 ft concrete equivalent is provided in the building construction. The large, shielded experiment room, containing several switching magnets and target locations, provides a versatile area for experiments.

Data Acquisition

Modern research requires "state-of-the-art" support in electronic instrumentation and data handling systems. At the heart of LINAC's advanced data acquisition facility are two on-line digital computers, a PDP-7 and a PDP-9 which accept and store data from the LINAC while exercising programmed control over the experimental apparatus. The PDP-7 and the PDP-9 are directly connected to over 50 external electronic devices which record nuclear events, change experimental parameters and store accumulated results.

The experimental system configuration can be changed quickly by loading an appropriate set of computer instructions. Instructions for particular configurations are in the form of programs stored on a system magnetic tape available to all users. Once a set of instructions has been developed for a particular measurement, the experimenter need only call for his program by name to retrieve it from the system tape and execute the program from computer memory.

A typical neutron "time-of-flight" measurement involves the operation of an electronic stopwatch capable of measuring time steps as short as 31 nanoseconds. Such measurement involves recording the number of events occurring at each time interval of interest. As data accumulate, a live display on an oscilloscope gives the experimenter information concerning the progress and condition of his measurement. Output information is stored on magnetic tape for further processing after the measurement.

Many experiments call for highly specialized nuclear instrumentation to be connected to the on-line computers. The flexibility of the third-generation computer allows easy access from nearly any type of measurement device. The possible experimental configurations are limited only by ingenuity of the experimentalist.

Data Processing

Processing of the great volume of data from the LINAC recorded by the PDP-7 on-line computer requires the capability of one of the largest data processing machines in the world. Data are currently processed on the CDC-6600 digital computer located at the Courant Institute of Mathematical Sciences at New York University. Processing is carried out from the LINAC site by means of a high speed telephone link to this computer. This remote

control link was developed jointly by the departmental staff and members of N.Y.U. and it is the first of its kind to be placed in operation.

A small digital computer, an IBM-1130, at the LINAC site converts input data into a series of audio tones which are transmitted by telephone to the N.Y.U. CDC-6600 180 miles away. Results are returned in a similar manner to be printed, punched or plotted by the 1130. Large amounts of information needing temporary storage can be shuttled to the half-million word disk file of the 1130 system.

When not used as a terminal, the IBM-1130 functions as a small data-processing system. Using Fortran IV or the Special Data Presentation System the research scientist can perform many small computations as well as obtain graphic output for further examination.

A PDP-15 computer with large oscilloscope display plus light pen and keyboard is utilized for interactive graphics. This facility permits rapid analysis and comparison of experimental and evaluated data and significantly adds to the analytical capacity of the laboratory.

TABLE 1

Rensselaer Electron Linear Accelerator (LINAC)

Type	Traveling Electromagnetic Wave
Frequency	L-Band, 1300 megahertz
Number of Waveguide Sections	9
Length of Each Section	3 ft.
Overall Length	54 ft.
Source of R. F. Power	L-Band Klystron
Klystron Manufacturer	Litton
Number of Klystrons	9
Peak Power Rating	10 megawatts
Average Power Rating	15 kilowatts
Maximum Electron Energy	100 million electron volts
Minimum Electron Energy	10 million electron volts
Average Electron Beam Power (Max.)	50 kilowatts
Average Electron Beam Current (Max.)	1 milliamp
Peak Electron Beam Power (Max.)	200 Megawatts
Peak Electron Beam Current	6 amp.
Electron Burst Widths	7,10,20,50,100,250,500 nanoseconds 1.0, 2.0, 3.3, 4.5 microseconds
Repetition Rates (Max.) 7 nsec-2 μ sec	800 sec ⁻¹
3.3 and 4.5 μ sec	360 sec ⁻¹
Electron Beam Diameter at Output Window	0.5 cm
Electron Beam Divergence	10 ⁻³ radian total angle
Average Neutron Production Rate (Max.)	$\sim 2 \times 10^{14}$ neutrons sec ⁻¹
Tantalum Target	
Peak Neutron Production Rate (Max.)	$\sim 10^{18}$ neutrons sec ⁻¹
Tantalum Target	
X-ray Production Rate	$\sim 5 \times 10^{10}$ Rad sec ⁻¹
Energy Resolution (optimum)	0.04 nanoseconds meter ⁻¹

Legend

1. Injector
2. R. F. Buncher
3. Accelerating Section
4. Input Waveguide
5. Heat Exchanger
6. Ion Pump
7. R. F. Dummy Load
8. Iris Structure
9. Electron Drift Tube
10. Energy Analyzer System
11. Klystron Modulator
12. Klystron

Fig. 13
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RENSSELAER POLYTECHNIC INSTITUTE

LINAC LABORATORY

Fig. 14

SECTION IV

SECTION IV - COOPERATIVE RESEARCH

The staff of the Rensselaer LINAC has been involved in cooperative research with three (3) types of groups. They are summarized in Tables 2, 3 and 4.

The magnitude of the results of these cooperative efforts must be considered not only a direct contribution to the USAEC program, but also as a basis for new programs and approaches to be initiated. As noted elsewhere, the alpha-²³⁹Pu experiments had a major impact on the LMFB program.

TABLE 2

Cooperative Research - Prime Contract

The staff of the Rensselaer LINAC has been involved in cooperative research with visitors from other laboratories in the United States, Great Britain and Japan. This research has made significant contributions (mentioned elsewhere in this report) to the U. S. nuclear reactor program. In addition, some of the research programs started at RPI have been continued and expanded at other laboratories

<u>Laboratory</u>	<u>Personnel</u>	<u>Research</u>
O.R.N.L.	R. Gwin, L. W. Weston, G. DeSaussure, R. Ingle, H. Weaver	Alpha measurements on ^{235}U , ^{233}U , ^{239}Pu .
M.T.R.	M. S. Moore, O. D. Simpson, T. Watanabe.	Fission Cross Section- ^{241}Pu .
M.T.R.	M. S. Moore, L. G. Miller, F. B. Simpson,	Scattering Cross Sections of ^{233}U , ^{235}U , ^{239}Pu .
Harwell	John Webb	Low energy neutron inelastic scattering.
Harwell	E. R. Rae	Neutron capture gamma ray spectroscopy.
O.R.N.L.	R. L. Macklin	Neutron capture cross sections
Tokyo Institute of Technology	N. Yamamuro	Capture cross sections
Japan Atomic Energy Research Establishment	T. Fuketa	Total cross sections

TABLE 4

Interactions With Accelerator Users - Other than Prime Contract

Several laboratories and also other departments at Rensselaer have performed measurements at the LINAC covering a wide variety of fields.

1. Bell Laboratories - Whippany, New Jersey

Response of PIN Diodes to high intensity bursts of radiation.

2. General Electric Research & Development Center - Schenectady, N.Y.

Neutron diffraction studies at high pressure.

3. MIT Draper Laboratories - Boston, Mass.

Irradiation studies to determine effect on electronic modules and gyrowheels used in inertial guidance systems.

4. Sandia Corporation - New Mexico

Photo conductivity measurements of various vendor furnished SA type capacitors.

5. United Aircraft Corp. - Norwalk, Conn.

Neutron bombardment test on selected circuitry.

6. Chemistry Dept., R.P.I., Troy, N. Y.

Decay properties of neutron excess Isotopes.

7. Departments of Physics and Nuclear Engineering, M.I.T.

High energy neutron scattering and polarization studies.

SECTION V

SECTION V - PH.D. AND MASTER THESES COMPLETED

Ph.D. Theses

Peter L. Hofmann	Nuclear and Thermal Design Considerations for Soluble-Poison Controlled Nuclear Reactors
Davut B. Ebeoglu	Time Dependent Neutron Transport
Frank D. Judge	Neutron Transport Theory in Pulsed Multiplying Assemblies
Mihran J. Ohanian	Eigenfunction Analysis of Hydrogeneous Neutron Spectra
Rudolf E. Slovacek	Measurement of the Asymptotic Neutron Spectrum in a Multiplying Medium
Richard C. Dahlberg	Scattering Kernels and Their Temperature Dependence
Thomas E. Dudley	The Spherical Harmonics Approximation in General Geometry with Application to the Thermal Equivalent Cell Problem
R. R. Fullwood	The Effects of Coherent Scattering on the Thermalization of Neutrons in Beryllium
Robert C. Kryter	The Measurement of Time-Dependent Thermal Neutron Spectra in a Pulsed Homogeneous D ₂ O Medium
Robert L. Hobson	Representations of Neutron Spectra for Thermal and Epithermal Energies
George J. Kirouac	Epithermal Neutron Inelastic Scattering by Room Temperature Water and Polyethylene
Jay Stanley Mendell	An Attempt to Detect Plasma Oscillations Stimulated by a Pre-Bunched Electron Beam from the RPI Accelerator
R. R. Lee	Calculation and Interpretation of Neutron Thermalization in Finite Blocks of Beryllium

PhD Theses Completed (Continued)

W. M. Moyer	Photoneutron Reactions in O^{16}
R. J. Cerbone	Position-Dependent Neutron Spectra in a Multiplying Medium
J. J. Bulmer	Thermal Neutron Spectra and Integral Parameters in Heterogeneous Systems
J. Douglas Jenkins	The Application of Variational Methods to Pulsed Neutrons Problem
Sung Sun Pan	Slow Neutron Inelastic Scattering by Transition Metal Hydrides
R. W. Hockenbury	Neutron Capture in Low Absorption Material
H. McNeill	Acoustic Instabilities in a Gaseous Core Nuclear Rocket
J. H. Menzel	Measurements of Time-Dependent Neutron Spectra in H_2O
F. McGirt	Re-entrant Hole Effects in Pulsed Neutron Experiments
H. N. Knickle	Theory of Coupled Space-Time Effects in Fast Pulsed Neutron Kinetics and Trans- port Theory
T. J. King	Neutron Scattering Measurements in the Resonance Region
S. Weinstein	Fission Neutron Multiplicity Measurements in the Resolvable Resonance Region
C. Lajeunesse	Low Energy Neutron Interactions with Uranium Carbide
F. G. Bischoff	Generalized Monte Carlo Methods for Multiple Scattering Problems in Neutron and Reactor Physics
F. E. Dunn	Analytic Studies of Fast Reactor Flux and Importance Spectra
P. C. Rohr	The Description of Space Time Dynamic Behavior of Nuclear Reactor Systems
R. G. Stieglitz	KeV Neutron Capture and Transmission Mea- surements on Cr^{50} , Cr^{52} , Cr^{53} , Cr^{54} , Ni^{60} and V

PhD Theses Completed (Continued)

T. E. Shea	Temperature-Dependent and Multi-Level Effects on Neutron Resonance Cross Sections
L. J. Esch	Temperature Dependence of Neutron Inelastic Scattering from Water
E. T. Burns	Fast Neutron Spectra from Space-Dependent Continuous Slowing Down Theory
D. C. Gibbs	Studies of Fast Neutron Spectra in Two-Region Systems
J. M. Clement	Total Neutron Cross Sections of Hydrogen and Deuterium in the MeV Region
Arthur P. Ginsberg	Improvements in Transport Theory and Their Applications to Fast Neutron Spectra
Tae Y. Byoun	Experimental Investigation of the Resonance Self-Shielding and Doppler Effect in Uranium and Tantalum
Alexander N. Mallen	Measurement and Analysis of Fast and Intermediate Neutron Spectra in a Sodium Assembly
Marvin Lubert	Analysis and Interpretation of Total and Capture Cross Section Data
Michael Danchak	The Assessment and Modification of Neutron Cross Sections Via Interactive Graphics
Samsuk Kang	Time-Dependent Neutron Slowing Down and Diffusion

MASTER THESES

H. James Willard Jr.

Investigations into Neutron Source
Targets for an Electron Linear Accelerator
Neutron Thermalization and Diffusion
Cooling in Water

Robert L. Hobson

Time Moments of the Boltzmann Equation
Photoconductivity of Radiation-Induced
Defects in Silicon

A. P. Ginsberg

A. L. Bates

KeV Neutron Capture in ^{54}Fe

B. J. Ward

KeV Neutron Capture and Fission Measure-
ments on Pu^{242}

Andrew J. Sanislo

Neutron Strength Function Calculations
Using an Angular Momentum Dependent
Optical Model

Jose Maria Sierra Alvarez

SECTION VI

SECTION VI - PUBLICATIONS

TITLE

Time Dependent Flux in Small Assemblies
 Measurement of Asymptotic Neutron Spectra
 in Multiplying Assemblies Containing ^{235}U
 The Use of a Sequential Routing Delay in the
 Study of Time Dependent Neutron Thermalization
 Energy Dependent Extrapolation Length Measure-
 ments in Polyethylene
 Multiplying Medium Asymptotic Spectrum
 Geometrical Transport Effects in the
 Spherical Harmonics Approximation
 Local Flux Shape Dependence on Reactor Period
 Modified Spherical Harmonic Approximations
 P-3 Calculations for Rods in a Closed Packed
 Square Lattice and in Wigner-Seitz Equivalent
 Cells
 A Relation Between the Diffusion Cooling
 Coefficient and the Asymptotic Neutron
 Spectrum Temperature
 Dependence of Power Spike on Temperature and
 Scattering Kernel in Beryllium Reflected
 Fast Reactors
 Scattering Kernels and Their Temperature
 Dependence
 Modified Spherical Harmonic Approximations
 Asymptotic and Steady State Spectrum Measure-
 ments in a Multiplying Medium
 The Effects of Coherent Scattering on the
 Thermalization of Neutrons in Beryllium
 Measurement and Analysis of Time-Dependent
 Neutron Spectra in D_2O
 Practical Operating Problems at the R.P.I.
 Linac
 Radioactive Gas Production from the R.P.I.
 Electron Linear Accelerator
 Electronic Instrumentation at the R.P.I.
 Linac
 Qualitative Effects of Radiation Damage
 on Equipment and Components at the R.P.I.
 Linac

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 W. A.
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Multiplying Medium Asymptotic Spectrum

Spatially Dependent Asymptotic Neutron Spectra Measurements in Polyethylene

Inelastic Scattering of Slow Neutrons by Zirconium and Titanium Hydrides

Analysis of Pulsed Neutron Experiments in Moderating Assemblies

The Effects of Coherent Scattering on the Thermalization of Neutrons in Beryllium

Double Differential Scattering Cross Sections for Polyethylene and Water

Transport Effects in the P-3 Treatment of Cylindrical Rods in a Square Lattice

Time Dependent Neutron

The Use of a General Purpose Computer as a Nuclear Event Analyzer

Simple Linear Bidirectional Monopolar Gate

A Filter Difference Method for Measuring Inelastic Scattering of Slow Neutrons

Thermalization Program at R.P.I.

The Direct Measurability of Reactivity (In \$) and Its Experimental Bounds (The "Bracketing-Procedure")

Measurements of Mean Emission Time in Multiplying Medium

Spatially Dependent Spectra in a Paraffin Moderator and a Paraffin Moderated Subcritical Assembly

Re-Entrant Hole Perturbation in Water

Future Trends in Cross Section Work with Electron Linacs

MeV Total Cross Sections with the Rensselaer Linac

Subcritical Reactivity Determinations - Comparison of Experimental Methods

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Dosimetry for Single Shot, Bremstrahlung Irradiations

On-Line Computer Controlled Automatic Sample Changer for Use With A Total Gamma Absorption Tank

An Analysis of Neutron Thermalization in Beryllium

Effects of Scattering Kernels on Temperature Coefficients in Reactor Analysis

Computation of Time Dependent Neutron Spectra in D_2O

Neutron Radiative Capture Cross Section Measurements from 1 eV to 1 MeV on Light and Medium Weight Nuclei

Neutron Inelastic Scattering by Zirconium Hydride

Time-Dependent Spectra in Polyethylene

Calibration of a Large Proton Recoil Detector For Fast Neutron Spectra Measurements

Modified Rod Drop Measurements

A Feasibility Study of Measuring Resonance Absorption in Thermal Die-Away Experiments

A New Technique for Measuring Weak Neutron Scattering in Low Energy Resonances

A Medium Fast Time-of-Flight Front End

Re-Entrant Hole Perturbation in Water

Gamma Ray Spectra from Radiative Capture of Thermal and Resonance Neutrons in Mercury and Tungsten

Neutron Radiative Capture Measurements at the RPI Electron Linac

Position Dependent Neutron Spectra in a Multiplying Medium

Neutron Resonance Capture in F, Mg, S, and Pb Below 300 keV

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Neutron Radiative Capture in Na, Al, Fe and Ni From 1 to 300 keV

Self-Indication Experiments with Iron and Nickel

A New Technique for Measuring Neutron Scattering in Low Energy Resonances

A Variational Principle for the Determination of Pseudofundamental Decay Eigenvalues

Neutron Position Dependent Spectrum in a Multiplying Assembly

Effect of Scattering Kernels on Temperature Coefficients in Reactor Analysis

A Model for Thermalization

Inelastic Neutron Scattering in Metal Hydrides, UC and UO_2 , and Applications of the Scattering Law

A Generalized Formulation of Point Nuclear Reactor Kinetics Equations

Measurement of the Neutron Fission and Capture Cross Sections for ^{233}U in the Energy Region 0.4 to 1000 eV

KeV High Resolution Neutron Radiative Capture Measurements

Analysis of Pulsed Fast Neutron Spectra in Multiplying Assemblies

Slow Neutron Inelastic Scattering by Niobium Hydride

A Generalized Formulation of Reactor Kinetics

Discontinuous Overlapping Groups in Space Energy Problems

Semidirect Least Squares Variational Methods in Initial-Value Problems

Time of Flight Measurements of Fast Neutron Spectra in Iron

Consistent Versus Conventional Few-Group Reactivity Calculations

Angular and Spatial Distribution of Fast Neutrons in a Depleted Uranium Assembly

A Fortran IV Program to Calculate Time Dependent Neutron Spectra in Pulsed Fast Multiplying Assemblies

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Recent Low Energy Inelastic Scattering Results
for Metal Hydrides and Uranium Carbide

Epithermal Neutron Inelastic Scattering by
Polyethylene

Consistent Versus Conventional Few-Group
Reactivity Calculations

Studies of the Angular Distributions of Fast
Neutrons in Depleted Uranium

Adequacy of Fast and Intermediate Cross-
Section Data from Neutron Spectrum Measure-
ments in Bulk Media

Neutron Capture Resonances of Tungsten in the
Range 150 eV to 100 KeV

Neutron Radiative Capture in the KeV Region

Data Reduction With a Small Remote Computer
Linked to a CDC-6600

Theory of Doppler Broadening of Neutron
Resonances

Neutron Scattering Measurements in Low Energy
Cd and Rh Resonances

Low Energy U-235 Measurements

Neutron Scattering and Capture Cross Section
Measurements

Re-Entrant Hole Perturbation in Pulsed
Neutron Experiments

Analytic Representation of Fast Reactor
Flux and Importance Spectra

Modal Analysis of Power Tilting

A Generalized Formulation of Reactor Kinetics

Time Dependent Neutron Thermalization in
Light Water

Development of Special Targets for Fast
Neutron Spectrum Studies

Time Moments for a Pulse of Cold Neutrons
in a Finite Medium

Doppler Broadening and Asymmetry of P-Wave
and Multi-Level Neutron Resonances

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Doppler Broadening of Resonances and Inelastic Neutron Scattering in Uranium Carbide

Overlapping Group Methods with Discontinuous Trial Functions

Asymmetric Discontinuities in Synthesis Techniques for Initial-Value Problems

Holpert A Fortran IV Diffusion Theory Program for Estimating the Effect of Re-Entrant Hole in Asymptotic - Decay Pulsed Neutron

The Average Angle of Scattering in Energy-Dependent Problems

Simple Analytical Models for Studying Fast Neutron Spectra

Modal Analysis of Power Transients

Neutron Cross-Section Measurements Spanning the Resolved-to the Unresolved Resonance Region

Methods of Resolving Interface Ambiguities in Discontinuous Variational Methods

An Analytic Study of Fast Reactor Flux and Importance Spectra

Neutron Radiative Capture in Na, Al, Fe and Ni from 1 to 200 keV

Re-Entrant Hole Effects in Fast Neutron Spectra

Spin Assignments in Pu-239 Resonances by Means of Neutron Scattering

Fission Neutron Multiplicity-Spin State Correlations for Pu-239 Resonances

Neutron Radiative Capture Resonances of Zirconium in the Energy Range 150 eV to 25 KeV

KeV Neutron Capture in Fe and Cr

Resonance Neutron Capture Gamma Rays From ^{186}W (n, γ)

Vacuum System for High Radiation Environment at the RPI Linac Laboratory

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Yield & Transmission Plots of ^{182}W , ^{183}W , ^{184}W ,
 ^{186}W , ^{90}Zr , ^{91}Zr , & ^{94}Zr .

Gamma Ray Spectra from the Reaction ^{27}Al ,
(n, n') ^{27}Al

Neutron Multiplicity-Spin State Correlations
for ^{239}Pu Resonances

The Influence of a Re-entrant Hole on Measure-
ments of of Fast and Thermal Neutron Spectra

The Small Computer as an Interface

PHOE2 - A FORTRAN IV Transport Theory Program
to Calculate the Effect of Re-Entrant Holes
in Asymptotic-Decay Pulsed Neutron Experiments

Neutron Multiplicity Measurements for ^{233}U ,
 ^{239}Pu Resonance Fission

KeV Neutron Capture and Transmission Measure-
ments in ^{60}Ni and V

Kinetic Studies in a Depleted Uranium Assembly

Measurement and Analysis of Fast Neutron Spectra
in Iron

A Monte Carlo Code for Neutron Capture Ex-
periments

Semi-Analytic Flux Representation for Fast
Pulsed Assemblies

A Numerical Solution of the Time Dependent
DPL Approximation

New Personnel Interlock System and Procedures
For the RPI Linac Lab

Neutron Radiative Capture and Transmission
Measurements of W and Zr Isotopes in the
KeV Region

Time Dependent Neutron Transport Theory for
Fast Pulsed Assemblies

Time Synthesis Using Discontinuous Green's
Function Modes

Neutron Slowing Down in Mixtures Containing
Scattering Resonances

Application of Analytic Methods to Fast
Reactor Spectra

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Re-Entrant Hole Perturbation Effects on Fast Neutron Spectra in Aluminum

Fast Neutron Flux Distribution in a Depleted Uranium Assembly

Measurements of the Temperature Dependence of Fast Neutron Spectra

Radiation Production at the RPI Linac

Time Dependent Neutron Spectra Measurement in H₂O

Nanosecond Timing for a Large Liquid Scintillator

Neutron Inelastic Scattering Measurements With a Gated Photomultiplier

Neutron Capture and Transmission Measurements Upon V, ⁵⁰Cr, ⁵²Cr, ⁵³Cr, ⁵⁴Cr, and ⁶⁰Ni.

¹⁶⁵Ho(n,γ) Resonance Spin Determination From Low Level Occupation Probability Ratios

Thick-Sample Neutron Transmission Measurements of the 229-EV Resonance in ⁶⁵Cu⁺

Hole Perturbation Effects on Fast Neutron Spectra in Bulk Media

Measurement of Thermal and Resonance Capture in Sodium

Capture Cross Section of ²⁴⁰Pu From 4 to 60 KeV

Small Sample Scattering as an Integral Check on the Neutron Scattering Cross Sections

Continuous Slowing Down Theory Extended to Inelastic Region

A Measurement of the Radiation Width of the 2.85 KeV Resonance and of the Thermal Capture Cross Section in Sodium

Spin Determination of Resonances in ¹⁶⁵Ho (n,γ) From Low Level Occupation Probability Ratios

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