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MEASUREMENTS OF FAST NEUTRON CROSS SECTIONS

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The University of Virginia

BASED ON LECTURES DELIVERED AT
THE UNIVERSITY OF MICHIGAN
FAST REACTOR PHYSICS CONFERENCE
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MEASUREMENTS OF FAST NEUTRON CROSS SECTIONS

by

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Lectures Presented At

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I. Introduction

In this series of four talks I propose to review the principle methods of measuring fast neutron cross sections, particularly those of interest to reactor physicists, and to give recent results which are of special interest.

In this discussion "fast" neutrons are those with energy from 1 kev to 10 Mev. There is a natural line of division in this range at around 50 kev, on either side of which the methods of producing and detecting neutrons and the cross sections themselves differ considerably. For convenience I shall refer to these two regions as the kev and Mev regions, respectively, when there is a need to distinguish between them.

By giving this outline of how measurements are made, what the problems are, how they have been surmounted, and what sort of accuracy is obtainable, I hope to promote understanding which will result in closer cooperation and more fruitful exchange between the reactor physicist and those who are engaged in making these measurements.

A number of my colleagues have been extremely helpful and generous in making available very recent results in the form of slides and preprints to make this a reasonably up-to-date presentation, and I should like to acknowledge their cooperation at this point. Let me note that the following list includes a large fraction of the laboratories and individuals who are particularly active in the field of fast-neutron cross section measurement:

E. Bretscher, A. T. G. Ferguson
Harwell

D. W. Colvin, M. G. Sowerby
Harwell

R. Batchelor
Aldermaston

I. L. Morgan
Texas Nuclear Corporation

Alan Smith
Argonne

J. Gibbons, L. Weston, R. Macklin
Oak Ridge

Graham Foster
G. E. Hanford

and my former associate at Los Alamos, C. D. Zafiratos, now at Oregon State University.

For reasons of economy and convenience, only a fraction of the experimental data which was presented in the form of slides at these lectures is being included in this published version. The selection which has been made for inclusion in this paper was governed largely by consideration of ease of reproduction of the material.

The prominence of national laboratories and AEC contractors in the foregoing list is indeed a significant indication of the fact that much of the work on fast neutron cross section measurement is being done as part of a program to measure the quantities which are needed by reactor physicists. At the same time it should be noted that some of the data which have been useful to the reactor physicists and some of the development of experimental techniques which are needed for neutron physics have emerged as by-products of the work of those whose primary interests are in nuclear physics and whose home bases are university laboratories. Professor Huber of Basel, Professor Barschall of Wisconsin, Professor Newson of Duke, and the late Professor Bonner of Rice all come to mind in this connection.

Despite the contributions neutron research has made to nuclear physics at a few universities, the idea has been prevalent that neutron physics is too difficult to be pursued without the special resources and facilities of a national laboratory. That this skepticism is being rapidly dissipated is due, in large part, to recent developments in fast neutron spectroscopy which have made neutron studies easier to pursue efficiently. Distinguished nuclear physics laboratories, which have regarded neutrons as too difficult to deal with, are now installing the new equipment and using the new techniques to produce results of a quality which had long been regarded as accessible only to charged-particle study. These laboratories may rarely use these techniques for studies of direct interest to reactor physicists, but the general application of the new methods represents a welcome extra dividend on the investment which has been made, largely on behalf of the reactor physicist, in the development of these methods.

The amount of nuclear data being published is so great that it may be appropriate to make a few remarks about the sources of compiled information to which the prospective user can turn.

In the January 1964 issue of Physics Today, Gove[1] presented a list of compiling centers, of which about eight concern themselves with the fast neutron data which will be covered in this talk. These are:

Reactor Physics Constants Center ANL

Radiation Shielding Information Center ORNL

Reactor Cross Section Evaluation Group BNL

Neutron Cross Section Compilation BNL

Fast Neutron Cross Section Center LRL

Neutron Cross Sections Service des Etudes Mathematiques et Nucleaires, Clarmart, France

Neutron Interactions important for reactor design IAEA (Westcott)

Sigma Committee (neutron cross sections) JAERI

Doubtless this does not exhaust the list of compilers, but it will suffice to direct the uninitiated.

Probably the best known and longest established compiling centers are those at Brookhaven and Livermore (R. J. Howerton). According to a recent letter from M. D. Goldberg of the Sigma center at BNL, Howerton's compilation is in the process of being brought up to date and a supplement to BNL-325 is also in preparation. Dr. Goldberg remarks that "the neutron business has grown so mightily of late that the supplement will probably require four volumes and a completely different format." The volume on fissionable materials will be available this summer.

The fact that such a large number of compiling centers exists is not by itself an indication of the rate at which useful data are being produced for compilation. Perhaps it is rather a relic of a time, which one hopes is fast disappearing, when the data were so inadequate that almost every laboratory that needed nuclear data kept someone busy surmising what numbers to use. The "house cross section man" has become institutionalized, playing a role which appears to have been created by Professor Weisskopf at Los Alamos during the war.

Those of you who are familiar with the excellent book by Yiftah, Okrent and Moldauer[2] on fast neutron cross sections will know by what artful dodges and piecing together of bits and scraps of information the house cross section man carried on his job as recently as 1960. But the situation is being rapidly remedied by the availability of much improved methods of making fast neutron measurements, which we shall be discussing in the course of these lectures, and by use of these methods at increasing numbers of facilities. Neutron data are indeed appearing at a rapidly increasing rate, and the compilers are being pressed to keep up with the data.

The extent of activity in this field is also indicated by the publication of books and conference reports, of which a few recent ones should be mentioned in the bibliography for this talk.

Most comprehensive is the 2200 page work edited by Marion and Fowler under the title <u>Fast Neutron Physics</u>,[3,4] which appeared in two volumes in 1960 and 1963. More recent results are reported in the proceedings of the Houston Conference on Fast Neutron Physics[5] of February 1963 edited by Phillips, Marion, and Risser, and the <u>Symposium on the Absolute Determination of Neutron Flux in the energy range 1-100 kev</u>[6] held in September 1963 at Oxford, whose proceedings have been published by the European American Nuclear Data Committee (EANDC). An earlier symposium collection, Neutron Time of Flight Methods,[7] sponsored by EANDC in 1961, also contains useful material.

The rate of growth of the subject is indicated by the fact that the range of material covered by Marion and Fowler in 2200 pages was covered in about one-tenth that space by B. T. Feld[8] a decade earlier. The changes in the character of the methods which are used for fast neutron measurements can be readily assessed by comparing the material presented in this lecture series with the material contained in an article of similar title in Reviews of Modern Physics for 1952 by Professor Barschall.[9]

It is appropriate at this point to note that the reactor physicist who has consulted all eight centers of data compilation and still has failed to find the information he needs, can turn to one of the several nuclear data committees now in existence whose function is to see that needed data are supplied. The Nuclear Cross Section Advisory Group of the AEC is probably the prototype of these organizations; the EANDC is also active in this capacity, and there are rumors that an even more inclusive international nuclear data committee may be organized.

However much the reactor physicist feels the need for more and better data, it is clear that his needs are not being overlooked. But if he should still fail to get what he wants by searching the literature or by calculation or by petitioning a nuclear data committee, he might try enlisting the interest of someone engaged in this sort of work. And should that too fail, there is always the recourse of "do it yourself". If this talk should induce one or more of you to spend a summer or a sabbatical year taking that last recourse, I shall feel very well rewarded indeed.

II. Classification and Definitions

The size and shape of the problem of measuring fast neutron cross sections is indicated by Figure 1 which illustrates a scheme and a notation developed by Professor Goldstein. In the discussion of the measurement of individual cross sections, we shall go from left to right and from the top down in this table.

Generally speaking, as one moves from left to right and downward on this table one is obliged to make more detailed measurements and eventually all problems come down to a matter of measuring spectra of neutrons or gamma rays which result from the interactions of monoenergetic neutrons with nuclei. By "measuring" we mean obtaining not only the distributions in energy and angle but also the cross sections.

The cross section for a particular type of reaction is defined by the equation

$$n\sigma = Y/F$$

where σ is the cross section of interest, n is the number of scattering nuclei per square centimeter, Y is the number of reactions of the sort one is interested in which occur, and F is the number of neutrons striking the sample which can produce these events. This definition applies to a sample which is thin in the sense that the incident neutron flux is not significantly diminished as it passes through the sample. Most experiments involve thick samples, and appropriate corrections must be applied to the results to obtain the cross section.

- Total cross section σ_T
  - Elastic Scattering cross sections: Total, σ_n : Differential $\sigma_n(\theta)$
  - Nonelastic cross section σ_X , $\sigma_X(<E')$
    - Inelastic scattering
      Total $\sigma_{n'}$; Differentials, e.g.,
      $\sigma_{n'}(E')$, $\sigma_{n'}(Ei)$, $\sigma_{n'}(E',\theta')$, $\sigma_{n'}(E_\gamma, \theta_\gamma)$
    - (n,2n) Reaction
      Total σ_{2n} ; Spectrum, e.g., $N_{2n}(E')$
    - Fission
      Total σ_f Spectra, e.g., $N_f(E')$, $N_f(E_\gamma)$
    - Other neutron producing reactions e.g., $\sigma_{n'\alpha}$ as in the C^{12} (n,n'α) Be^8 reaction
    - Neutron Disappearance Reactions σ_D
      - Radiative capture
        Total: σ_γ
        Spectrum $N_\gamma(E_\gamma)$
      - Reactions producing other particles e.g., σ_p as in the $O^{16}(n,p)N^{16}$ reaction

ψ = lab angle;

θ = C.M. angle

Scheme of Neutron Cross Section. (From Goldstein, Reference 18)

FIGURE 1

Perhaps the most obvious and direct method for determining a cross section involves making measurements of Y and F separately, then taking the ratio. One finds, however, that it is frequently quite difficult to make separate measurements of these quantities with the necessary precision. Thus one of the challenges confronting the experimenter is to devise methods of determining the ratio which do not require separate measurements of Y and F. The most familiar instance in which this is accomplished is in the measurement of the total cross section. Here one measures the transmission T in a geometry in which essentially all neutrons which interact with the sample are excluded from detection. Then the ratio Y/F is given by

$$Y/F = 1 - T$$

for a thin sample. The generalization to a thick sample is straightforward.

Methods have been developed for measuring cross sections other than the total cross section without determining Y and F separately, and these will be described as the various cross sections are discussed. It is worth noting that all cross sections of interest to the reactor physicist can be measured without making absolute determinations of neutron flux intensity. In fact, the indirect measurements have usually displayed the higher precision. Contrary to the impression frequently conveyed, absolute measurements of neutron flux are not necessarily or even usually involved in high-quality fast neutron cross section measurements.

Frequently this discussion will be illustrated with recent data, and wherever possible these results will be compared with the results of the appropriate theories. Theoretical fits of the data provide, at different times, checks on the data, the theory, and a means of extrapolating data into areas where no measurements have or can be taken.

One clarification of terminology is in order. Many neutron sources are essentially "targets" in which charged particles produce neutrons through various reactions. When the material whose neutron cross section is being measured is also called a target, confusion results. The word "sample" will be used to describe the test material.

III. Neutron Sources

By accident or design almost all neutron sources currently used in fast neutron work are pulsed sources, with the notable exception of those sources which utilize radioactive alpha or gamma emitters and the (α, n) or (γ, n) reaction. The use of pulsed neutron sources in conjunction with time-of-flight methods has proven to be so powerful a tool for the measurement of fast neutron cross sections that one cannot profitably discuss the usefulness of neutron sources for cross section measurements without taking account at once of their adaptability to pulsing and the time profile of the pulses which are produced.

A list of the most important fast neutron sources and some of their characteristics, drawn from a compilation by Eric Paul, (reference 7, p. 375), with additional data from Cowan (reference 7, p. 367), and Rainwater (reference 7, p. 321), is given in Figure 2.

The linacs are travelling wave accelerators which typically accelerate electrons to 30 Mev. The electrons strike a target and produce bremsstrahlung which in turn produces neutrons through the (γ, n) reaction. Approximately one neutron is produced for each 100 electrons striking the target.

The synchrocyclotron is used to provide protons at energies of several hundred Mev. These protons, upon striking a target, produce neutrons through nuclear evaporation reactions. Two to ten neutrons are produced for each high energy proton.

Figure 2. Neutron Sources for Fast Neutron Measurements

SOURCE	NEUTRON-PRODUCING REACTIONS	TYPICAL SOURCE CHARACTERISTICS	
Electron Linac	(γ,n), gammas from bremsstrahlung	5×10^{10} neutrons/burst 400 bursts/sec 20 ns burst width	RPI Installation
		Continuous spectrum of neutrons most used in region below 100 kev	
Synchrocyclotron	(p, xn)	5×10^{11} neutrons/burst 60 bursts/sec 25 ns burst width	Columbia University Installation
		Continuous spectrum of neutrons most used in region below 100 kev	
Van de Graaff	(p,n) $T(p,n)He^3$ $D(d,n)He^3$ $Li^7(p,n)$	10^3 neutrons/burst 10^6 bursts/sec 1 ns burst width	LASL Installation
		May produce monoenergetic or polyenergetic spectrum, depending on reactions in target. Most used in range from 100 kev to 10 Mev.	
Self-Contained Radioactive Sources	(α,n) (γ,n) fission	Pu-Be source uses (α,n) reaction, produces continuous spectrum of neutrons. Sb-Be source uses (γ,n) reaction, can produce monoenergetic reactions at 24 kev. Cf-252 source produces fission spectrum of neutrons with total production rate which can be calculated to within 1%.	

Figure 2 (continued)

SOURCE	NEUTRON-PRODUCING REACTIONS	TYPICAL SOURCE CHARACTERISTICS
Fast Chopper	fission in reactor	10^7 neutrons/burst 100 bursts/sec 10,000 ns burst width
Pulsed Reactor	fission	10^{16} neutrons/burst 40,000 ns burst width
Explosion	fission	10^{22} neutrons/burst 10 ns burst width

Linacs and synchrocyclotrons have roughly equivalent qualities as fast neutron sources. The synchrocyclotron, however, is more costly and in demand for many types of experiments. Both machines are sources of a so-called "evaporation" spectrum of neutrons with an effective "temperature" in the neighborhood of 1 Mev. They are often used with a moderator to enrich the spectrum below 100 kev. In this region these sources are competitive with or superior to the Van de Graaff neutron sources.

The Van de Graaff accelerates charged particles, typically protons or deuterons, to energies of several Mev. Van de Graaff accelerators modified for pulsed use typically provide 10^6 bursts per second of protons or deuterons at energies up to 6 Mev. The bursts may be shortened to approximately 1 nsec. duration using Mobley magnet or klystron bunching techniques. The shortened bursts have peak currents of about 5 ma.

These bursts of charged particles strike an appropriate target, producing neutrons through a reaction such as those listed in Figure 2. The number of neutrons produced per burst through a particular reaction depends on the magnitude of the cross section for the reaction at the energy of the incident charged particles, and the spread in neutron energy which is tolerable or desired. The energy of these neutrons depends on the energy of the charged particles, the Q of the reaction, and the angle of observation. Thus there a number of parameters to be considered in choosing the best source and geometry for a given experiment.

The time-averaged neutron production rate of Van de Graaff sources in present use is typically several orders of magnitude smaller than that of the linacs and synchrocyclotrons. However, the Van de Graaff is capable of providing monoenergetic as well as polyenergetic bursts of neutrons, and with considerably better time resolution. In addition, the energy spread in a "monoenergetic" burst of neutrons from a Van de Graaff is less than the energy spread obtained by using a linac and time-of-flight techniques at neutron energies greater than about 50 kev. These features make the Van de Graaff a superior source for most purposes in the Mev region, while the linac and synchrocyclotron have strong advantages in the kev region.

Radioactive sources provided neutrons for many of the early neutron cross section measurements, and still find important use in connection with capture measurements.

Fast choppers, used with reactors served for many of the early cross section measurements in the kev region, are now considered obsolete for this purpose. The pulsed reactor produces an intense burst of neutrons, but the duration of the burst is too long for most fast neutron cross section measurements. Bombs have been used only to a very limited extent for cross section measurements. Their general usefulness for this purpose remains to be proven.

IV. Fast Pulsing Technique

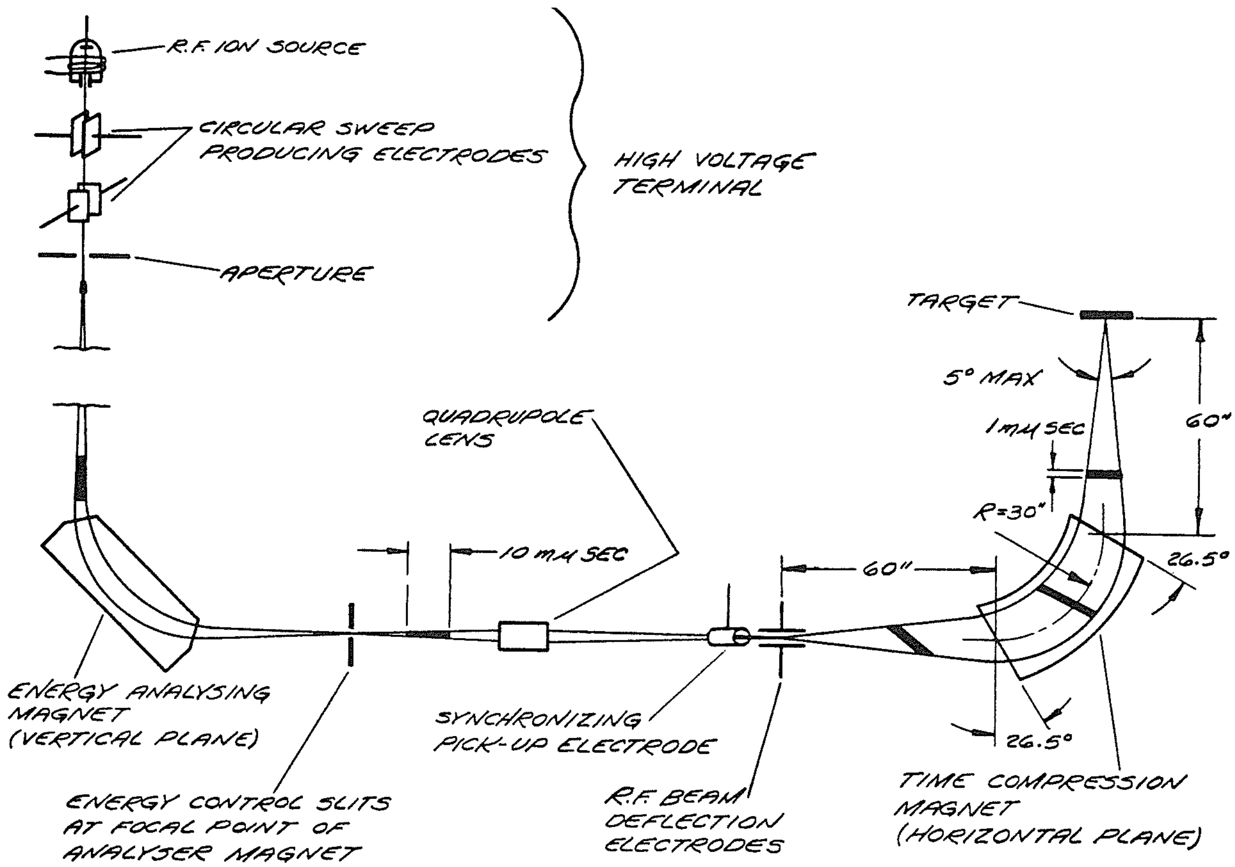
The striking advances in the quality and quantity of fast neutron data which are being obtained today compared to a decade ago are due in large part to the developments in pulsed neutron sources and their accessories, although improvements in shielding, geometry, detection, and data recording have also played important roles. The tempo of progress may be illustrated by the development of the pulsed-beam Van de Graaff.

An early attempt to use such a device for fast neutron measurements which gave significant data was recorded in 1954[10]. The system consisted of a pair of electrostatic deflection plates located at the exit from the machine, to which rf voltage of a few mc was applied. The beam passing between the plates was swept over an aperture, producing pulses whose peak current was just that of the dc beam which could be accelerated by the machine, and was typically not in excess of 25 microamperes. The next stage, which was reached a few years later by W. Good and collaborators at Oak Ridge, was to pulse the beam in the terminal of the accelerator, which allowed an increase of perhaps a factor of 10 in peak current, to 250 microamperes. More recently, klystron bunching techniques and the so-called Mobley bunching magnet have made it possible to obtain peak currents of about 5 ma with Van de Graaffs over the full range of their energy. Application of bunching methods to tandem accelerators continues to progress. Until the current available from the negative ion source required by a tandem is increased considerably, however, the higher current available from the single-ended positive ion machine gives it a strong advantage for many neutron studies.

Figure 3 shows the schematic diagram of the arrangement by which the dc Van de Graaff machine is converted to a pulsed machine using terminal pulsing and the Mobley buncher.

In this arrangement charged particles emerge from an ion source in the terminal of the accelerator and are interrupted at a rate of about 1 mc to produce bursts of about 10 ns duration which are accelerated down the column of the accelerator. These bursts are then shortened by a mechanism which is evident from the figure. Ions which arrive earlier are deflected outward by a synchronized voltage applied to the deflector plates. Trailing ions are deflected inward. By properly programming the rate of increase of deflection voltage, the increase in flight path traversed by the early-arriving ions is just compensated, and the pulse of ions which arrives on target will have a duration which is equal to the quotient of twice the diameter of the undeflected beam and the velocity of the ions. Twelve-fold bunching is readily achieved by these means, giving pulses of about 0.8 ns duration. Neutrons are then produced in bursts of corresponding duration.

In this arrangement the scheme for measuring time spectra is basically that in use with many similar systems. The time interval to be measured is the interval between the production of a neutron in the target and the time at which it is detected in the neutron detector at the end of the flight path. Initial



Schematic of Van de Graaff Pulsing Arrangement Employing Terminal Pulsing and Mobley Magnet

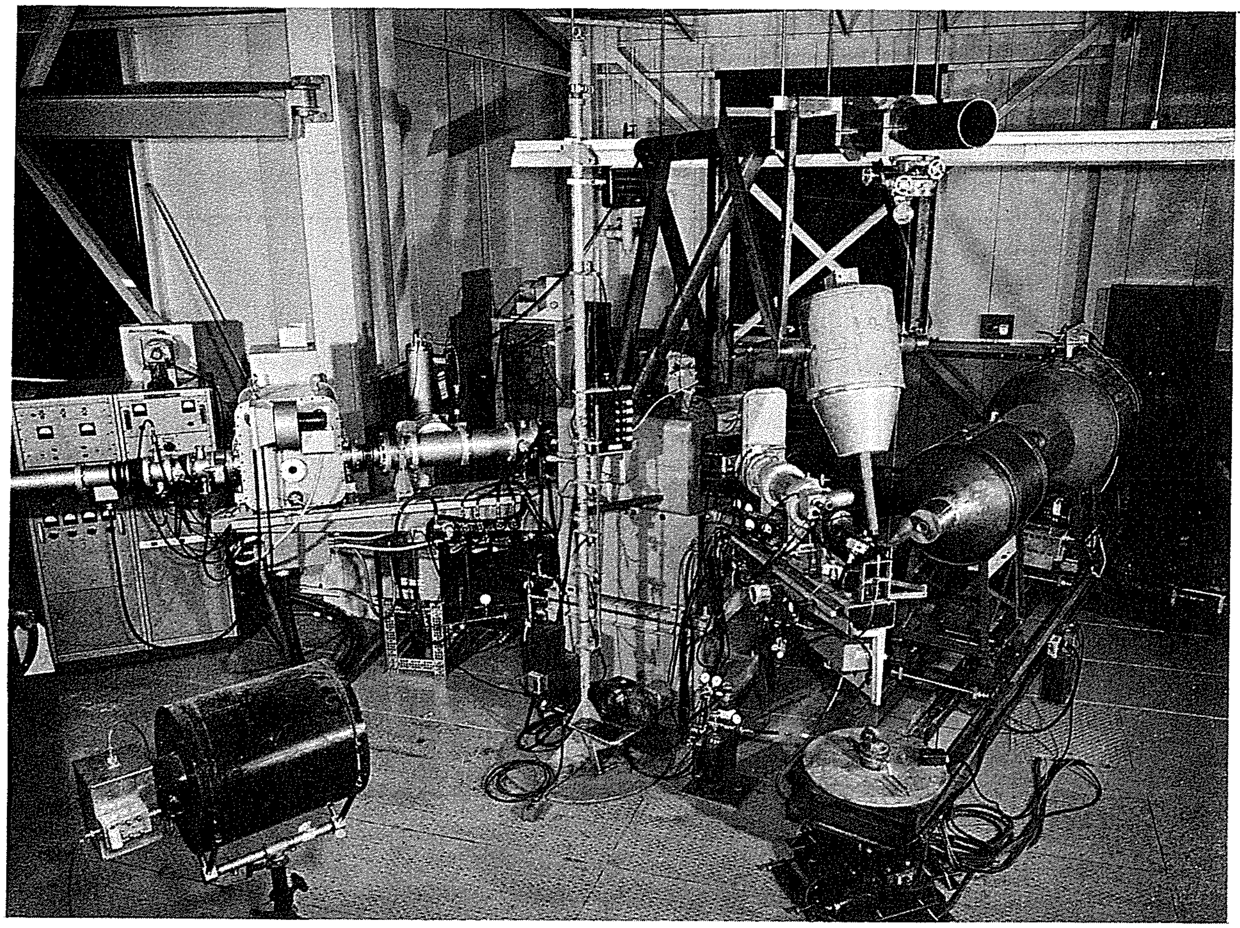
FIGURE 3

time is marked by a pulse electrically induced by arrival of the proton burst at the target. Terminal time is marked by the amplified output pulse from the neutron detector. Neutrons are detected via proton-recoils whose scintillations in an appropriate phosphor are coupled to a fast photomultiplier.

There now exists a large assortment of time-measuring instruments. All utilize some sort of device which digitalizes the time information and stores it in a magnetic memory. In one system in common use, the time interval is converted to an analog voltage in the form of a pulse, whose height is then measured by a pulse-height analyzer. Some of these systems make effective use of 4000 channels of time information.

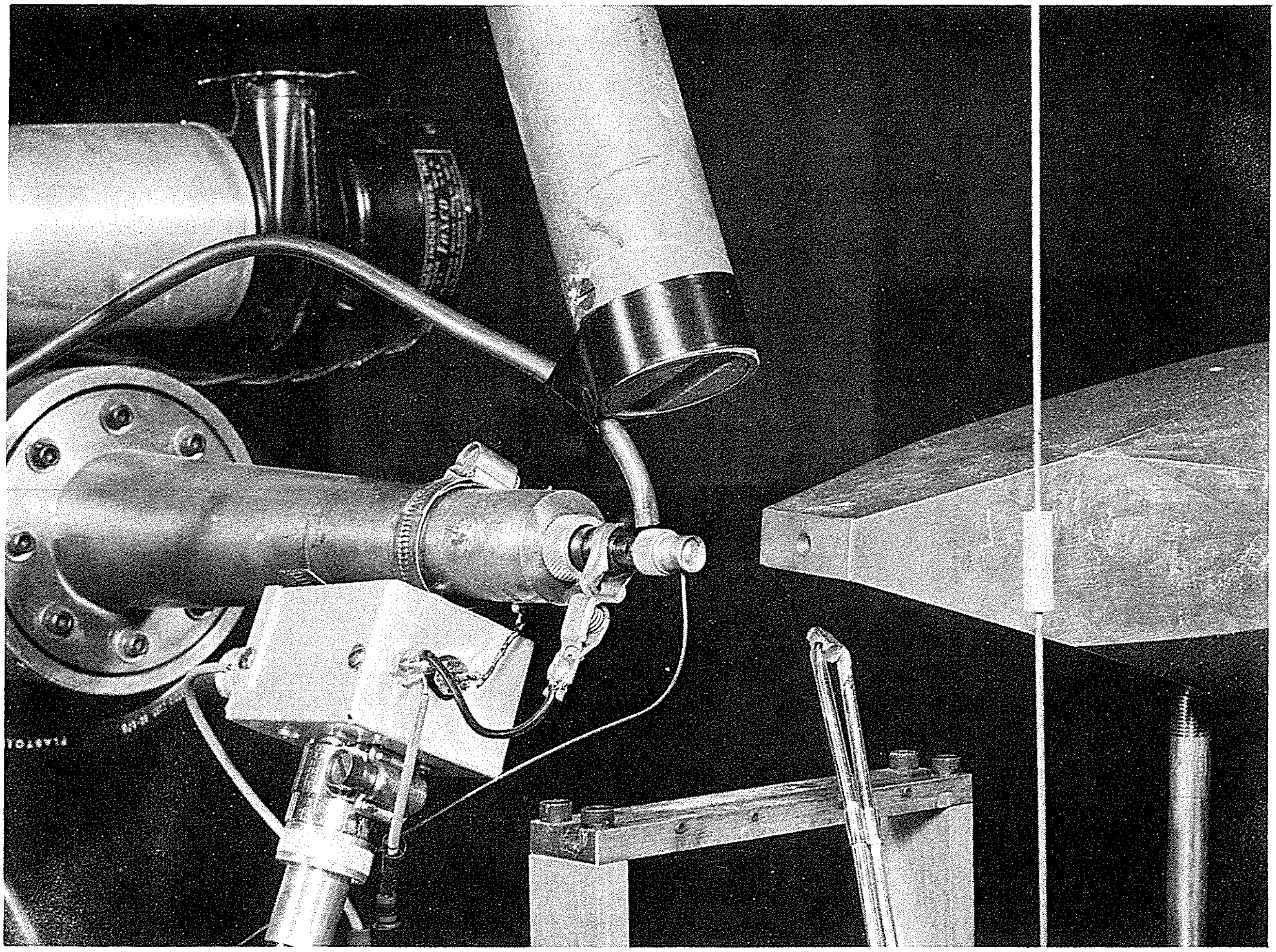
Figure 4 shows a system of the type just described, set up at Los Alamos for studies of elastic and inelastic scattering. The detector, buried in the massive shield mounted on a cart, is two meters from the sample. The detector can be positioned to allow observations over a wide range of scattering angles. Figure 5 shows a close-up of the target, sample, and several monitoring detectors. The (copper) wedge on the right is the first neutron shield between target and detector.

Under present conditions the rate at which data is produced by these systems is considerable. Often computers handle and process the data. This is particularly true in the work on total cross sections.



Photograph of Neutron Spectrometer at Los Alamos

FIGURE 4



Closeup of Target and Sample Region, Los Alamos Neutron Spectrometer

FIGURE 5

V. Total Cross Sections

Systematic measurements of total neutron cross sections have now been under way for over two decades, and a vast amount of data has been accumulated. Topics of interest are the widths, spacings, and spins of individual resonances, the statistical distributions of those properties, and the background of potential scattering on which the resonances are superimposed. The cross section averaged over resonances is a quantity which plays a very important role in practical work and in the optical model of the nucleus. For light and medium weight nuclei, individual resonances are a conspicuous feature even of low resolution results for fast neutrons, and presumably are of interest to the fast reactor physicist, while the cross section averaged over resonances is of interest to the reactor physicist over the whole energy range which we are discussing.

Total cross sections are the easiest to measure, since,as we have already indicated, we require only a determination of n, the number of scattering nuclei per cm^2, and T, the transmission, which requires only the determination of a ratio of counts with sample "in" and "out" in appropriate geometry, taking proper account of backgrounds.

Pulsed sources, which provide neutrons continuously distributed in energy over the kev region, such as linacs, the synchrocyclotron, or a fast chopper, usually with a moderator to enrich the spectrum in the kev region, combined with time-of-flight techniques enable one to measure transmissions simultaneously as a function of neutron energy over a wide range. Flight paths as long as 200 meters have been used in this work.

The detectors used in the range of energy below 100 kev usually rely on the B^{10} ($n,\alpha\ \gamma$) reaction, either by detecting the alpha particle or the gamma ray. In the Nevis-Columbia set-up the detector is a 15 kg mass of B^{10} viewed by four NaI crystals, each 11 inches in diameter by 2 inches thick.

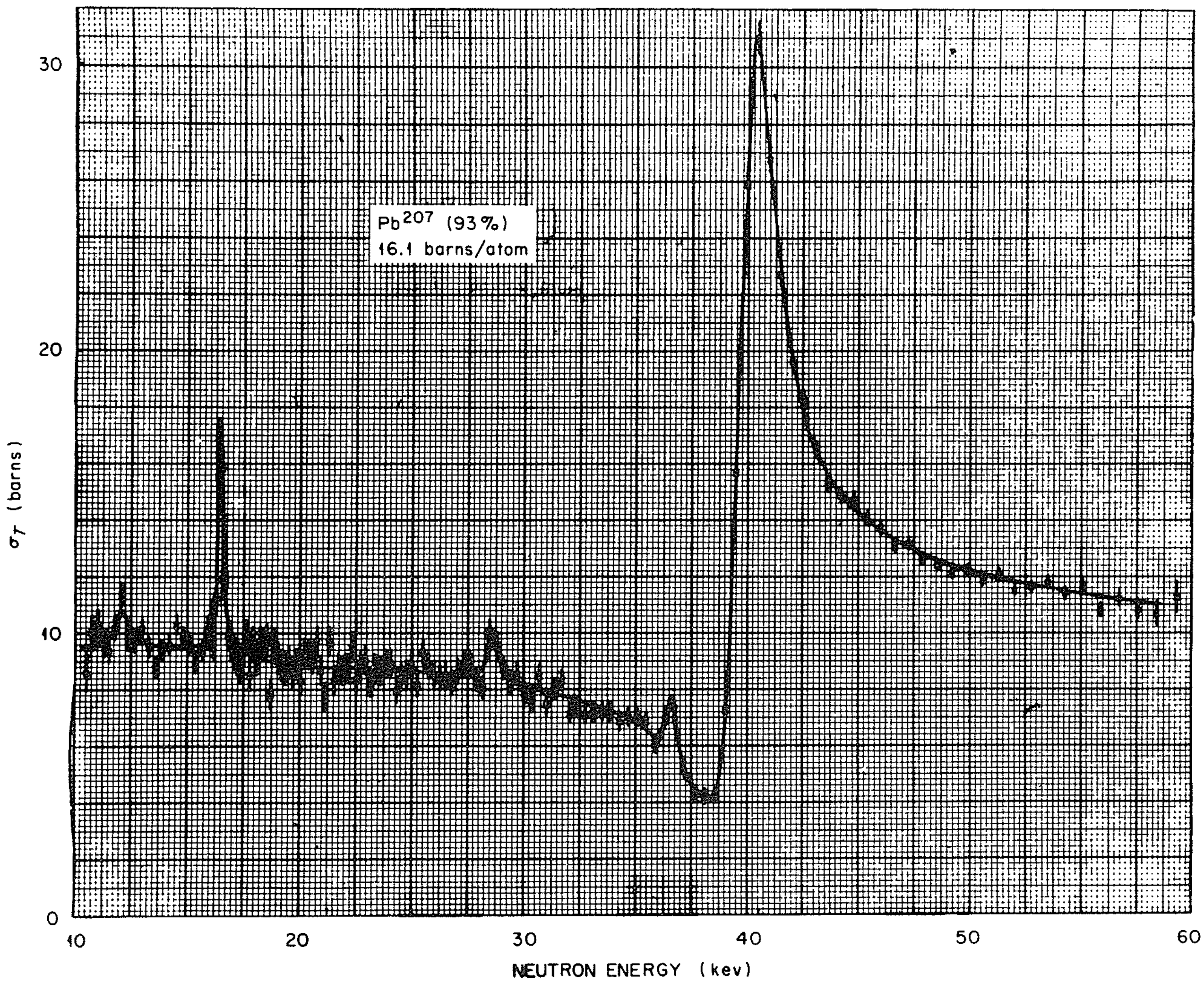
Newson at Duke and Hibdon at Argonne have adapted the Van de Graaff for this work, using monoenergetic neutrons produced by the Li^7(p,n) reaction. By using neutrons produced in the back direction relative to the direction of the incident protons, it has been possible to cover the kev range as well as the Mev range which is the more familiar domain of the Van de Graaff. More recently a group at Oak Ridge has made use of a pulsed Van de Graaff, generating neutrons with a continuous distribution of energies, and has successfully used time-of-flight techniques in the kev range.

The resonances in the total cross section are due to virtual states of a compound nucleus consisting of the sample nucleus and the incident neutron. They present us with otherwise unobtainable data on the characteristics of individual levels at excitation energies corresponding to the sum of the kinetic energy of the incoming neutron (in the center of mass system) and the binding energy of the neutron in the nucleus A + 1. In a nucleus such as U^{235}, in which the binding energy is about 5 Mev, the level spacing at that energy of excitation is in the range of a few ev. A distinctive feature of the resonance method of detecting these states at high excitation is that one need measure only the kinetic energy of the incident neutron in order to locate a level in the compound nucleus,

Figures 6 and 7 show recent total cross section measurements, plotted against incident neutron energies. The number of points are an indication of the quality of data now obtainable.

An excellent synopsis which deals in a comprehensive way with the statistical features of resonances is due to J. A. Harvey (reference 7, p. 23), and was presented at the Time of Flight Conference in Paris in 1961. I refer those interested in systematic features of resonance data to the symposium report for that conference.

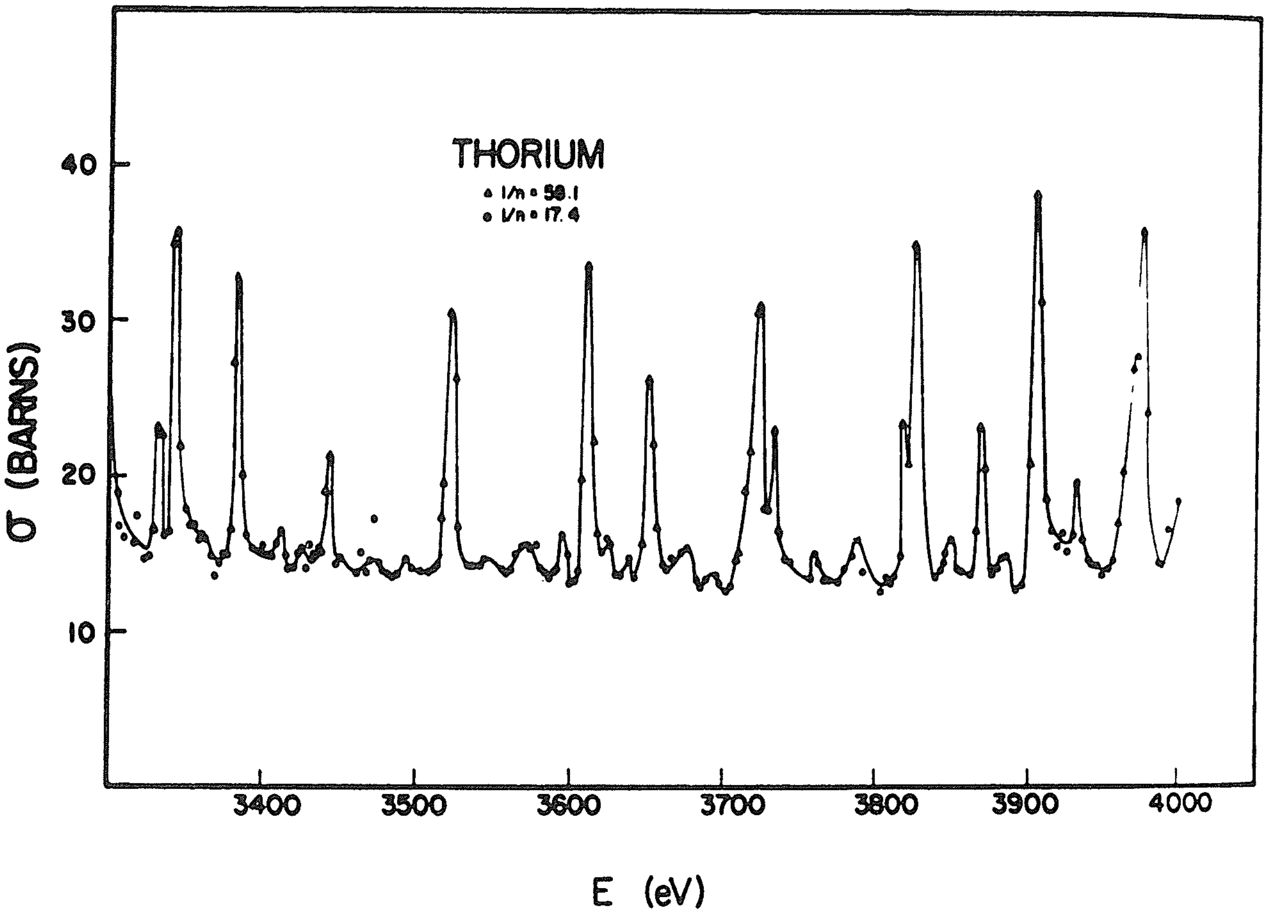
There are two features of the resonance data which should be mentioned here, however. One is the strength function, or the ratio of width to spacing for a given l-value, averaged over energy, because it is calculable on the optical model and thereby interrelates with a great mass of other data. The other is the average level spacing or level density, which plays an important role in the calculation of nuclear reactions according to the statistical model. The essential result is that the logarithm of the level density increases with the square root of the excitation energy at a rate which depends on the nuclear species. It also increases systematically with mass number, but is particularly low for nuclei in the vicinity of the magic numbers. The mass dependence is at least qualitatively accounted for by the Fermi Gas Model, but account must be taken of magic-number effects even at the nuclear excitations corresponding to binding



Total Cross Section of Pb-207 in the kev Region

W. H. Good, J. Biggerstaff, Oak Ridge National Laboratory, private communication

FIGURE 6



Total Cross Section in Thorium in the Low kev Region

J. B. Garg, J. Rainwater, and W. W. Havens, Jr., Phys. Rev. 134B, 985 (1964).

FIGURE 7

energy excitation.

In the energy range from 100 kev to 10 Mev, experimental techniques in the past have depended almost entirely on use of monoenergetic neutron sources such as those provided by the Van de Graaff, with which one acquires data one energy point at a time. This method has produced large amounts of useful data, but many gaps remain. Recently, D. G. Foster and D. W. Glasgow at Hanford have put into operation a time-of-flight apparatus which has greatly increased the speed of taking data, and apparently the quality as well. Foster and Glasgow have amassed an impressive amount of new data, some of which they have kindly made available for presentation here.

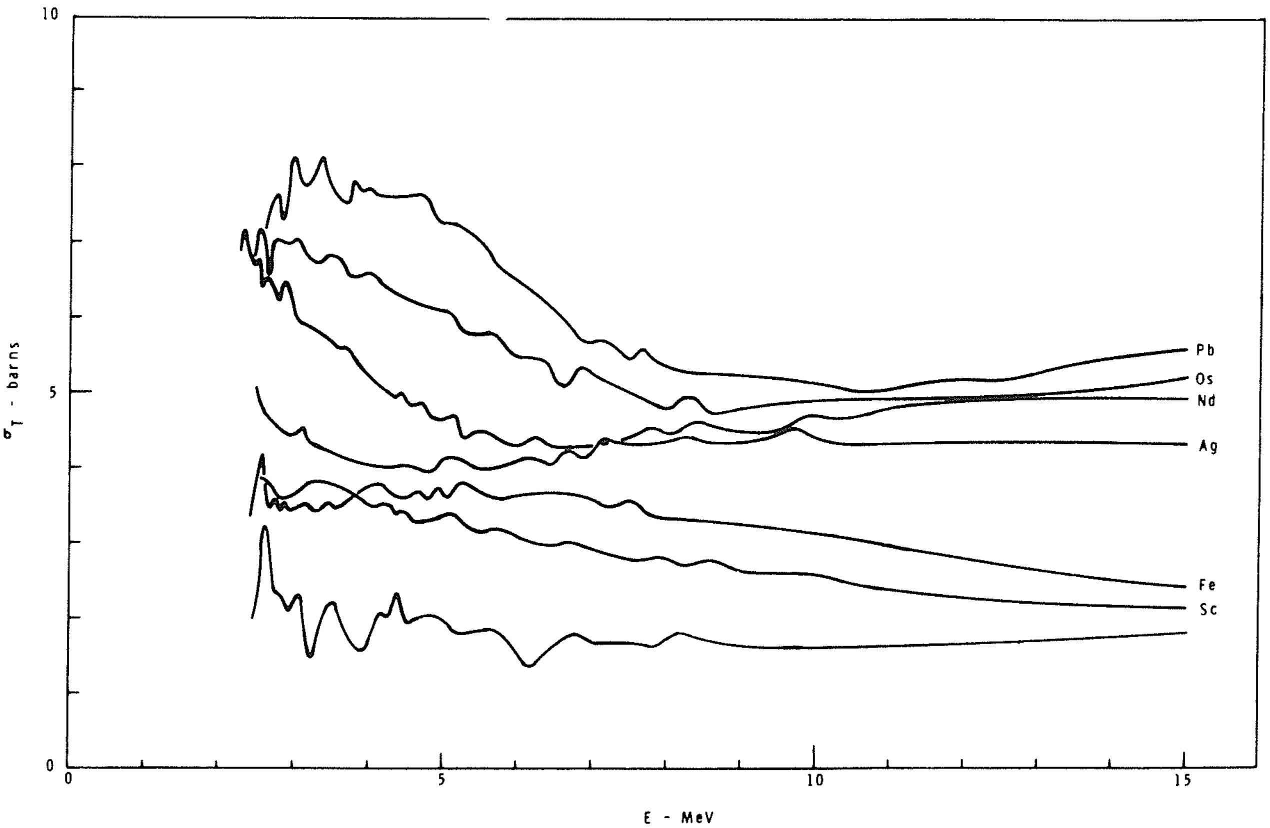
The system is of some interest because it makes effective use of a 2 Mev Van de Graaff accelerator, and it appears to be doing a job hitherto thought accessible only to a tandem generator using the customary monoenergetic point-by-point methods.

Basic to the system is the combination of a source of neutrons whose energy extends continuously up to about 16 Mev, with pulsed beam time-of-flight methods. The reaction used is the exceptionally exothermic $Li(d,n)Be^{8*}$ reaction, which has a Q (when the reaction proceeds to the ground state of Be^8) of more than 15 Mev. Since this is a binary reaction and the states in Be^8 are few and far between, one might expect to get a very discontinuous neutron spectrum from this source. However, even the ground state is unstable against decay into 2 alpha particles, and the low-lying excited states of Be^8 have very large widths associated with their instability against alpha decay. Thus, the reactions are, in effect, three-body processes. Although there are still gaps in the neutron spectrum from a thin lithium target, smoothing is accomplished by use of a thick target. The spectrum provides neutrons at useful intensity from 3 to 16 Mev for a 2 Mev accelerator.

In Foster's arrangement the source neutrons pass through the sample in a short burst, and then the different energy groups are sorted out by time-of-flight techniques. The detector is a proton recoil scintillation counter at the end of a flight path of 10 meters.

Figure 8 shows Foster's results for a number of nuclides. One of the unexpected features of these results is the clear evidence of fluctuations in these cross sections at excitation energies where the level density is expected to be so great as to preclude fluctuation effects on the scale exhibited by these data. These unexpected fluctuations have aroused great interest and also some skepticism on experimental grounds. They have been designated intermediate resonances, and it has been suggested by Feshbach and others that they are evidence for so-called "door-way" states.

Foster's work extends the use of efficient timing methods for total cross section measurement to the whole energy range which is of interest to the fast reactor physicist and it is probable that all the data of this sort one might require should be available in the relatively near future. Foster's arrangement requires little sample material, so that even nuclear species which are available or safe to use only in small quantities can



Total Cross Sections for a Number of Nuclides at Incident Neutron Energies from 2 to 15 Mev

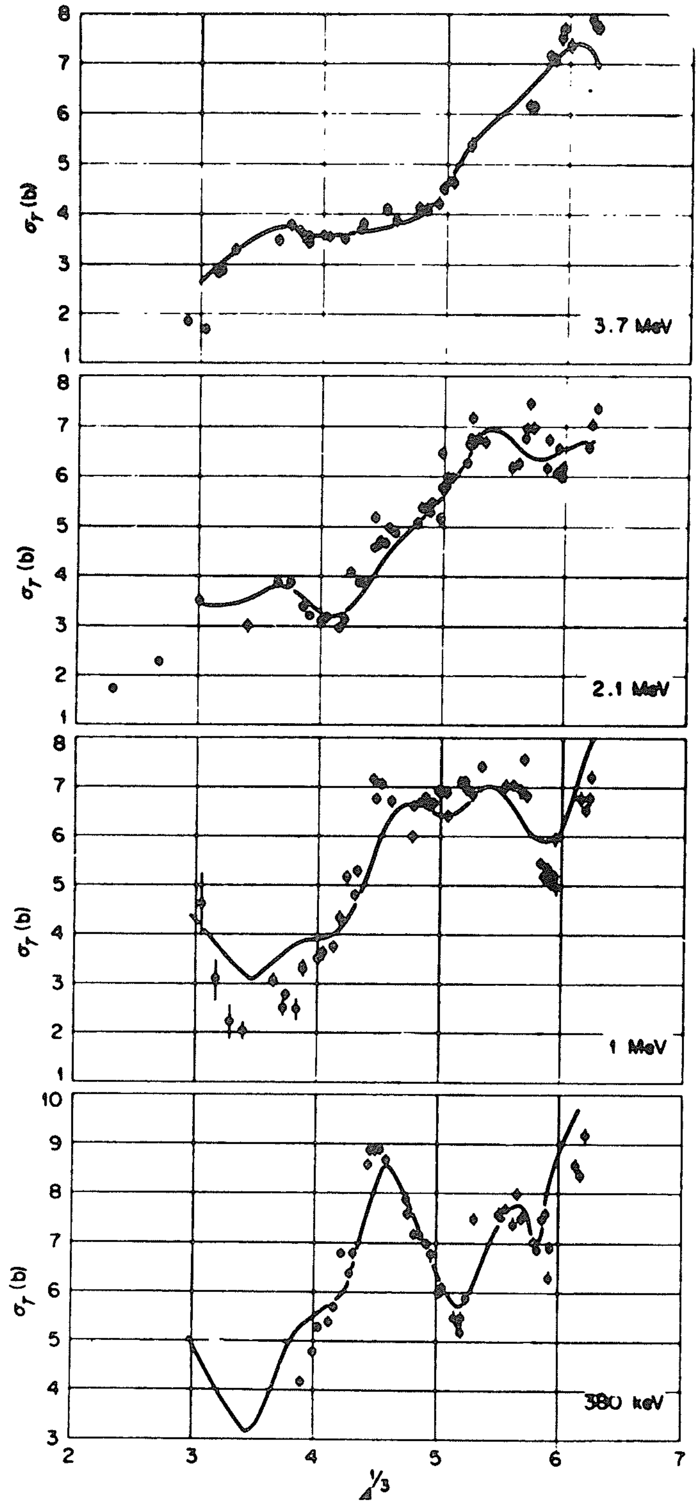
D. G. Foster and D. W. Glasgow, private communication

FIGURE 8

be examined. Questions of accuracy will presumably be resolved shortly.

We turn now to a brief discussion of agreement between theory and experimental measurements of average total cross sections. It appears that in the Mev region the optical model provides a reasonably good fit to experimental values for total cross sections over a wide range of incident neutron energies and for nuclides in the intermediate and heavy range of masses. This situation is illustrated by Figure 9, which shows theoretical and experimental results for the total cross section, plotted as a function of atomic number, for the incident neutron energies 380 kev, 1 Mev, 2.1 Mev and 3.7 Mev. It is clear that the fit is relatively good.

To sum up, one can say that such needs as remain for total cross section data in the fast neutron region probably will be available soon either from direct measurement or by interpolation among the many species which have been measured.



Measured Total Cross Sections at Four Incident Neutron Energies Plotted Against Atomic Weight and Compared with Optical Model Predictions (Solid Lines)

From Perey and Buck, Nuclear Physics 32, 353 (1962)

FIGURE 9

VI. Nonelastic Cross Sections

The total cross section is usefully written as a sum of nonelastic and elastic cross sections, where the elastic cross section describes all scattering reactions in which the kinetic energy of the neutron does not change in the center of mass system, and the nonelastic cross section includes all other types of reactions.

Three basic methods are used in measuring nonelastic cross sections. In the so-called "sphere method" (reference 4, chapter V.H.) one measures the neutron transmission of a spherical shell of material surrounding a monoenergetic neutron source, using a detector which can detect only neutrons which have not been degraded in energy as they pass through the shell. The second method involves measuring the differential elastic scattering cross section, integrating over solid angle, and subtracting the integral from the total cross section. The third method involves measuring separately the various partial cross sections which account for the nonelastic cross section.

The sphere method is based on the following reasoning. If an isotropic source of monoenergetic neutrons is surrounded by a spherical shell of material whose nuclei may be regarded as infinitely massive, then the intensity of neutrons of the original energy which is observed in a given direction will be diminished. The decrease will be independent of the magnitude of the elastic part of the cross section and will be sensitive only to the non-elastic part, the elastic "outscattering" being just compensated by the elastic "inscattering". Of course the detector must be able to discriminate between neutrons of the original energy and those which have lost energy. This has been accomplished by using a high-biased proton recoil detector.

According to a reciprocity theorem developed by Bethe, a similar result obtains if an omni-directional detector is placed inside the spherical shell and the source is outside. The source need not then be isotropic. Note that either arrangement avoids the measurement of neutron flux.

The analytical work on the shell method was published by Bethe, Beyster, and Carter[11] in the mid-fifties, and the experimental results of a number of workers appeared at about the same time. There seems to be little to add to what has been done either on the analytical or the experimental side. The results of the shell experiments impress me as being at least as likely as any other fast neutron data to endure in their present form. If our knowledge of nonelastic cross sections is going to be improved, the improvement will probably have to come about by way of more accurate elastic and total cross-section measurements.

Some cautions should be kept in mind in using the results of shell measurements, however, particularly the caution emphasized by the experimenters themselves about trying to infer information on the spectra of inelastic scattering from the published results taken at detector biases other than the highest. And in a few cases there is evidence that inelastic scattering to low-lying states was not completely sorted out from elastic scattering, but it is a pity to carp at work which has been carried out with such admirable thoroughness and which has proven so useful. The accuracy of many of these measurements is about 0.05 barns, and is difficult to match by any other method.

Although the reactor physicist is most interested these days in the components of the nonelastic cross section, which consists mostly of inelastic scattering and capture, and he wishes to know these cross sections separately and in detail, the integral results on the nonelastic cross sections are frequently useful as a check on the methods which give more refined data. Measurements of inelastic scattering and capture will be discussed separately later.

The trend of nonelastic cross sections is quite similar from one element to another, consisting of a monotonic decrease with increasing energy in the kev region where capture predominates, followed by a fairly steep rise in the Mev region where one begins to excite nuclei appreciably by inelastic scattering. The non-elastic cross section levels off at a value of 1/3 to 1/2 of the total cross section a few Mev above the threshold for inelastic neutron scattering.

VII. Scattering

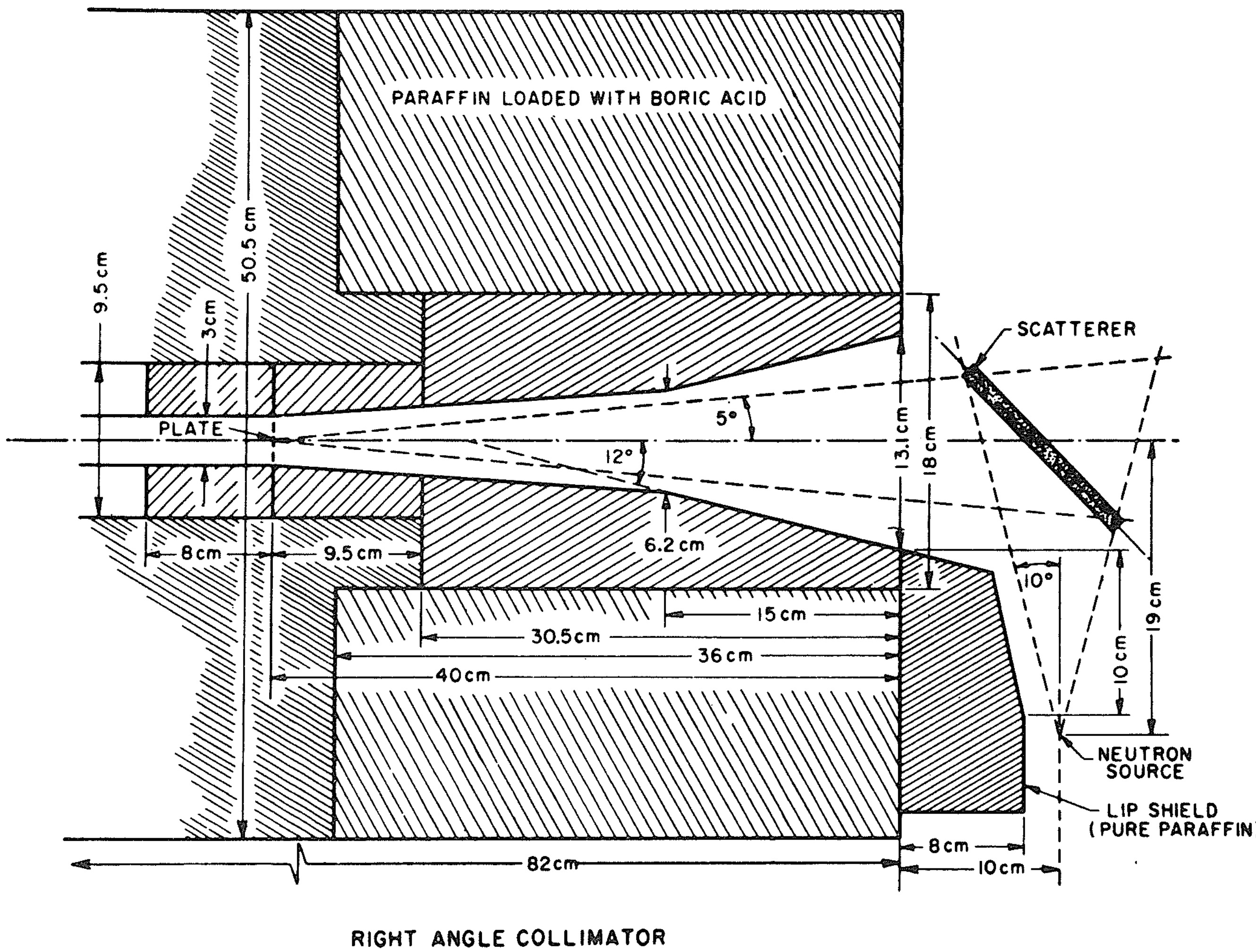
It is convenient to talk about elastic and inelastic scattering together because nowadays they are measured with the same experimental arrangement and are treated together in theory. The earlier measuring techniques were different, however, and it is pertinent to review them briefly.

The technical problems involved in measuring elastic scattering were considerably easier to solve than those involved in measuring inelastic scattering, because the latter required the development of an efficient neutron spectrometer. Thus, elastic scattering techniques were mastered earlier and our knowledge of elastic scattering is considerably more complete even today than of inelastic scattering.

The early techniques supplied a large amount of useful and reliable data. In general they employed monoenergetic dc neutrons and high-biased recoil detectors. The detector was placed in the position normally occupied by a sample to obtain a normalizing count. It was then removed to a position shielded from the neutrons, and a count obtained with the sample in place. The ratio of the two counts, times the square of the scatterer-detector distance, divided by the number of nuclei in the scatterer, gives the elastic scattering cross section per unit solid angle. In this way one again avoids measuring absolute neutron flux. Corrections must, of course, be applied for background, multiple scattering, loss of neutron energy on scattering, etc.

The extensive results of Walt and Beyster and Walt and Barschall (reference 4, chapter V.B.) using this technique are deservedly well-known, as is the excellent work of Coon and collaborators.[12] If any of the elastic scattering measurements made in the last decade are going to stand the test of time, the exceptionally careful measurements of elastic cross sections at 14 Mev by Coon, Davis, Felthauser and Nicodemus are strong candidates for that distinction. By using a ring geometry with thin cylindrical scatterers, they were able to make effective use of special virtues of the 14 Mev neutron source, and Coon has convinced me at least that it would be difficult to improve the results with any of the later methods. This, let me add, is unusual, because timing usually affords very great advantages over the older methods which used steady beams and high-biased proton recoil detectors.

The early methods for observing inelastic cross sections were quite difficult to use, as will be evident from the description which follows of an effort by Jennings[13] and collaborators at Westinghouse in the early 1950's to observe spectra of inelastically-scattered neutrons. Figure 10 shows the arrangement used for this experiment. The source was a Van de Graaff producing 4 Mev neutrons by the d-d reaction. The detector was a nuclear emulsion in which scattered neutrons produce proton recoil tracks.



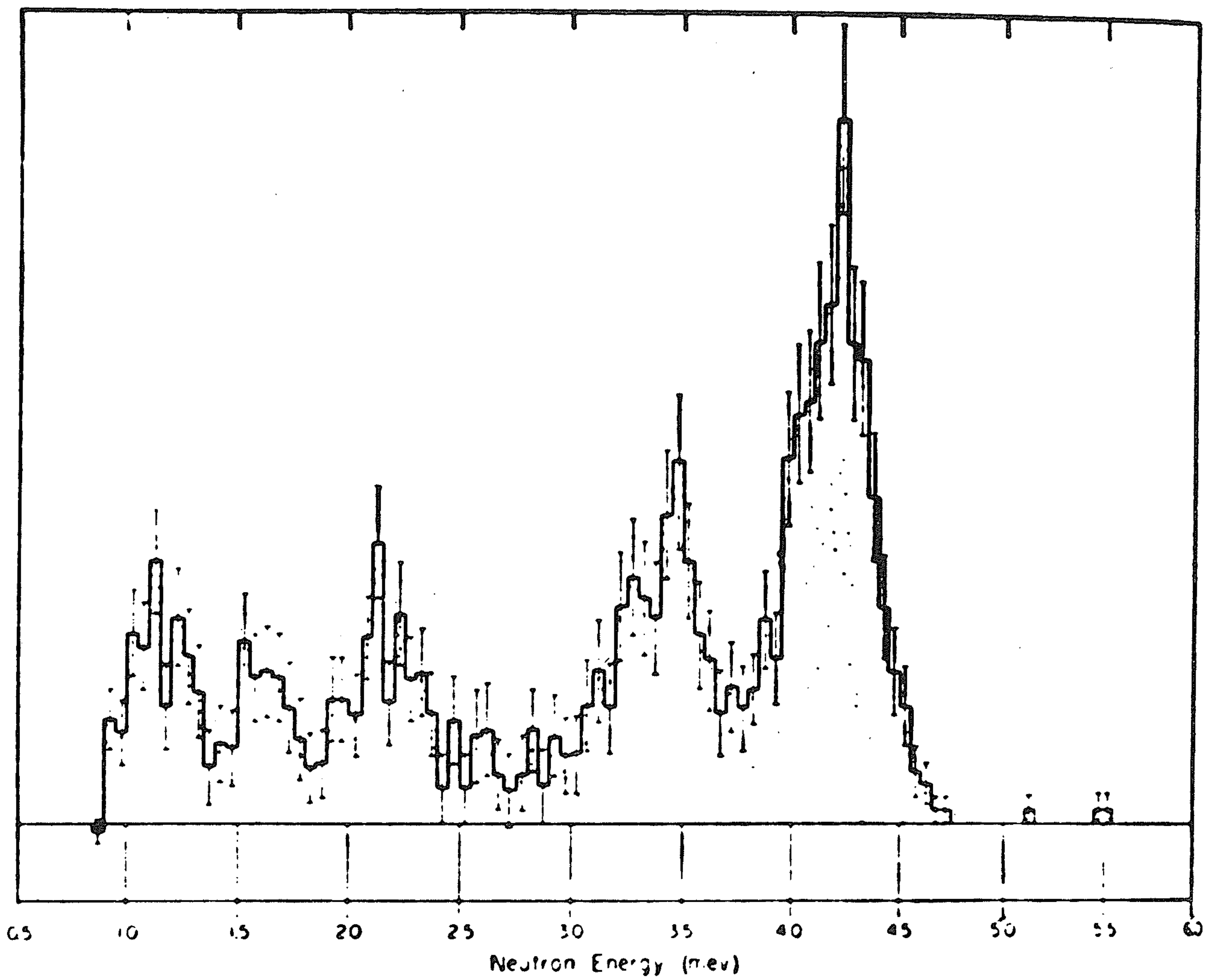
Schematic of Experimental Apparatus Used by Jennings, et.al., reference 13, in Early Observation of the Spectra of Inelastically Scattered Neutrons

FIGURE 10

Measurements of the lengths and directions of the tracks enable one to infer the spectrum of neutrons which was incident on the emulsion. Clearly this is a very tedious method of obtaining information. It is also very inefficient, utilizing as it does a detector which has less than 1% efficiency for neutron detection, and which subtends only a very small solid angle at the sample. Nevertheless, the success which Jennings had in obtaining a spectrum of inelastically-scattered neutrons is noteworthy because it was one of the first results of this type to be obtained, and helped to establish a vital point which up to that time had not been clearly settled--namely, that it <u>is</u> in fact possible to observe the spectrum of scattered neutrons while shielding a detector effectively against the direct neutron flux from the target. Probably such measurements could not have been obtained if neutron cross sections were - let us say - five-fold smaller than they are.

Figure 11 shows the spectrum obtained by Jennings and collaborators in 1954 for neutrons inelastically scattered from iron.

The demonstration that one can observe spectra of inelastically-scattered neutrons in a geometry such as that illustrated in Figure 11, encouraged the development, to which Jennings and collaborators also contributed, of a high resolution time-of-flight method for measuring neutron spectra, which has come of age in the last few years. In this method a nearly monoenergetic burst of neutrons from a Van de Graaff or similar source strikes the sample. A time spectrum of the scattered neutrons is registered



Results obtained by Jennings et.al, reference 13, for the spectrum of neutrons scattered from iron. This histogram was drawn from measurements of 1869 tracks in plates exposed to scattered neutrons as shown in Figure 10.

FIGURE 11

by a neutron detector placed at some distance from the sample and connected to time-of-flight measuring equipment. This spectrum can be used to obtain an inelastic cross section without measuring the absolute neutron flux but by comparison with n-p scattering, using a method illustrated in the following example.

Let us assume that we wish to determine the inelastic cross section for excitation of the 0.85 Mev level in Fe^{56}, and that the energy of the incident neutrons is 2.00 Mev. We note that the energy of neutrons scattered from hydrogen nuclei is given as a function of angle by

$$E_s = E_0 \cos^2\theta = \left[2.00 \text{ Mev}\right] \cos^2\theta$$

where θ is the laboratory scattering angle. (Polyethylene (CH_2) is a convenient sample material.) Also we note that the differential n-p cross section $\sigma(\theta)$, is given in terms of the n-p total cross section σ_T by:

$$\sigma(\theta) = \sigma_T \frac{\cos\theta}{\pi}$$

and of course we can measure σ_T by a transmission measurement. These results follow from two-body kinematics and the well-known fact that neutrons scatter isotropically from protons in the center of mass system at neutron energies up to 10 Mev.

With the hydrogenous scatterer in place, the detector is set at an angle θ_1 , such that $E_s = 1.15$ Mev. Ignoring self-shielding and multiple scattering, the count rate for scattering from the hydrogen is given by:

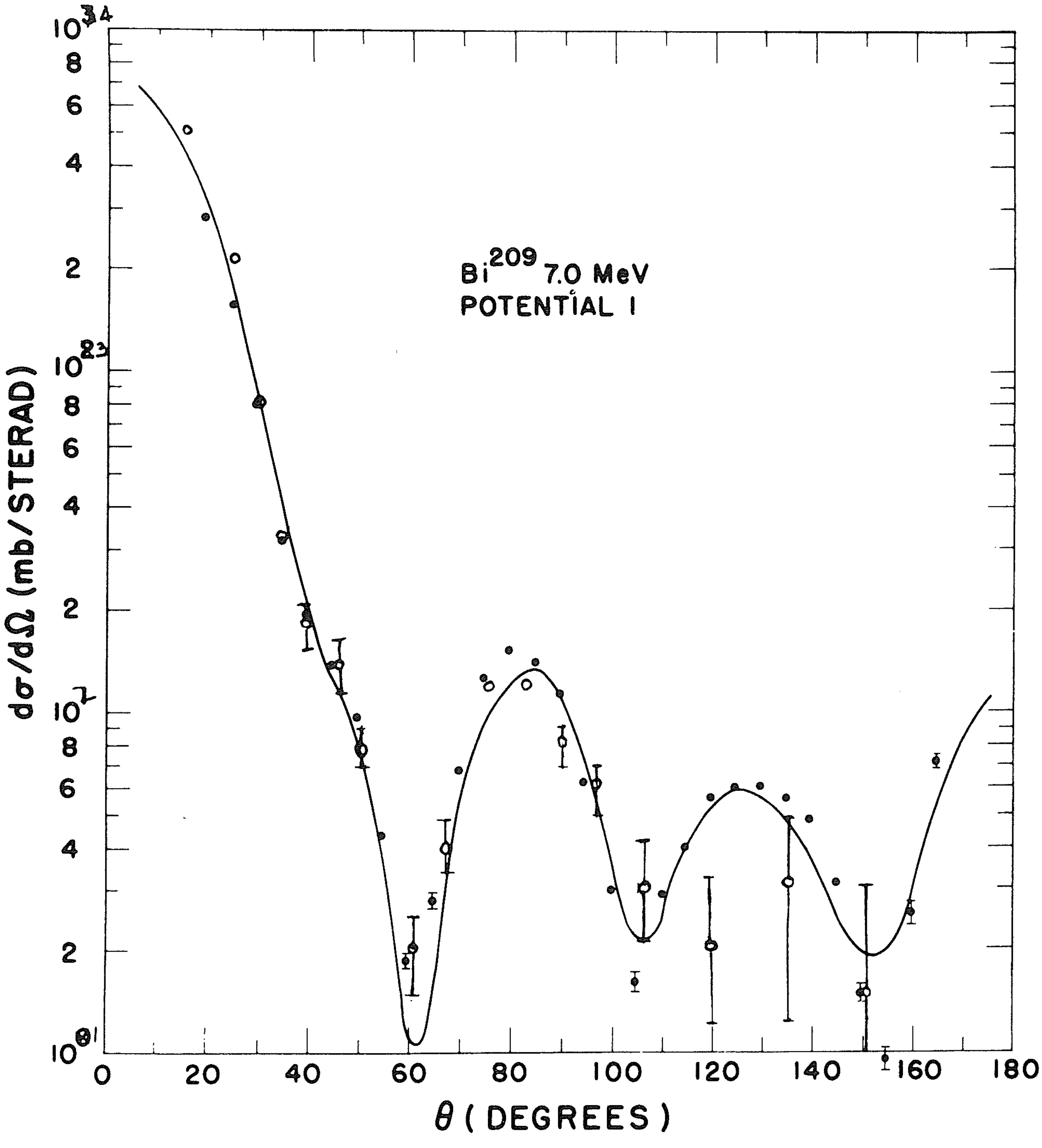
$$C_H = \frac{1}{\pi} \phi N_H \sigma_T \cos\theta_1 \Delta\Omega_D \epsilon_D (1.15 \text{ Mev})$$

when $\Delta\Omega_D$ is the solid angle subtended by the detector at the sample, ϵ_D (1.15 Mev) is the detector efficiency at 1.15 Mev, ϕ is the neutron flux at the scatterer per square cm., and N_H is the number of hydrogen nuclei. Now inserting the iron sample, and readjusting the detector to an arbitrary angle θ, the count rate in the inelastic "line" is given by

$$C_{Fe} = \phi N_{Fe} \sigma_n (\theta) \Delta\Omega_D \quad \epsilon_D (1.15 \text{ Mev})$$

(again ignoring the corrections mentioned above). The ratio of these two count rates yields the ratio of the inelastic differential cross section in iron to the total cross section for neutrons scattering from protons. The latter is well established. Thus one obtains the inelastic scattering cross section in Fe^{56}.

A description has already been given of a typical experimental facility for measuring scattering cross sections by use of timing methods--the one at Los Alamos. Figure 12 gives an interesting recent example of the results on elastic scattering obtainable with such a facility (solid points) compared with older data (open circles). The older data were obtained almost a decade ago using a high-biased proton recoil detector. Errors at back angles have been reduced almost a factor of ten, and a larger range of angle is accessible. At the same time it



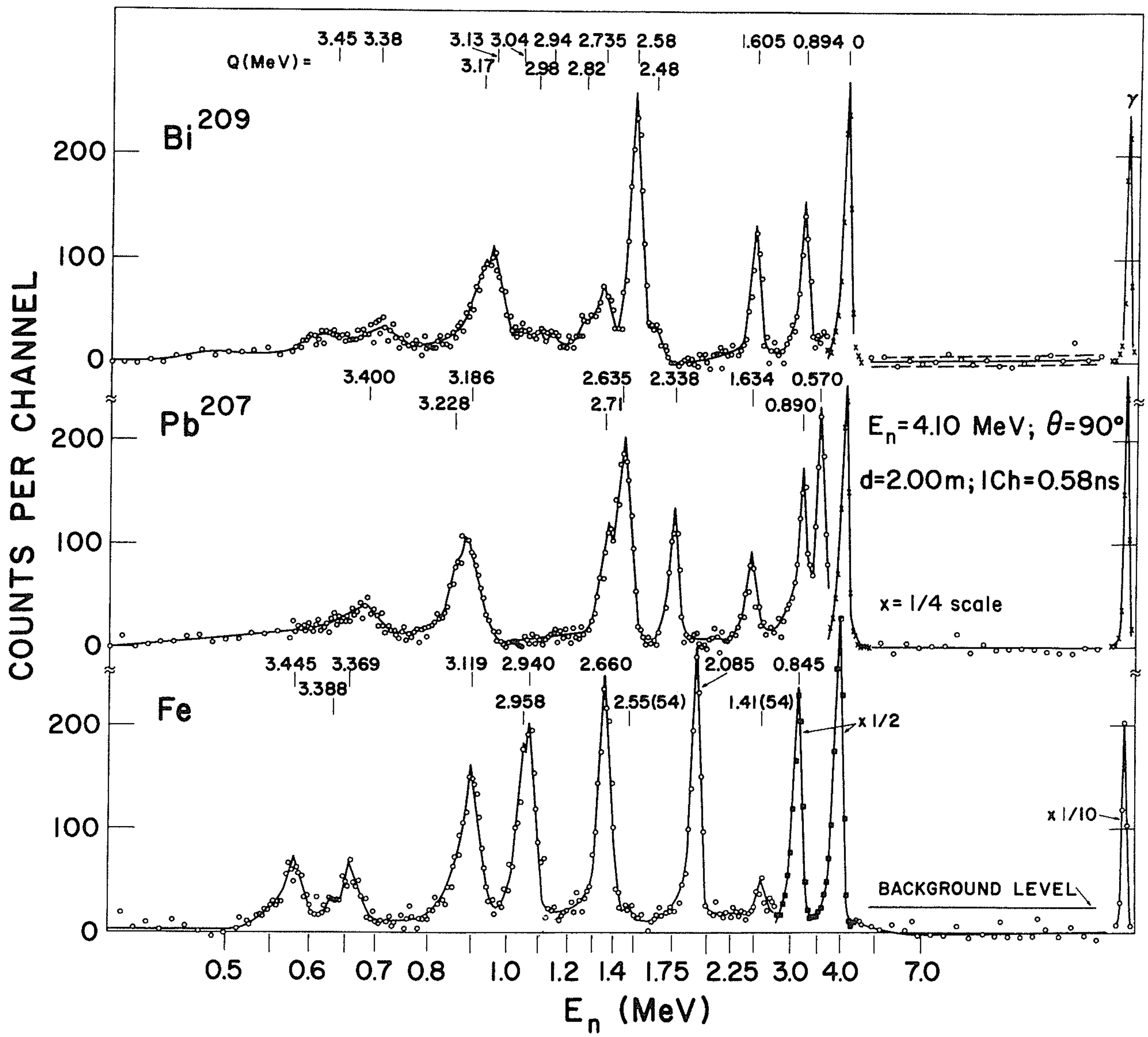
Differential elastic scattering cross section in Bi-209 at 7 Mev. Open circles are data of Beyster, Walt, and Salmi, Phys. Rev. 104, 1319 (1956). Dots are data of Cranberg, Zafiratos, Oliphant, and Levin, private communication, and the curve is an optical model fit to the older data due to Perey and Buck 32, 353 (1962).

FIGURE 12

is interesting to note the surprisingly good agreement between the new data and the optical model fit to the old data, represented by the solid line. At this point some cautionary remarks are in order about being too optimistic about the power of the optical model to predict elastic scattering results. For lower neutron energies the results of the model are good but not altogether reliable. For light nuclei the model is of little value.

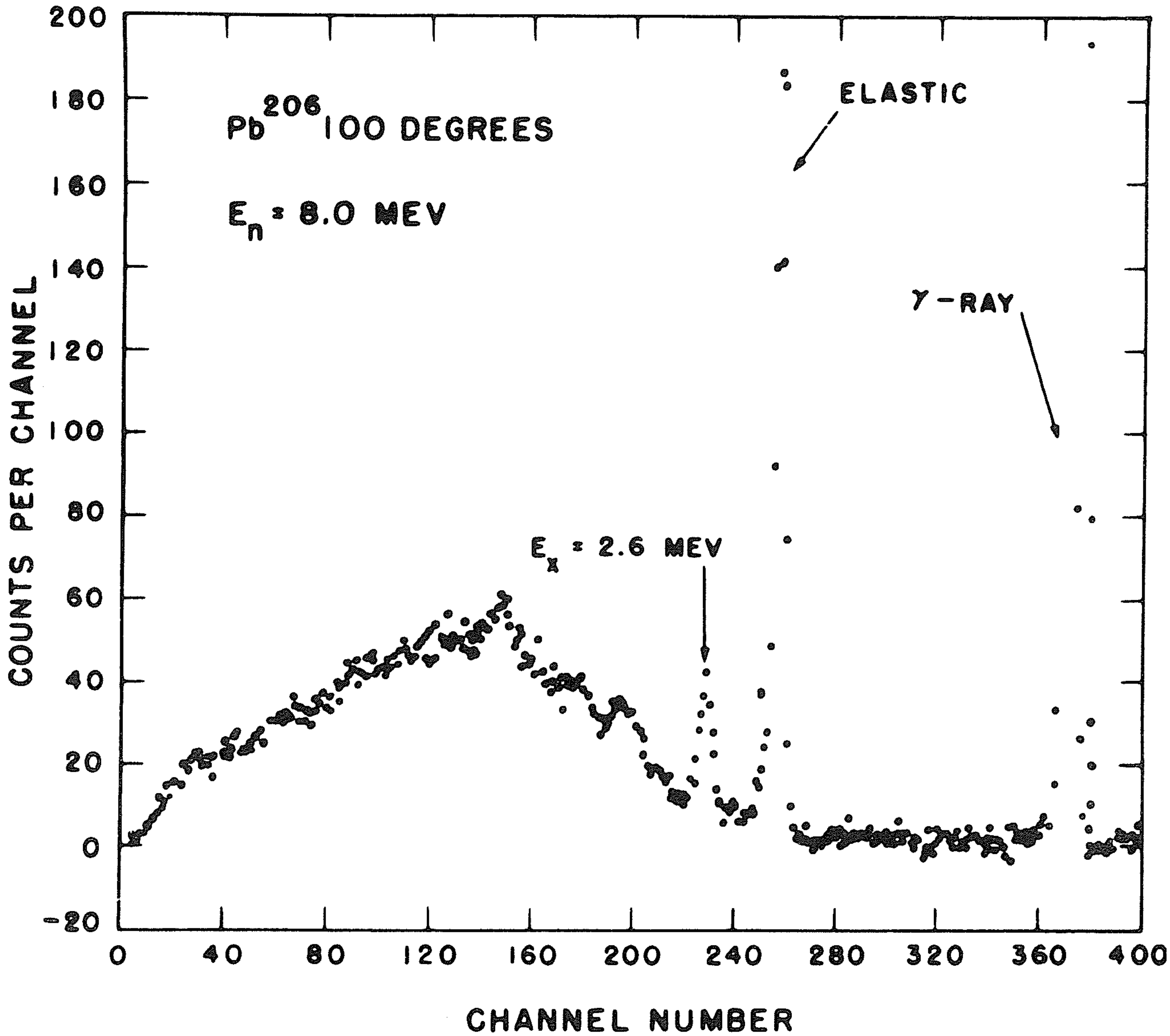
Figure 13 gives some idea of the advantages of the new techniques for measuring inelastic scattering spectra. These measurements were taken in approximately twenty minutes running time, compared with the several days needed to expose an emulsion. The samples were perhaps one tenth the size of samples used in earlier work, making multiple scattering and attenuation corrections much simpler. The improved resolution can be seen by comparing this figure with results in Figure 11.

Figure 14 shows counts versus time-of-flight for inelastic scattering of 8.0 Mev neutrons from Pb^{206}. Starting on the right, the first peak is due to de-excitation gamma rays from the sample, which are emitted essentially immediately after inelastic scatter events. The next peak represents elastically scattered neutrons; then the counts due to inelastically scattered neutrons appear. Over most of the energy range one sees only a continuum. The resolution does not allow one to pick out individual states. However, one peak is visible in the inelastic scattering at an energy which corresponds to excitation of a collective state of the nucleus, the so-called octupole state at



Spectra of Neutrons Scattered from Bi-209, Pb-207 and Fe.
Cranberg, Zafiratos, Levin, private communication

FIGURE 13



Time Spectrum of Neutrons Scattered from Pb-206, for an Incident Neutron Energy of 8 Mev.

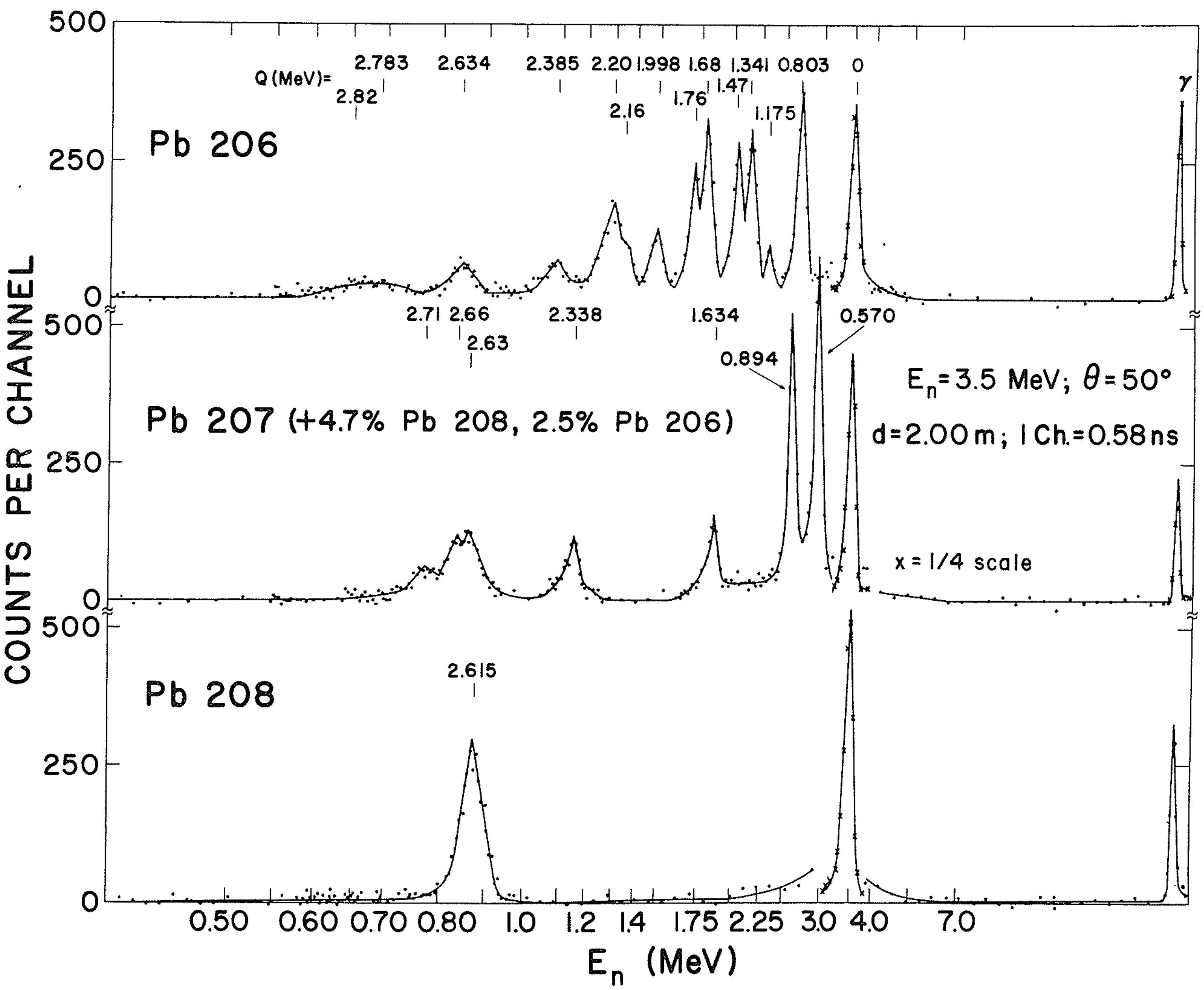
Cranberg, Zafiratos, and Levin, private communication.

FIGURE 14

an energy of 2.6 Mev. At incident neutron energies as high as 8.0 Mev this state is thought to be excited primarily by direct interactions, that is, interactions in which no compound nucleus is involved. Satchler (private communication) has developed a theoretical analysis of direct interactions which fits very well the recent Los Alamos measurements on this peak at incident neutron energies of 8.0 Mev.

Figure 15 shows spectra of inelastic scattering from Pb 206, 207, and 208 at incident neutron energies of 3.5 Mev. At this energy one can observe the individual neutron groups corresponding to excitation of individual levels in the target nucleus. In doubly-magic Pb 208 only the previously-mentioned octupole state is available for excitation. In Pb 206 and 207, neutron "holes" in the last shell results in more complex spectra. At this lower incident neutron energy it is apparent that one can measure the dependence of the cross section corresponding to excitation of a particular nuclear level on incident neutron energy and angle of scatter. The data can be compared with predictions of the Hauser-Feshbach theory (reference 4, chapter V. J.) once the contribution due to direct interactions is subtracted. (Direct interactions are not considered in this theory.) The direct interaction contribution can be calculated from Satchler's work. One finds that at 3.5 Mev this contribution is quite small.

In order to carry through a calculation for the inelastic cross section using the Hauser-Feshbach theory, one needs to know the location, spin, and parity of all states in the target nucleus up to the energy of the incident neutron. These are known for



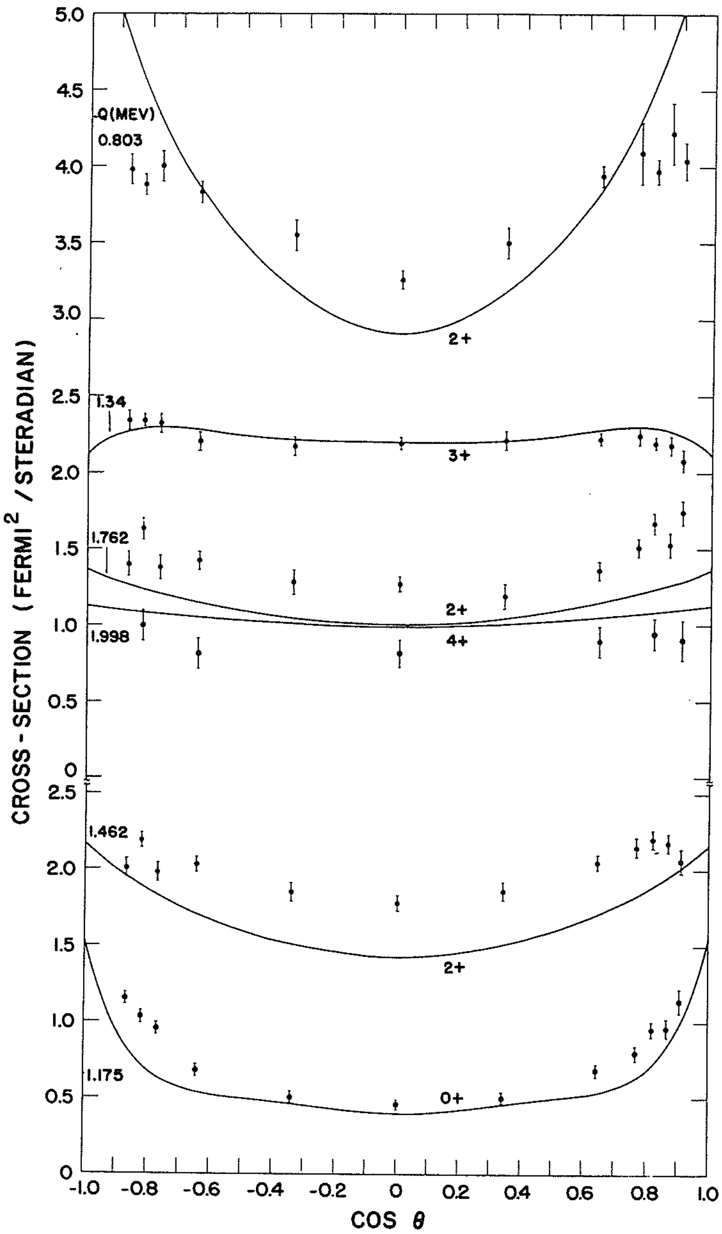
Spectrum of Neutrons Scattered from Pb-206, Pb-207 and Pb-208
Cranberg, Zafiratos, and Levin, private communication.

FIGURE 15

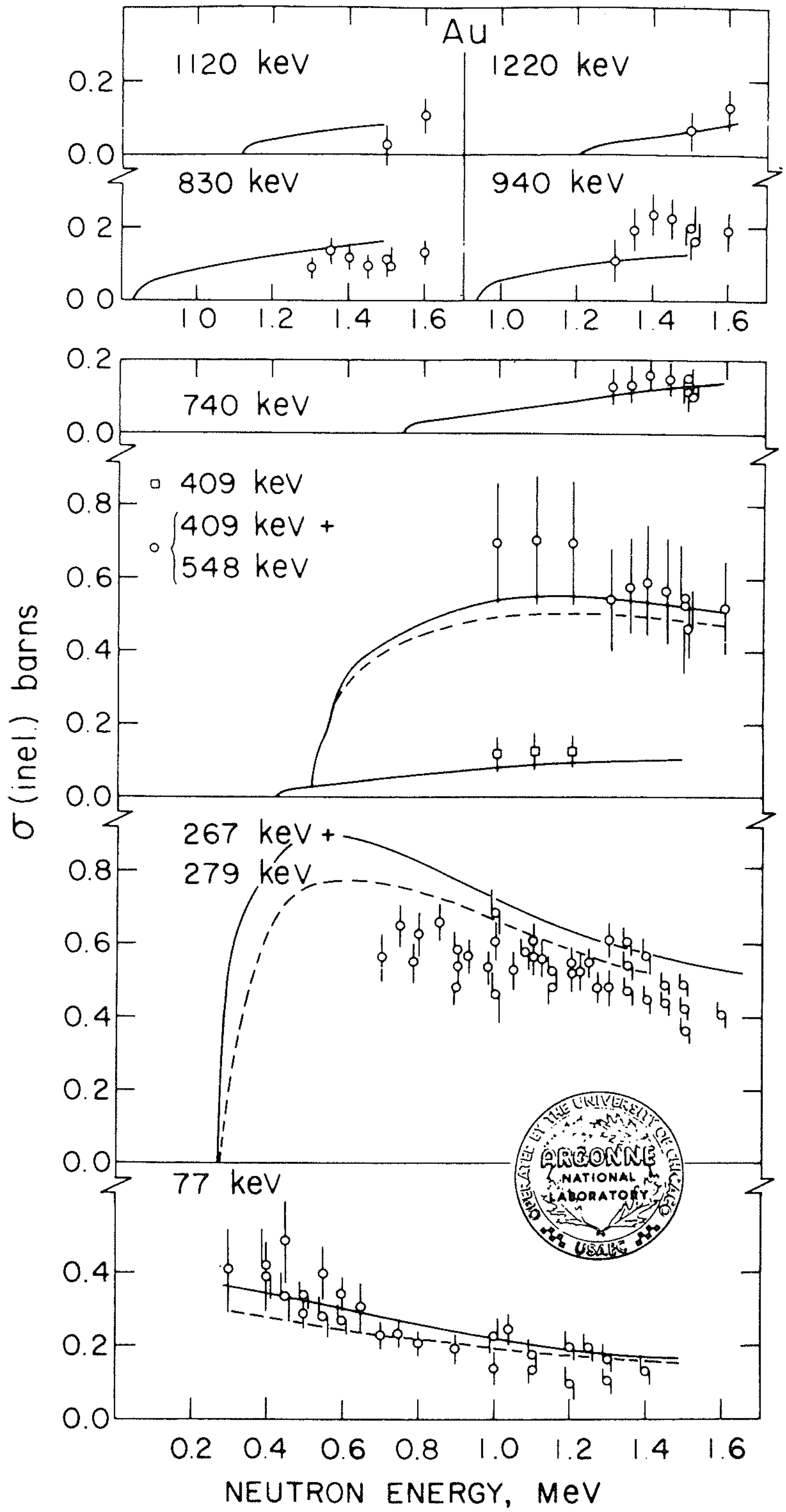
Pb 206 up to 2.5 Mev. Figure 16 shows differential inelastic scattering cross sections in Pb 206 for incident neutron energies of 2.5 Mev, and corresponding theoretical curves based on the Hauser-Feshbach theory using preliminary values of optical model parameters obtained from a fit to elastic-scattering data for bismuth. The Hauser-Feshbach theory predicts that the cross section will by symmetric about 90°. The pattern of agreement between theory and experiment for this case is good, but not perfect. Note the large anisotropy of the neutron group corresponding to excitation of the 0-spin state.

Figure 17 shows recent data for inelastic scattering in Au^{197}, obtained by Alan Smith at Argonne. The solid curves are cross sections calculated from Hauser-Feshbach theory using optical model parameters determined by fitting to experimental elastic scattering data.

This type of data is being collected rapidly using the new techniques. A few important cross sections are particularly hard to measure, however. Among these are inelastic scattering cross sections in U^{235} and Pu^{239}. These are difficult measurements because observations are complicated by the presence of fission neutrons and radioactivity. Only two sets of data are available, both almost a decade old, and these differ by a factor of two. A much better job could be done now using higher intensity pulsed sources and the pulse-shape discrimination techniques recently developed to sort out proton recoils from electron pulses in a scintillator. If anyone is interested in better measurements, they should request them. This concludes discussion of data on



Angular Distributions in the Center-of-Mass System for the Neutron Observed in Inelastic Scattering in Lead-206 for an Incident Neutron Energy of 2.5 MeV.
(From Reference 14)
FIGURE 16



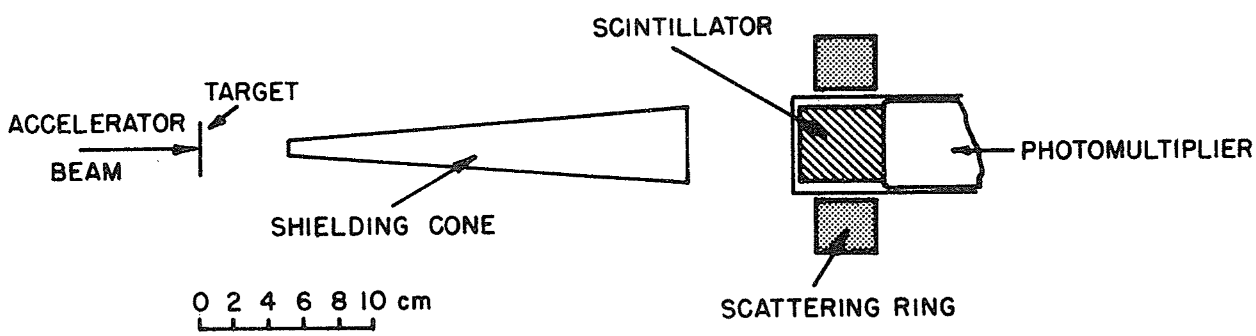
Measurements of Inelastic Scattering Cross Sections in Gold Compared with Predictions from Hauser-Feshbach Theory.
Alan Smith, private communication.

FIGURE 17

inelastic scattering of neutrons obtained from detection of neutrons.

Now let us consider the related cross sections for production of de-excitation gamma rays. Observations of the gamma rays provided the first evidence that inelastic neutron scattering events actually take place. Early measurements of the cross sections for production of de-excitation gamma rays were made using experimental arrangements similar to that depicted in Figure 18. These measurements suffered from a number of limitations. First, results were obtained only at 90°. Second, neutrons were scattered from the sample into the NaI crystal detector, where they generated additional gamma rays which could not be distinguished from those coming from the sample; and third, the strong Compton continuum in the small NaI crystals which were used made it quite difficult to unscramble the energy spectrum of the gamma rays.

A system developed at the Texas Nuclear Corporation overcomes these three difficulties. This system uses a pulsed Van de Graaff producing monoenergetic neutrons. The sample is placed close to the neutron source, and the detector is at some distance from the sample. After a burst of neutrons strikes the sample, the de-excitation gamma rays reach the detector well before neutrons scattered from the sample reach it, and the detector is gated to observe only these de-excitation gammas, being cut off before the neutrons arrive at the detector. The detector is easily rotated about the sample in this arrangement to measure the angular dependence of cross sections. Thus the first two



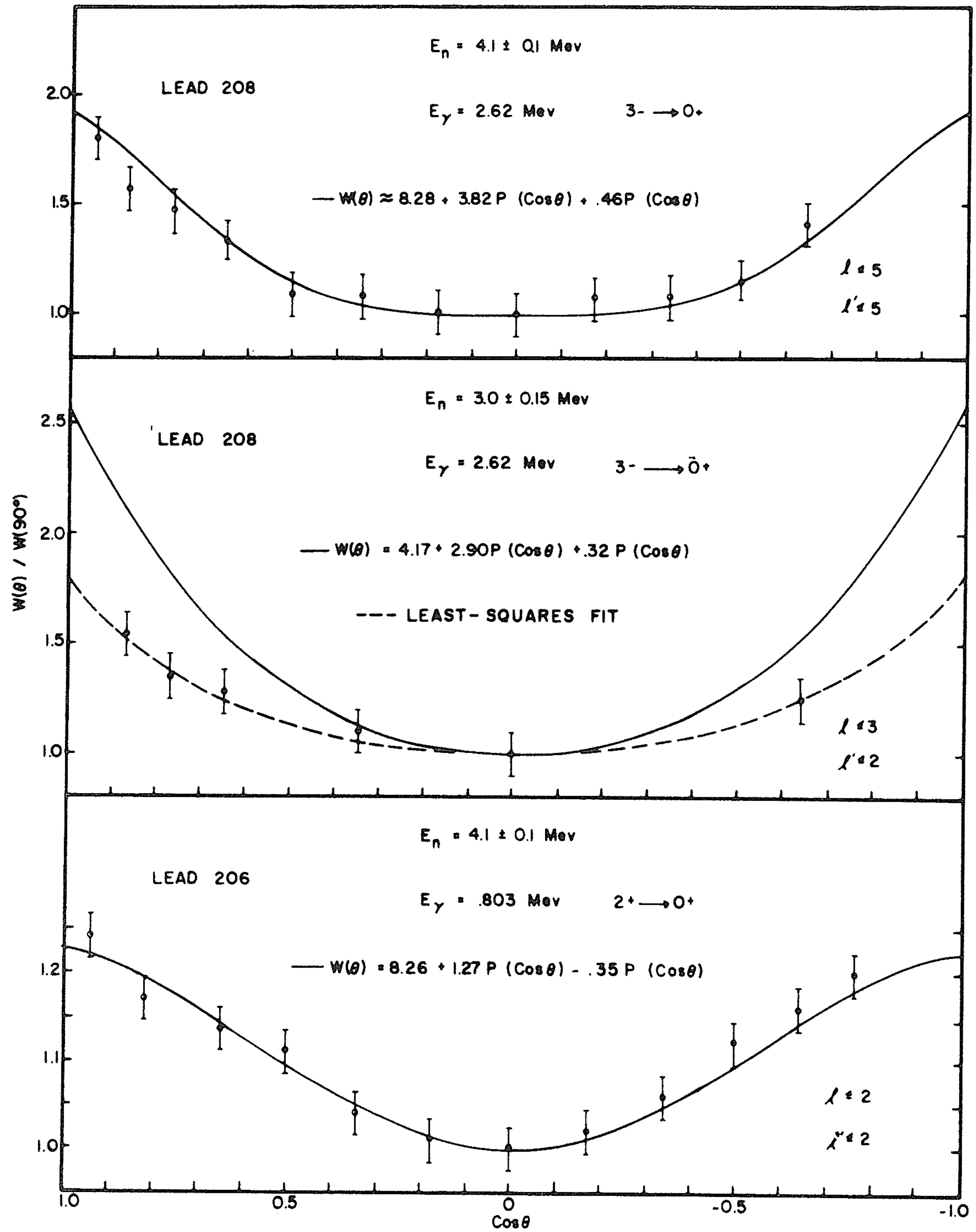
Ring Geometry Arrangement for Studying γ Rays From Neutron Inelastic Scattering.

FIGURE 18

limitations of the older systems are circumvented.

The third limitation, the strong Compton continuum, is largely suppressed by using a detector devised by Raboy and Trail, consisting of a NaI crystal surrounded by a relatively large annular ring of NaI. Anti-coincidence techniques are employed to allow only signals due to those gammas which interact with the inner crystal but not with the outer one to be passed to a multichannel analyzer.

Figure 19 shows typical results obtained with this system for angular distributions of de-excitation gamma rays. These results are compared with calculations from Hauser-Feshbach theory. Computer codes for these calculations have been devised by R. G. Satchler. Two results common to the experimental and theoretical results are worth noting. First, the results are symmetric about 90°, a result of conservation of parity. Second, there can be considerable variation in the cross sections with angle, this variation increasing near threshold for excitation of a particular gamma ray. These points need to be kept in mind when one uses older measurements of inelastic cross sections based on gamma-ray data taken only at 90°, as in the arrangement shown in Figure 18.



Angular Distribution of Gamma Rays Associated with Inelastic Scattering in Lead
I. L. Morgan, private communication

FIGURE 19

VIII. Capture Cross Sections

A very large amount of data on capture cross sections began to appear in about 1955. The popular methods have been sphere transmission, activation measurements, and detection of the gamma rays which accompany the capture process itself.

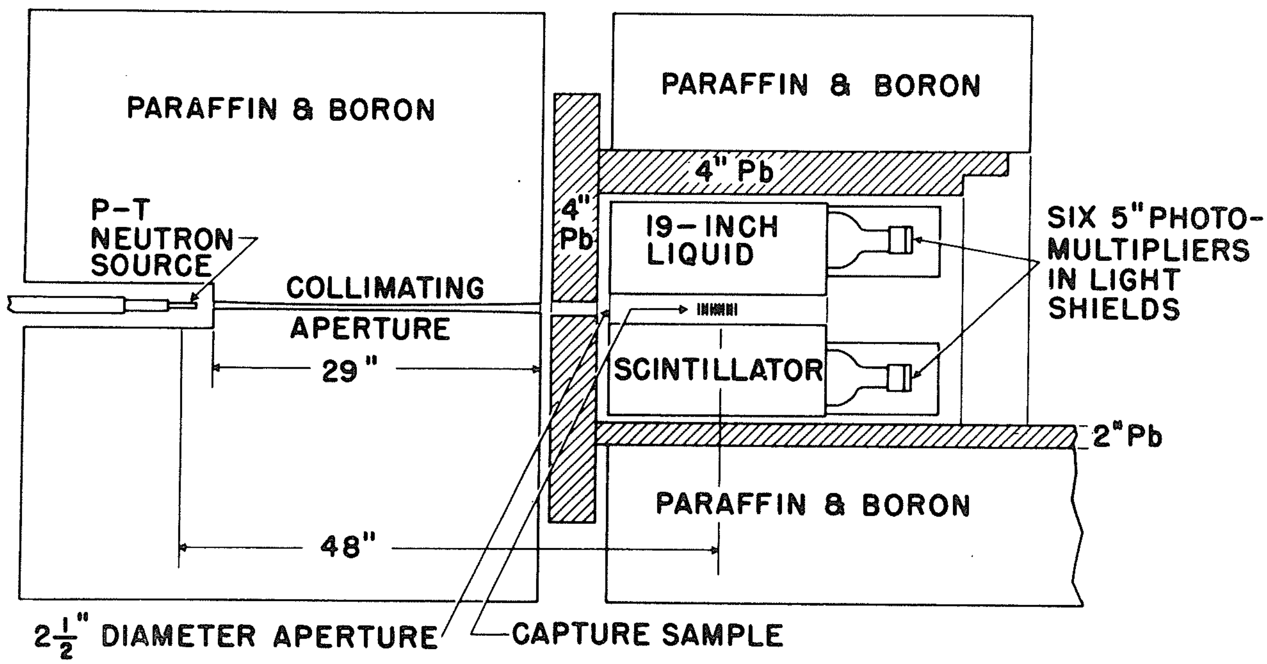
The sphere method has been described previously as a means of measuring non-elastic cross sections. Clearly, when the capture cross section accounts for all the non-elastic cross section, this method gives the capture cross section directly. For almost all nuclei except those which are thermally fissionable, the non-elastic and capture cross sections are equal below the threshold for inelastic neutron scattering. The sphere method has been used to obtain particularly valuable results using the 24 kev neutrons produced by the Sb-Be photoneutron source. Measurements are made of the transmission of spherical shells which enclose the photoneutron source. The detector is some form of boron counter, usually the so-called long counter. The resulting measurements of capture cross sections are thought to be accurate to plus or minus 7 to 10%. Depending as they do on determination of a ratio only, these measurements provide some of the firmest anchor points for normalization of much other data.

Many useful results have been obtained with activation measurements, in which the capture cross section is determined by measuring induced activity and incident neutron flux. Of course this method works only for nuclides which are radioactive, and determination of the incident flux poses severe problems.

The most popular method in recent years, and the one which has produced the largest volume of results, depends on detection of the gamma rays emitted promptly in the capture process. In a typical nuclide these gamma rays may be single or the result of a cascade giving as many as five gamma rays, which carry away the binding energy of the neutron plus its kinetic energy, or a total energy, typically, of about 8 Mev.

One of the most productive approaches to this problem involves the use of large scintillators which enclose the sample almost completely, as shown in Figure 20--an apparatus used by a group at Los Alamos.[15] Large liquid scintillation detectors were pioneered at Los Alamos by Reines and Cowan in connection with their work on the anti-neutrino, and the application of such a detector to the problem of neutron capture was suggested by M. Goldhaber.

Neutrons from an accelerator target travel down the collimator, strike the sample, and are either captured, scattered, or pass through without interaction. If they are captured, the resultant gamma rays are detected by the scintillator, hopefully with efficiency close to 100%. Neutrons scattered into the detector may be captured in it, but by suitable choice of materials in the scintillator these events give a substantially lower energy pulse than the gamma rays from a typical capturing sample, and may be discriminated against on the basis of pulse height. Detectors such as that just described have been used



Schematic of Apparatus Used by a Group[15] at Los Alamos to Observe Capture Gamma Rays

FIGURE 20

successfully with linacs and choppers to cover a wide neutron energy range.

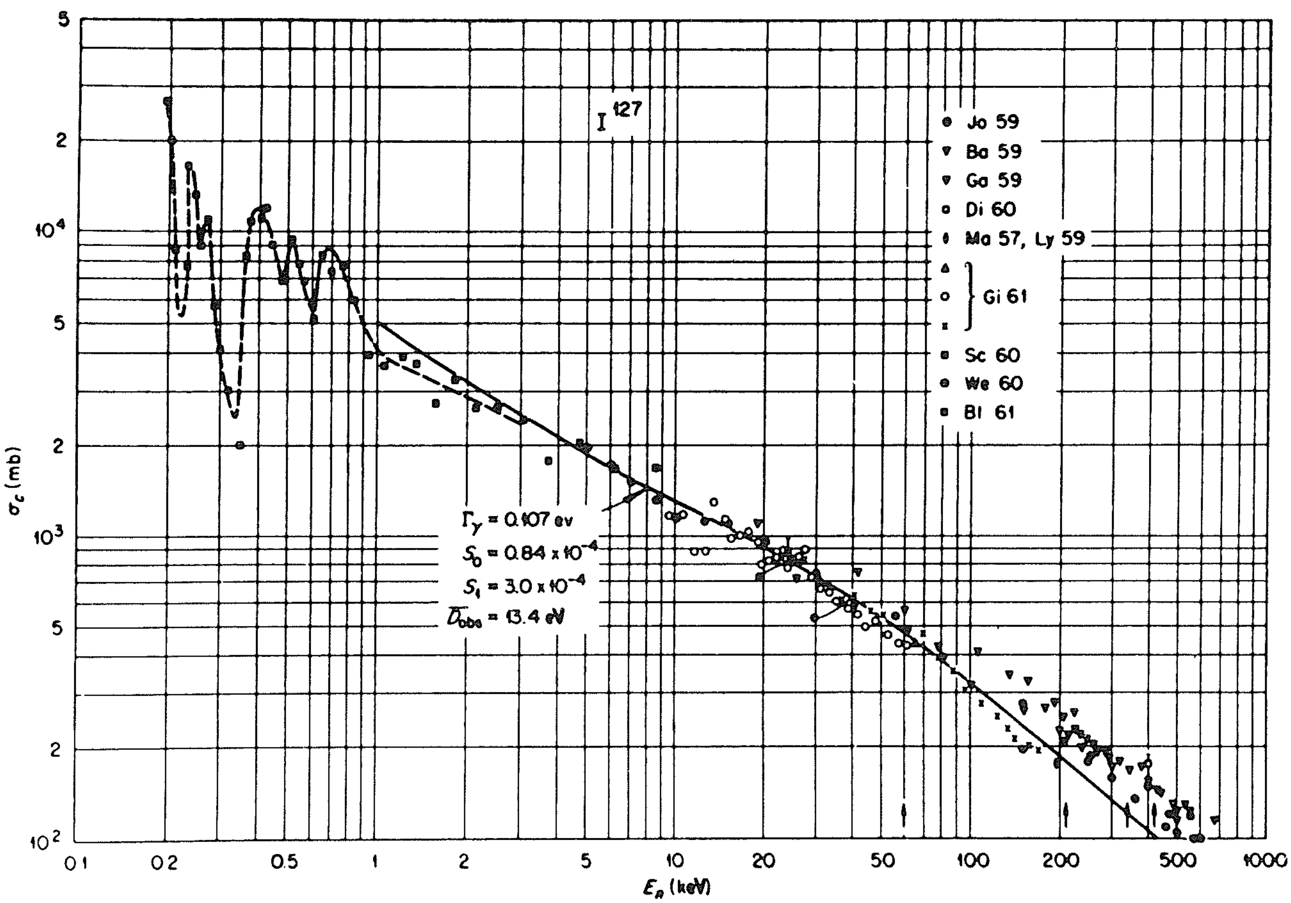
Representative results are shown in Figures 21 and 22 for iodine and gold.

The data for iodine are all quite consistent with one another and with a curve drawn in Figure 21 which represents a calculation based on the statistical model, using average values of resonance parameters obtained from the analysis for total cross section data. The situation with gold, on the other hand, illustrates the larger scatter of results which have been obtained by different workers using different methods. A comparison with a calculation similar to that for the iodine data is also given in Figure 22.

A common method of avoiding a determination of incident neutron flux in this work is to compare the absorption rate in the sample with that in a sample whose cross section is known from sphere measurements at 24 kev. One infers the relative neutron flux at other neutron energies by observing the yield of the B^{10} (n, $\alpha\gamma$) reaction as a function of neutron energy, assuming it has a 1/v dependence.

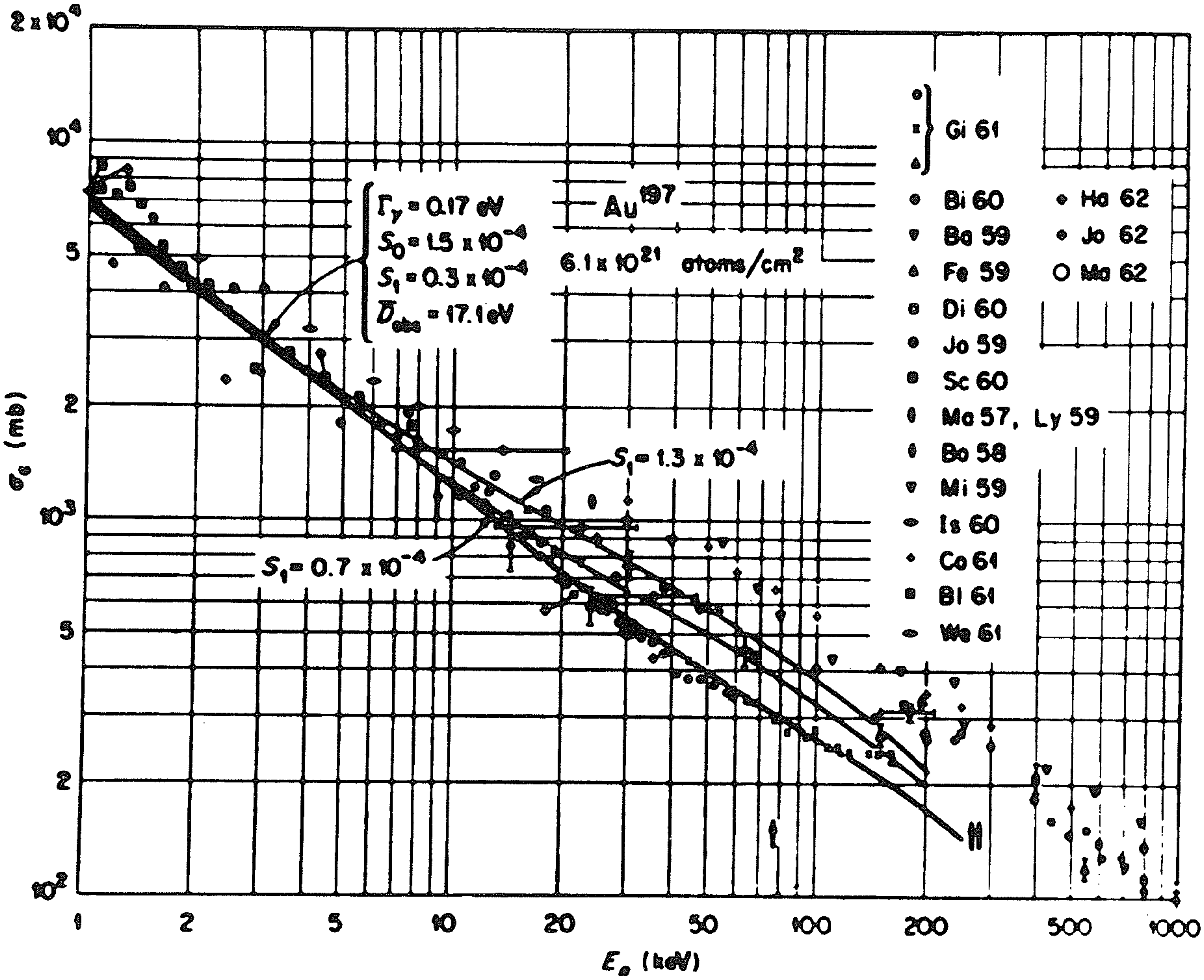
Much attention is being devoted to determining the cross section for the B^{10} (n, $\alpha\gamma$) reaction as a function of energy to facilitate this kind of work.

Another method which has been attracting increased interest involves use of the so-called Moxon-Rae detector (reference 7, p. 439). This represents a novel and ingenious method of determining the yield of capture events. The detector has an efficiency



Various Experimental Results for the Capture Cross Section in I-127. The Solid Line was Computed Using Known Resonance Parameters and the Optical Model. From Reference 4, p. 1740.

FIGURE 21



Various Experimental Results for the Capture Cross Section in Au-197
From Reference 4, p. 1737.

FIGURE 22

of only a few percent but it is extremely simple to use. It is particularly effective with time-of-flight systems because its time resolution of 2-3 nsec. compares very favorably with the 10 or 20 nsec. for the large scintillators.

Essentially the Moxon-Rae detector consists of a thick slab of low Z material in contact with a thin slice of scintillator. Gammas are converted to electrons in the thick slab and the recoil electrons or pairs are detected in the scintillator. In effect, the device works like a thick-walled Geiger counter as used for the detection of gamma rays. Its distinctive and essential feature is that its efficiency is closely proportional to gamma-ray energy. This is due to the fact that the range of electrons in the converter is proportional to gamma ray energy, so that the more energetic gamma rays are detectable in a greater thickness of converter. This proportionality between efficiency and gamma ray energy plays a crucial role in making the efficiency for detection of capture events independent of the multiplicity of the gamma rays produced in a capture event. This can be seen as follows. The probability of detection of a given capture event will be proportional to the product of $m\epsilon$, where m is the average multiplicity and ϵ is the efficiency of detection of a gamma ray averaged over gamma-ray energy. Since ϵ is proportional to the energy of the gamma ray detected, and m is inversely proportional to this energy, the probability of detection should be independent of multiplicity.

Of special interest to the reactor physicist is capture in the fissionable nuclides. Here the problem is to sort out fission events from capture since both produce prompt gamma rays which are comparable in total energy and multiplicity. Two procedures are used here, each of which is a variant of the large liquid scintillator method. In one method, the fissionable material is spread on the plates of an ionization chamber which is centered in a large liquid scintillator. If a fission event occurs, there is a chamber pulse in coincidence with a scintillator pulse, whereas in capture the chamber pulse is absent. In the other method, advantage is taken of the fact that when a fission event occurs, neutrons are released and, after moderation in the scintillator, are captured, typically in a few microseconds, so that there is a pulse available for detection after the prompt pulse due to fission gamma rays. This after-pulse also occurs if a neutron is scattered by the fissionable material, but there is then no prompt pulse. In these measurements also, beam pulsing is used with monoenergetic or continuous energy neutrons either to reduce background or to allow one to cover a range of neutron energies simultaneously.

These sorts of measurements give not only the capture cross sections for the fissionable nuclides but also the quantity reactor physicists call α, the ratio of capture to fission.

IX. Fission

The characteristics of nuclear fission which are of particular interest to reactor physicists are the spectrum and number of neutrons from fission and the fission cross sections themselves.

The spectrum of neutrons from fission of U-235 was measured by a group at Los Alamos[16] in the mid-fifties. This was not the first measurement, but warrants discussion since many later measurements have been normalized to those results.

Rosen and Frye used nuclear emulsions to cover the range from 0.35 to 12 Mev, and Nereson and Cranberg covered the range from 0.175 Mev to 2.7 Mev by timing methods, using U-235 in a spiral ionization chamber. Zero time was obtained from the fission pulse in the chamber. The simplest way of stating the results is in the form of a distribution per unit energy interval

$$n(E) \alpha \ E^{1/2} e^{-0.775E}$$

where E is neutron energy in Mev.

If these measurements were done today they would probably be done much more rapidly with pulsed-beam methods using a small solid piece of U-235 as the sample. The calibration of the energy-sensitivity of the detector would be done not by comparison with a long counter, assuming the long counter has an energy response which is flat with energy, as was done at the time, but by calibration against n-p scattering, which is far more reliable. Perhaps this will be done one day when need is felt for a more accurate spectrum of fission neutrons.

Some variation in the shape of the fission neutron spectrum has been reported from one fissionable nucleus to another, for example in Pu-239, but this variation appears to be small. Such effects could be much more thoroughly investigated with the new methods.

Determinations of the average number of neutrons per fission, $\bar{\nu}$, have long been of keen interest to reactor physicists. The data appear to be reasonably well represented in most cases by a linear variation of $\bar{\nu}$ with incident neutron energy, the slope being dependent on the fissioning nuclide. Much careful effort has been expended on the determination of this quantity, most recently by Colvin and Sowerby[17] at Harwell. They use a so-called "boron pile," which is actually a cubic graphite lattice 2.2 m on edge, in which is buried a large number of boron counters.

This assembly constitutes a neutron detector with an efficiency of about 65% over the energy range from 0.19 to 4.9 Mev. A fission ionization chamber at the center of the pile is irradiated by slow neutrons from a pile or fast neutrons from a Van de Graaff. Delayed coincidences are detected between the fission events in the chamber and the counts from the boron counters due to fission neutrons which have been moderated in the pile. The efficiency of this arrangement has been determined with great care by using the so-called associated-particle method. In this method, the fission chamber is replaced by a fast ionization chamber containing a gaseous deuterium compound, and the latter is irradiated with monoenergetic photons from a radioactive source or from a Van de Graaff. Each time a deuteron is photodisintegrated a neutron is released into the pile, and the associated proton recoil appears in the counter and is counted. By suitable choice of gamma-ray energy the range of neutron energies indicated above was covered.

The most recent value for $\bar{\nu}$ from this work for thermal neutrons and U-235 is 2.429$\pm$0.018, according to a communication[17] dated 1963, and results of the various workers appear to be in agreement within their claimed errors.

Measurements of $\bar{\nu}$ have also been made with a large liquid scintillator such as has been described in the work on capture. Here the neutrons from fission are moderated by the hydrogen in the scintillator and are captured within about 10 microseconds by a heavy element in the solution such as cadmium, giving a readily detected capture pulse of 9 Mev. The efficiency of the detector in this case is determined by placing a small proton recoil detector in the middle of the large liquid scintillator. The number and energy of neutrons scattered into the large liquid scintillator is given directly by the number and height of the pulses in the recoil counter. The determination of detector efficiency depends, of course, on the well-known n-p differential cross section.

Measurements of $\bar{\nu}$ for U-235 and other fuels are of direct interest to reactor physicists. On the other hand, an accurate value for $\bar{\nu}$ for Cf-252 is of direct interest to the physicist who wishes to construct neutron sources of known intensity, because an observation of the spontaneous fission rate of Cf-252 together with an accurate measurement of $\bar{\nu}$ provides one with a source of neutrons of accurately known intensity. It is on this account that Colvin and Sowerby's measurement[17] of $\bar{\nu}$ for Cf-252 is of interest, and their value of 3.780 ± 0.024 gives us a basis for constructing neutron sources whose strength is known to better than 1%.

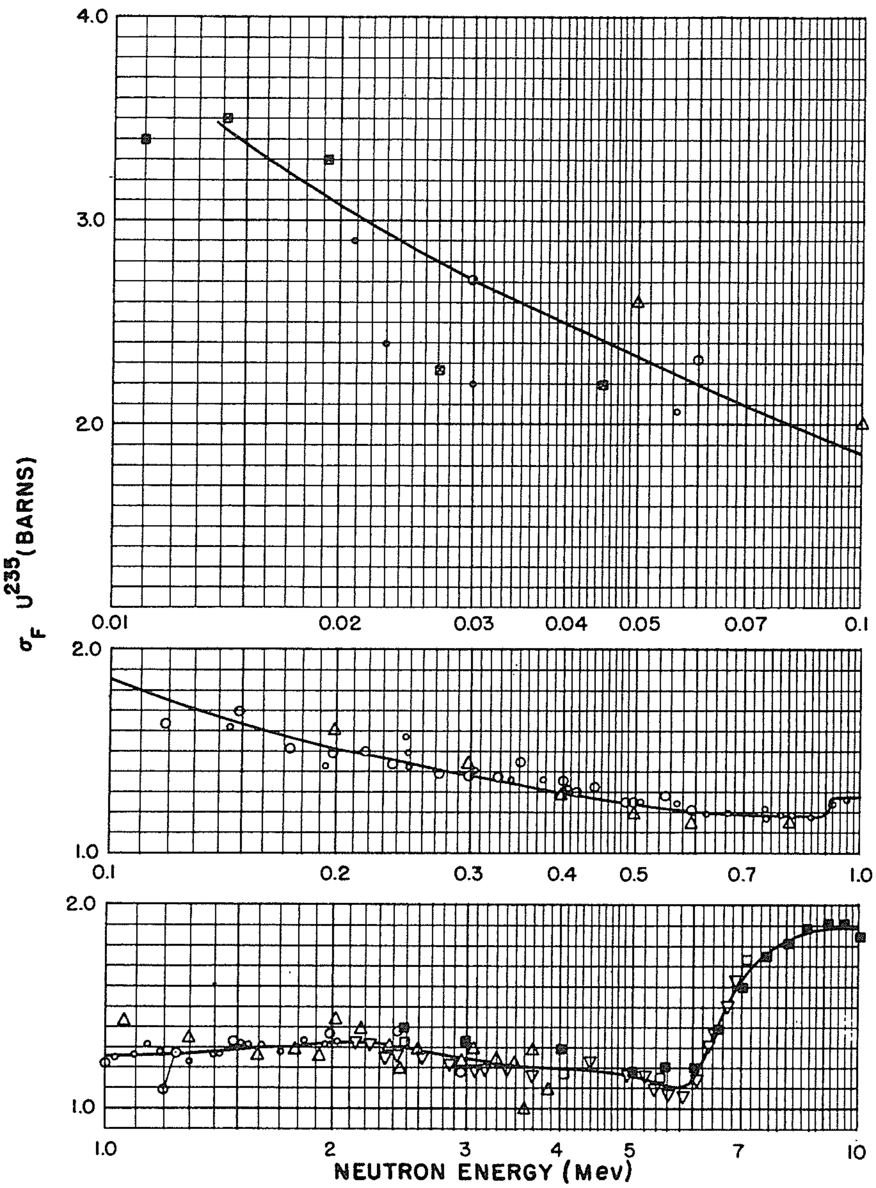
The determination of fission cross sections for fast neutrons presents special problems. For thermal fissioning materials such as U-235 it is necessary to cover the complete range of neutron energy, and one must bridge the gap between the regions in which the B^{10} (n, $\alpha\gamma$) and the n-p cross sections serve presently as standards. This gap extends from 1 kev to about 100 kev. Thus one is left with the choice of measuring the incident flux, extrapolating from established standards, or establishing new standards in the gap region. Doubtless this means that U-235 itself will become a standard. Indeed, it already has been widely used as a basis of comparison, but must become better known itself.

How confusing the situation is with respect to the fission cross section of U-235 is indicated by the following quotation from Henkel's review in Marion and Fowler's book (reference 4, p. 2011).

"The one experiment which serves to connect low energy data with the fast neutron measurements is the work of Yeater, Mills, and Gaertner at KAPL in which the U-235 excitation function was measured for neutron energies of 6 ev and 2000 ev. A velocity selector was used in conjunction with the KAPL 100 Mev betatron as the neutron source, and the U-235 fission cross section was measured relative to the B-10(n, $\alpha\gamma$) cross section, assuming the latter obeys the 1/v law. The fission cross section was referred to the absolute value between 0.3 and 0.7 ev (Hu55)."

The reference (Hu55) is to the Brookhaven compilation. Looking at the most recent BNL compilation shows the data for U-235 with a caption headed "normalized to 582 barns at 0.0253 ev", with no explanation given for the basis of choice of the normalizing value. The references in BNL 325 to thermal cross sections for U-235 are to two unpublished results and a French result in a conference proceeding which I have not yet located. Much of our present knowledge of the fission cross section of U-235 for fast neutrons is summarized in Figure 23.

The U-235 fission cross section data clearly leave much to be desired. There is now a program under way at Los Alamos, among other places, to produce improved results using pulsed-beam techniques. There will doubtless be more normalizations to the n-p cross section in the Mev region in addition to the several which have already been done. And Batchelor at Aldermaston has promised (reference 6) to make sphere measurements on B^{10} to obtain much needed data on this cross section so that it may be used to determine fission cross-sections by comparison in the range 1 kev to 100 kev.



From Reference 4, P. 2012
FIGURE 23

X. Conclusion

Despite the frequently made allegation that neutron flux measurements are fundamental to the measurement of neutron cross sections, it is clear from what has been said that this is not so, and that in fact neutron cross section measurement rests on comparisons with a few scattering and reaction cross sections, in particular those for n-p scattering, for $B^{10}(n, \alpha\gamma)$, and for capture in some of the heavy elements, all of which are inferred from ratio measurements. Apparently it is only for determination of $\bar{\nu}$, a pure number, not a cross section, that an absolute neutron flux has been determined with any precision.

From the point of view of systematic data it appears that the needs of the reactor physicist are being rapidly fulfilled. From the point of view of precision and accuracy much remains to be done, particularly in the energy range from 1 kev to 100 kev. It seems probable that these data will be available soon after some reliable reference has been established in this energy interval.

If I may close this talk with a prediction, perhaps it will not be too rash to say that by the year 1970 the fast reactor physicist may be satisfactorily supplied with the nuclear information he needs on the basis of experimental data alone.

The rapid development of pertinent theory and calculational technique offers the additional prospect that a comprehensive description of neutron interactions with nuclei will be available which will allow systematic and reliable calculations to be made where experimental data may still be lacking.

References

1. Harry Gove, Physics Today 17, 44 (1964).

2. S. Yiftah, D. Okrent and R. A. Moldauer, Fast Reactor Cross Sections, (Pergamon Press, London, 1960).

3. J. B. Marion and J. L. Fowler, eds., Fast Neutron Physics, Part I (Interscience Publishers, New York, 1960).

4. J. B. Marion and J. L. Fowler, eds., Fast Neutron Physics, Part II (Interscience Publishers, New York, 1963).

5. G. C. Phillips, J. B. Marion, and J. B. Risser, Progress in Fast Neutron Physics (University of Chicago Press, Chicago, 1963).

6. Symposium on the Absolute Determination of Neutron Flux in the Energy Range from 1-100 kev, St. Johns College, Oxford, EANDC-33U.

7. J. Spaepen, ed., Neutron Time of Flight Methods (Euratom,1961).

8. B. T. Feld in Experimental Nuclear Physics, Vol. II, Part 7, ed. by E. Segre (John Wiley, New York, 1953).

9. H. H. Barschall, Rev. Mod. Phys. 24, 120 (July, 1952).

10. Lawrence Cranberg, R. D. Moffatt and R. K. Smith, LA-1654 (April, 1954).

11. H. A. Bethe, J. R. Beyster, and R. E. Carter, Journal of Nuclear Energy 4, 3, 147 (1957).

12. J. H. Coon, R. W. Davis, H. E. Felthauser and D. B. Nicodemus, Physical Review 111, 250 (1958).

13. B. Jennings, J. Weddell, I. Alexeff, and R. L. Hellens, Physical Review 98, 582 (1955).

14. L. Cranberg, C. D. Zafiratos, J. S. Levin and T. A. Oliphant, Physical Review Letters 11, 341 (October 1, 1963).

15. B. C. Diven, H. C. Martin, R. F. Taschek, J. Terrell, Physical Review 101, 1012 (1956).

16. L. Cranberg, G. Frye, G. Nereson, and L. Rosen, Physical Review 103, 662 (1956).

17. D. W. Colvin, M. G. Sowerby, Document EANDC (UK) 30U, 1963.

18. Herbert Goldstein, _The Theory of Fast Neutron Cross Sections_, to be published by the Michigan Memorial-Phoenix Project.