# THREE DECADES OF FAST-NEUTRON EXPERIMENTS

Measurements of neutron cross sections and spectra have improved from the early days of homebuilt equipment through the war time developments in the Manhattan District to the present use of commercial accelerators and electronics.

HENRY H. BARSCHALL

EXPERIMENTS WITH NEUTRONS in the MeV region are important both for learning about properties of nuclei and for applications in nuclear technology; yet relatively few nuclear physicists work in this area. The reason may be that experiments with neutrons are more difficult than those with charged particles, because neutrons can neither be accelerated nor detected directly. Consequently the accuracy of fast-neutron experiments is typically an order of magnitude poorer than that of charged-particle experiments. This comparison partially reflects the enormous advances of recent years in charged-particle experiments, particularly with solid-state detectors.

For charged-particle interactions, cross sections can be measured to 2% easily and with great effort to 0.1%. Comparable accuracy for fast neutrons has been achieved only for total cross sections that can be measured in simple transmission experiments, but not for partial or differential cross sections. Even the cross sections of the heaviest elements, which are of great importance in nuclear-technology applications, are not very well known in spite of many attempts to measure them accurately; they include the fast-neutron fission cross sections and radiative-capture cross sections. Measurements of fission cross sections at different laboratories often differ by more than 10%, radiative-capture cross sections by 50% and those for less important nuclides even by a factor of two.

My own interest in fast-neutron physics dates back almost to its beginning. I shall attempt here only to reminisce about developments with which I had direct contact, and will not attempt to give a complete review, nor to give credit to all those who made these developments possible.

In reading Hans Bethe's review article[1] of 1936–37, one is impressed by how much Bethe knew about the interaction of neutrons with nuclei less than five years after the discovery of the neutron. In fact he describes most of the basic phenomena in neutron physics with the notable exception of fission, which was not discovered until two years later. On the other hand, quantitative measurements on neutron interactions had hardly been started then; they required important technological advances, some of which I shall discuss.

## *Experimental methods around 1940*

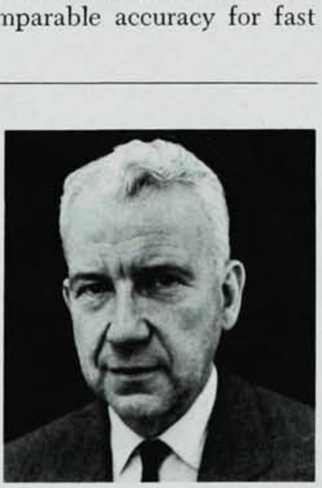
My contact with neutron physics began more than 30 years ago at Princeton when my thesis adviser, Rudolf Ladenburg, introduced me to his neutron generator, which he had recently acquired with funds from the Rockefeller Foundation. It was an impressive installation. Most visible was a huge 400-kV dc power supply that served to accelerate deuterons onto a $D_2O$ ice target. Neutrons with energies between 2 and 3 MeV were produced in the reaction.

$$D + D \rightarrow He^3 + n$$

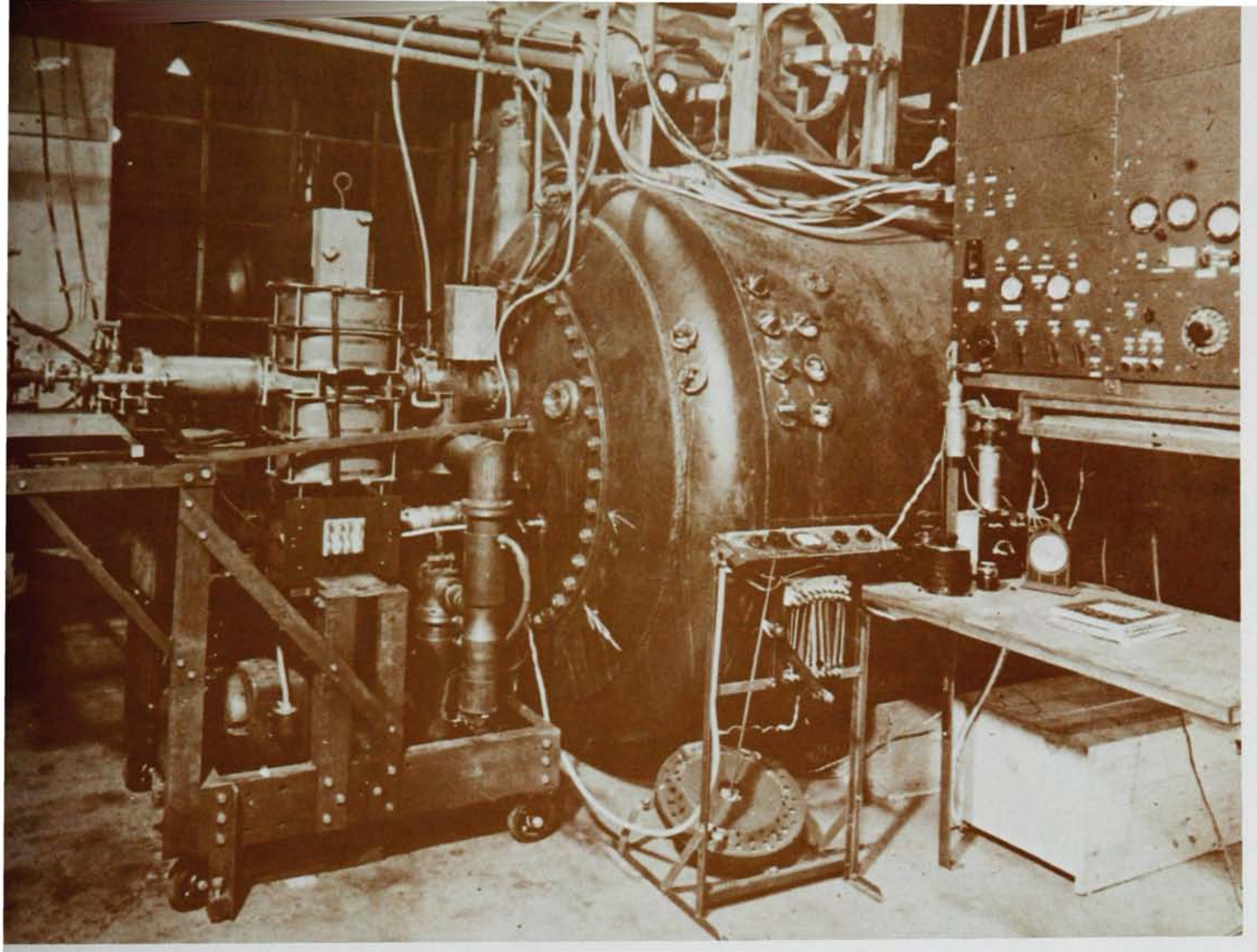
which is still a common source of neutrons.

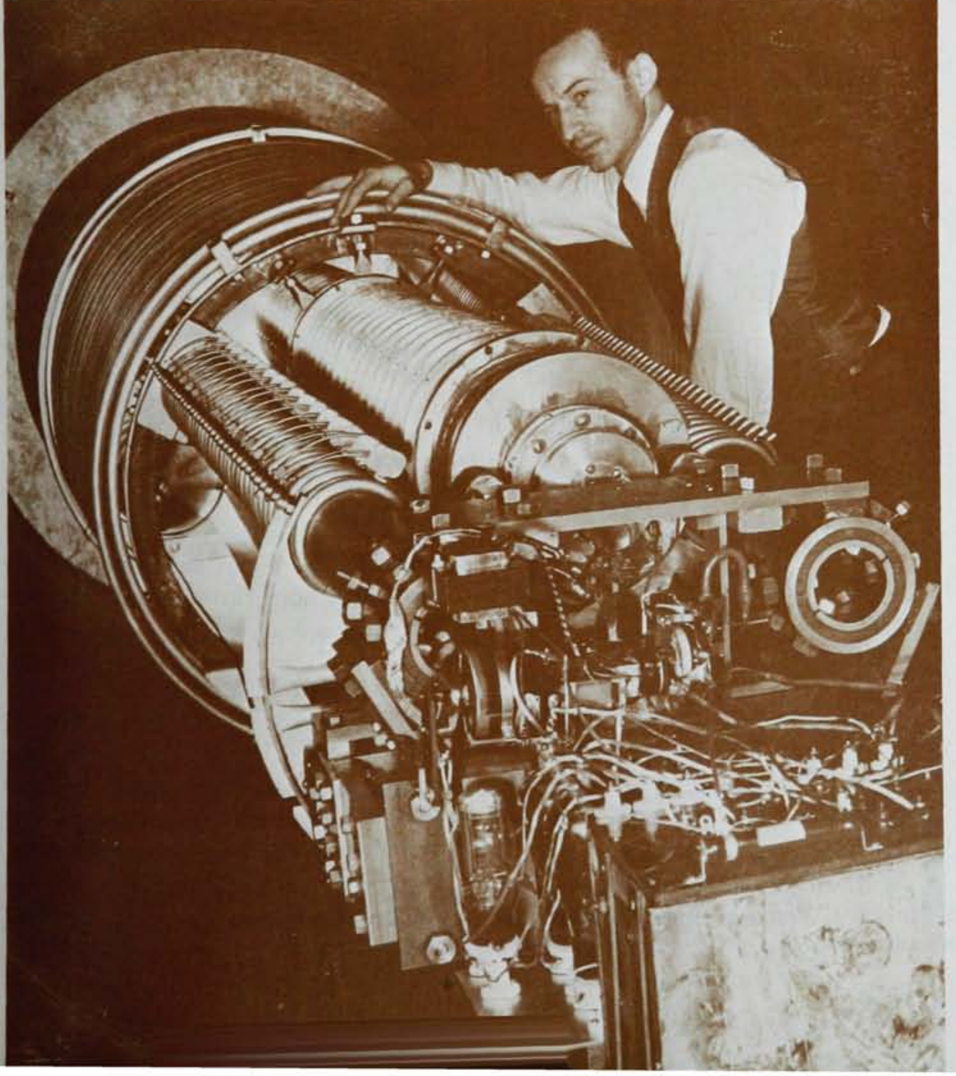
30 years ago neutron experiments were far more difficult than they are nowadays. Very little commercial high-vacuum equipment was available. We used homemade diffusion pumps. We found leaks in the vacuum system by observing the color and appearance of a gas discharge and sealed the leaks with glyptal or homemade sealing wax. Because we did not have dosimeters for determining the radiation level, we used a piece of glass that had been covered with fluorescent material. If, in the darkened room, we could see the bones of our hand when we placed it behind the glass, we concluded that the radiation level was too high and that a leak required fixing. We did not even worry about the radiation hazard from neutrons, although we sat quite close to the unshielded neutron source. Fortunately for us the source was not strong enough to be a very serious hazard.

The lack of commercial electronics was the most serious difficulty in performing neutron experiments, and we had to build our own amplifiers



The author is a professor at the University of Wisconsin at Madison, where he has been since 1946. He took his MA and PhD at Princeton University before going to Los Alamos in 1943. Barschall received the Bonner Prize of the American Physical Society and is a past chairman of the APS Division of Nuclear Physics.





THE "LONG TANK" completed at the University of Wisconsin, Madison, in 1940. This electrostatic accelerator yielded protons and deuterons with energies from a few hundred keV to about 4 MeV. On left R. G. Herb, who designed the accelerator, stands in it with its end/plate removed. —FIG. 1

and scalers. The most time-consuming activity was the endless struggle to reduce 60-cycle pickup and microphonic noise. There were no pulse-height analyzers. Instead we used a mechanical galvanometer that we also made ourselves. The deflections of a light beam were recorded on a photographic film and measured with a magnifying glass.

Although these experimental methods were primitive by current standards, the theoretical understanding of neutron interactions was very good. For example a measurement[2] of the pulse-height distribution of alpha particles recoiling from the impact of 3-MeV neutrons was readily and correctly interpreted by John Wheeler,[3] who concluded that spin-orbit forces were very large in nuclear interactions. This was in 1940. It was a decade before this fact was fully appreciated in the development of the shell model.

### *Discovery of fission*

In January 1939 Niels Bohr, who had just arrived from Europe, told us about the discovery of fission and asked us to demonstrate the phenomenon to him in our laboratory at Princeton. Even with our primitive tools it took only a short time to show him the large pulses produced in an ionization chamber when uranium was bombarded by fast neutrons. Bohr and Wheeler then suggested several experiments, which we undertook, to test their theory of fission.

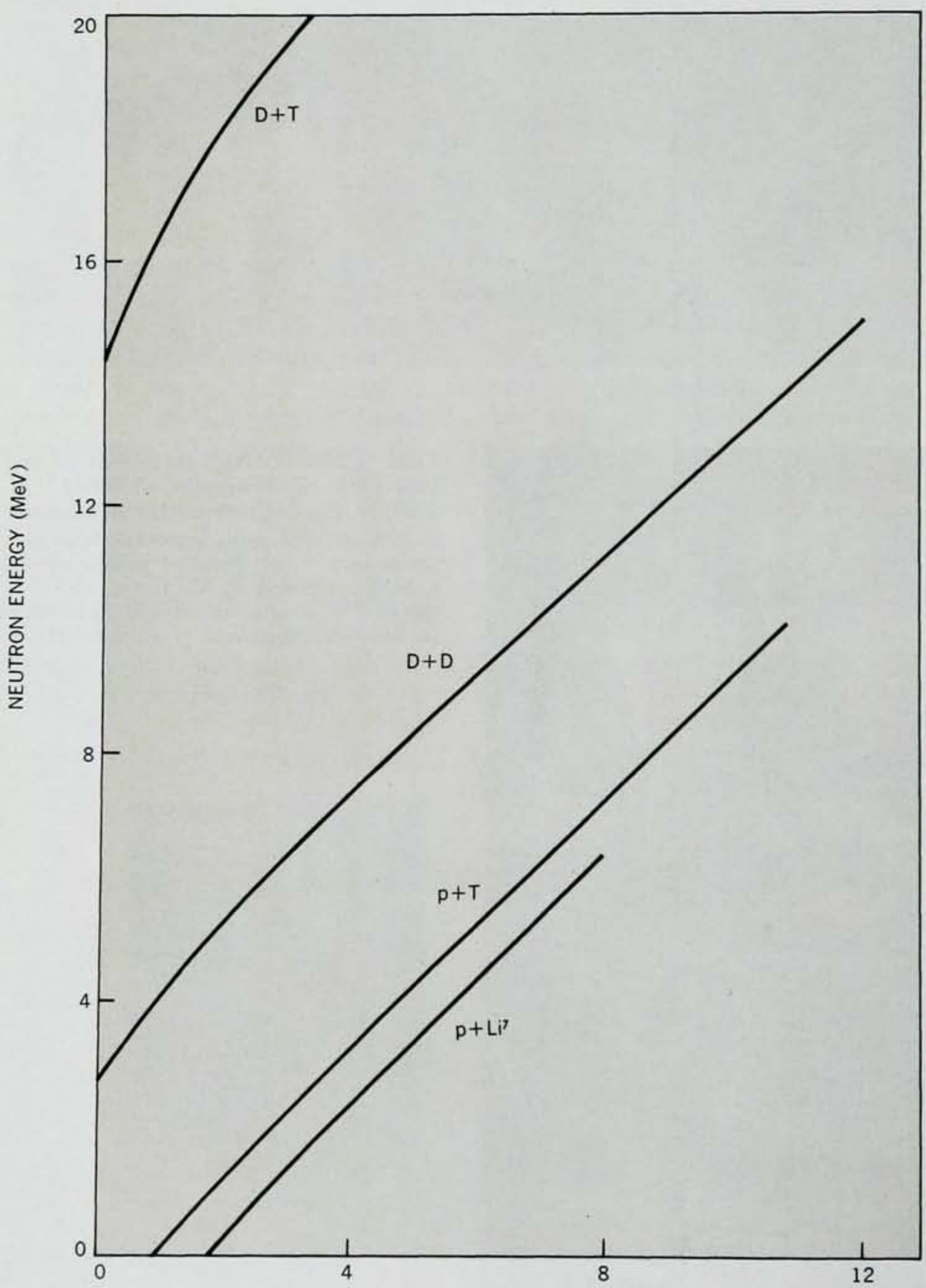
I submitted my first abstract to an American Physical Society meeting that was held in May 1941 in Washington. The abstract[4] reported measurements of cross sections for the elastic and inelastic scattering of neutrons by aluminum, iron, copper and lead. During the meeting, shortly before I was scheduled to present my paper, someone suggested to me that for security reasons I should not give it. I did not take this advice, because I could not see the connection between my experiments and national security, and because all the measured cross sections had been published in the abstract.

When I submitted the same results to *The Physical Review* the paper was accepted but did not get published, again for security reasons. I pointed out that the results had already been published in an abstract and finally, eight months later, the paper appeared.[5] Eight months seemed a very long delay then, when *The Physical Review* usually published papers less than two months after submission.

Shortly after the 1941 Washington meeting I had to abandon research in neutron physics. I could still go to the laboratory to fix equipment, but could not participate in the experiments. I had to wait over two and a half years before resuming my contact with neutron physics. Although enemy aliens were not usually naturalized in wartime, in July 1943 the district judge of Douglas County, Kansas, (where I lived at the time) received during his vacation a request, which had originated with the Manhattan District of the Corps of Engineers, to hold a special naturalization hearing. Soon after I was naturalized I went to Los Alamos and discovered why scattering of fast neutrons by heavy elements had become a classified subject and why there was an urgent need for knowing more fast-neutron cross sections.

### *Wartime advances*

At Los Alamos I learned of technological advances that had profoundly changed neutron physics. Remarkable advances in electronics had resulted from the development of radar. New, much faster, amplifiers were no longer sensitive to 60-cycle pickup and microphonics.




ENERGIES OF NEUTRONS emitted in the forward direction, from the reactions listed in the table on page 57, for various bombarding energies. —FIG. 2

The most important advance was, however, the development of a neutron source with easily variable energy, made possible by the work of Ray Herb at the University of Wisconsin at Madison. He had constructed two electrostatic accelerators, known under the code names "short tank" and "long tank," which had been secretly moved from Madison to Los Alamos. The long tank (see figure 1) could accelerate protons and deuterons to energies from a few hundred keV to about 4 MeV. By bombarding targets with these protons and deuterons, neutrons of variable energy could be produced.

**Neutron-producing Reactions**

| | | |
|---|---|---|
| D + D | $\rightarrow He^3 + n +$ | 3.3 MeV |
| $p + Li^7$ | $\rightarrow Be^7 + n -$ | 1.6 MeV |
| p + T | $\rightarrow He^3 + n -$ | 0.8 MeV |
| D + T | $\rightarrow He^4 + n +$ | 17.6 MeV |

The table above shows the most common reactions used as sources of monoenergetic neutrons. Figure 2 shows the energies of neutrons emitted from these reactions in the forward direction. With the reaction

$$p + Li^7 \rightarrow Be^7 + n$$

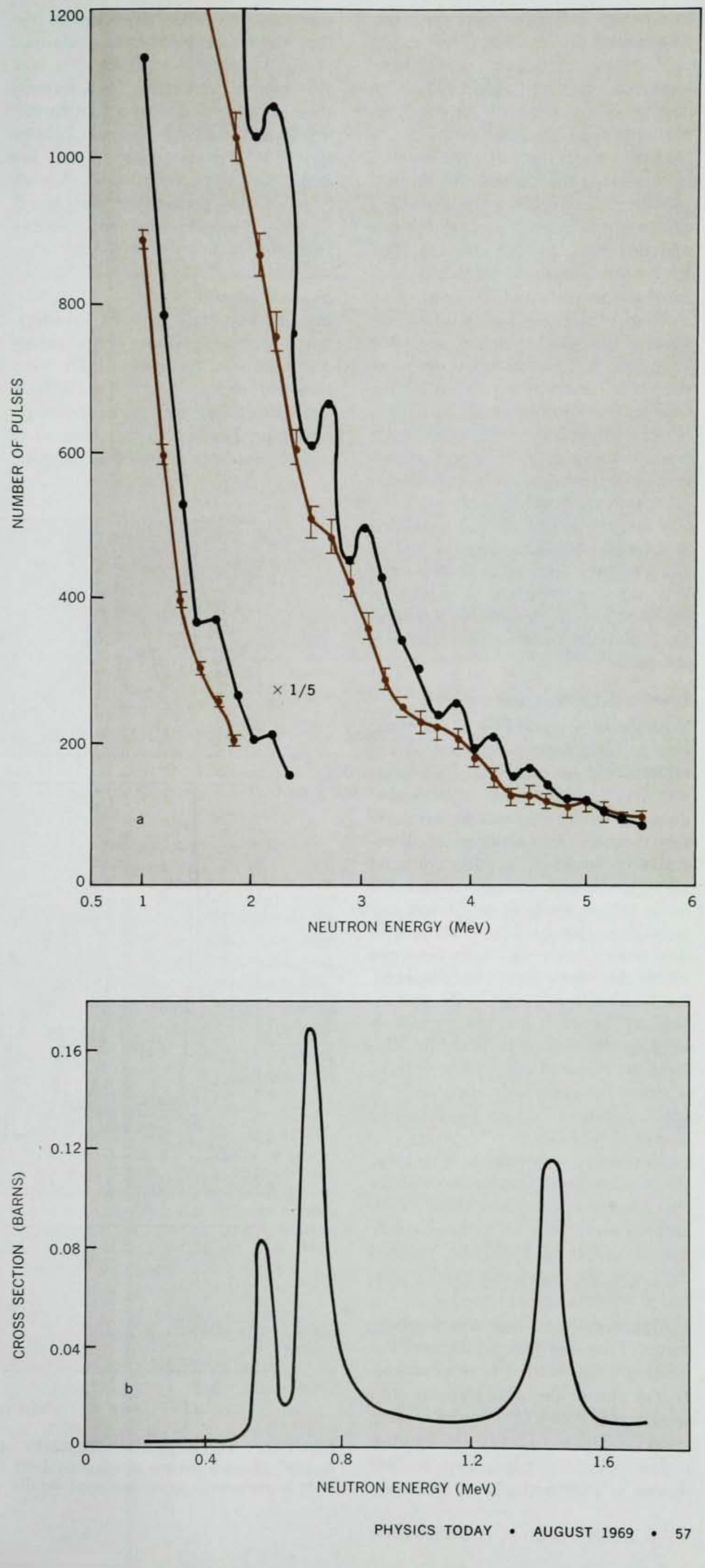
it was possible to produce neutrons up to about 2 MeV, and with the reaction

$$D + D \rightarrow He^3 + n$$

neutrons with energies between 3 and 6 MeV. The enormous advantage of this method for investigating the energy dependence of neutron interactions is illustrated in figure 3. It shows the results of two measurements on the reaction

$$n + N^{14} \rightarrow C^{14} + p$$

One of them was carried out at Hanford[6] with a radioactive neutron source




**DISINTEGRATION OF NITROGEN by neutrons according to measurements carried out in 1945. Top graph (a) shows distribution of pulse heights observed at Hanford when nitrogen is bombarded by neutrons with a continuous energy spectrum. Colored line is with $NH_4NO_3$ absorber; black line is without absorber. Note change in scale at 2 MeV. Lower graph (b) shows cross-section measurement, again for nitrogen, at Los Alamos with a source of neutrons of variable energy. —FIG. 3**

that produced a continuous spectrum. The energy distribution of the resulting distintegrations was observed in an ionization chamber (figure 3a). The wiggles in the pulse-height spectrum are attributed to resonances in the reaction. Cross sections were deduced by observing the decrease in the amplitude of the wiggles when a nitrogen absorber was inserted between source and detector. In this way the Hanford workers thought they had measured a cross section of 60 barns.

Concurrently, at Los Alamos, we studied the same reaction with the long tank, but neither group knew of the other's measurements until later. Our results[7] are shown in figure 3b. It was surprising to see such large peaks in fast-neutron cross sections, although large resonances had previously been observed for slow neutrons.

When the long tank was scheduled to return to Madison after the end of the war, I was anxious to go there also to continue to work with it on neutron experiments. I applied for a job at the University of Wisconsin and was accepted.

### *Improved neutron sources*

With the Li + p and D + D reactions, only a limited range of neutron energies could be reached. Two postwar developments made it possible to produce, with electrostatic accelerators, monoenergetic neutrons at all energies up to 30 MeV. First, around 1950, the Atomic Energy Commission made tritium available as a target material. By bombarding tritium with deuterons, neutrons with energies above 14 MeV could be produced. By bombarding tritium with protons the gap between the two previously used reactions could be bridged. The latter source is strictly monoenergetic, whereas the previously used Li + p reaction turned out to produce two groups of neutrons.

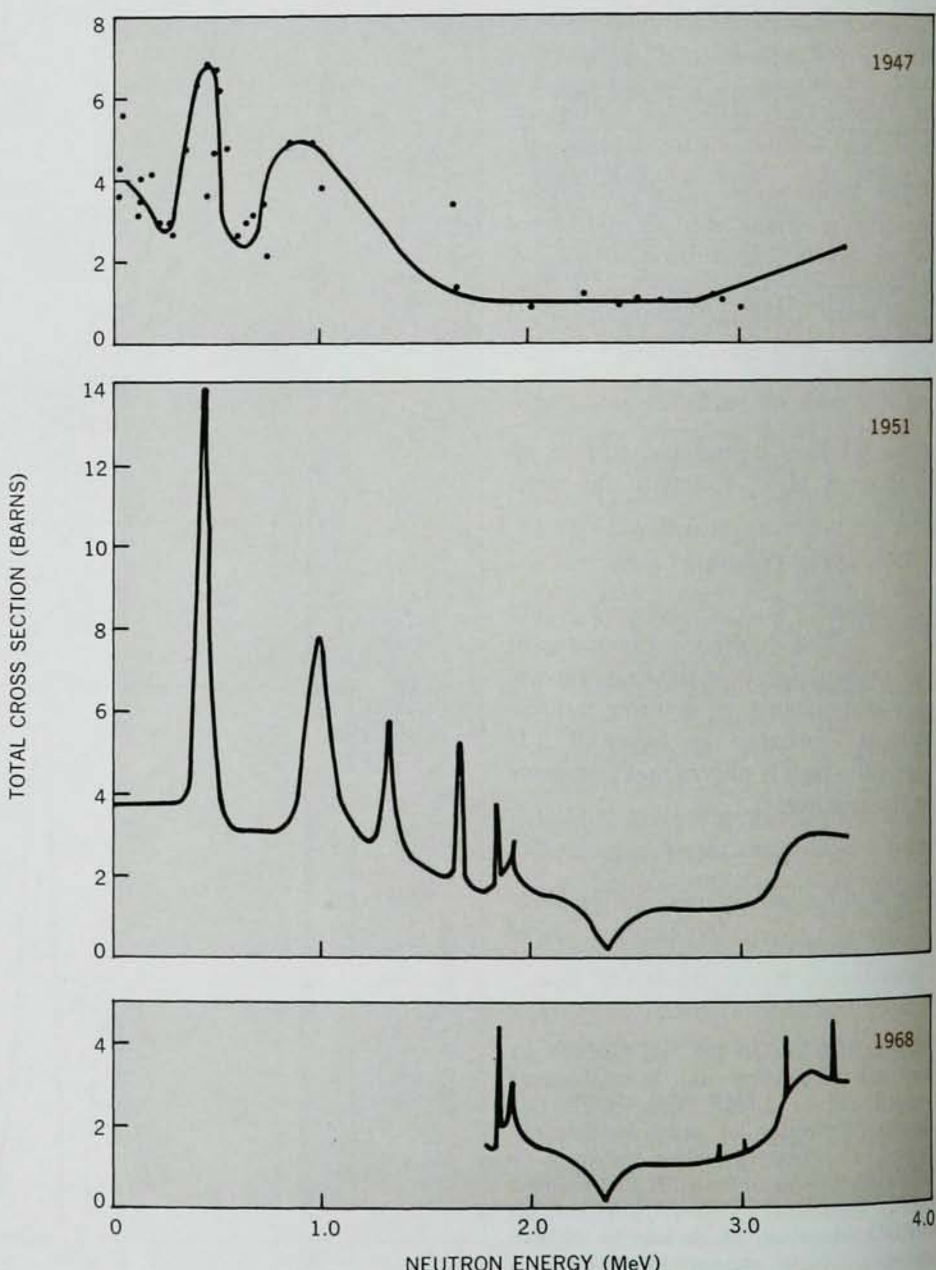
The second important new tool was the tandem electrostatic accelerator that became operative in 1958. With such an accelerator twice the charged-particle energies could be reached than with the previously used single-ended accelerators.

Figure 4 shows how the measurements of the energy dependence of fast neutron cross sections have advanced. It is a plot of the total neutron cross section of $O^{16}$ as a function of neutron energy. The top part of the figure is a data collection taken from a 1947 review article[8] and shows what was known at that time. The center portion shows measurements, performed at our laboratory[9] in 1951, that contain many more details. Just recently these measurements have been further refined at Oak Ridge National Laboratory,[10] where new sharp peaks, less than 1 keV wide, were found. Knowledge of the position of the levels, found in charged-particle experiments, aided the discovery of these peaks.

### *Neutron spectra*

Another important type of investigation is the measurement of the energy distribution of neutrons. Early measurements of such spectra were difficult and tedious, because the ranges of recoiling protons had to be measured in a cloud chamber or in a photographic emulsion. For slow neutrons a much more convenient method had been available for some time, that is, the measurement of distribution of flight times over a known distance. The flight times for fast neutrons were too short for the detectors and the available electronics until about 1950. Then organic scintillators and advances in electronics made possible the measurement of flight times with an accuracy of nanoseconds. Multichannel analyzers and, later, computers allowed efficient collection of the time information.

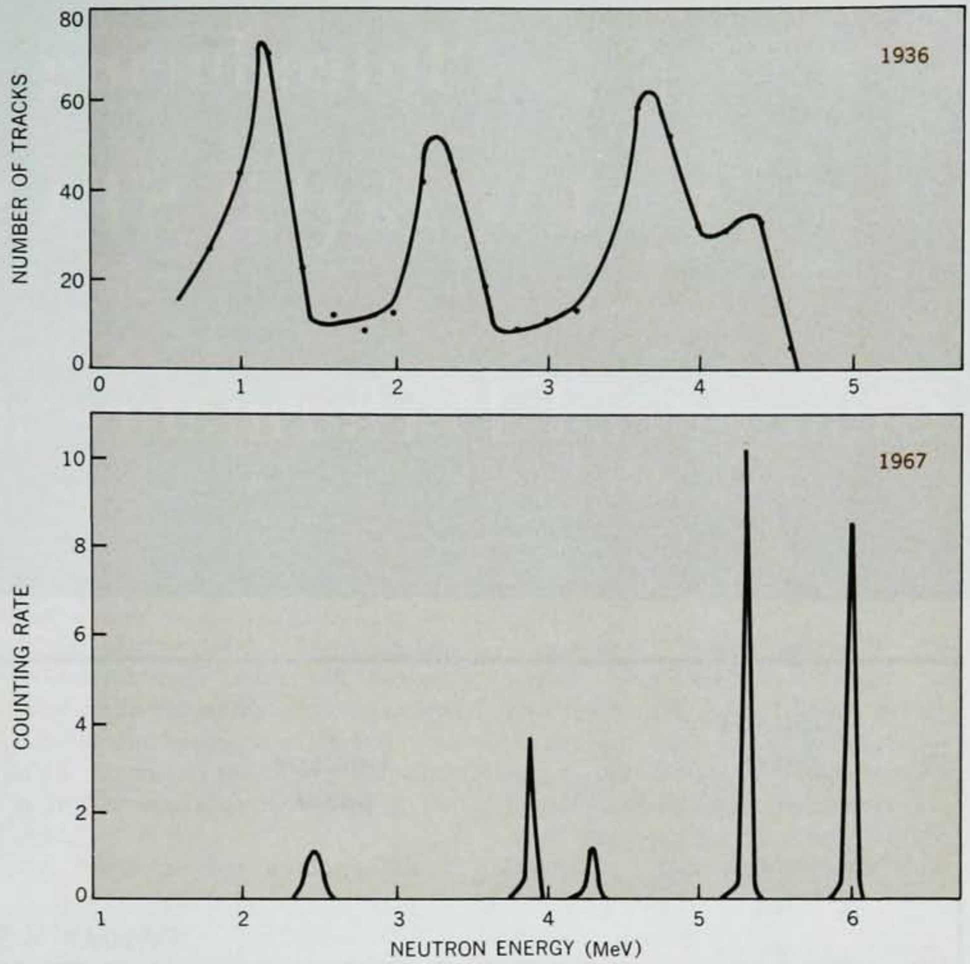
Figure 5 illustrates the advances in neutron spectroscopy in three decades with measurements of the spectrum of neutrons produced when $Be^9$ is bombarded by deuterons. The upper por-




**NEUTRON TOTAL CROSS-SECTION of oxygen, according to measurements made in 1947 (from a review article), in 1951 (at Madison) and in 1968 (at Oak Ridge). Note improvement in resolution of details. —FIG. 4**

tion shows a measurement by Tom Bonner[11] in 1936. A cloud chamber served as spectrometer. In the lower portion is shown the neutron spectrum from the same reaction measured[12] by time of flight at Battelle Northwest in 1967. The two measurements differed in both bombarding energy (0.9 MeV versus 1.8 MeV) and observation angle (90 deg versus 25 deg) and are therefore not strictly comparable. The different bombarding energies are partly taken into account in figure 5 by a shift in neutron energy scale. Although the 1936 measurement was a great accomplishment at the time and was qualitatively correct, the improvement in the results obtained by the new method is striking.

High-resolution spectroscopy, either by bombarding particles of varying but well defined energy, or by high-resolution observations of energy spectra, is essential for the study of nuclear energy levels. On the other hand, measurements carried out with quite low resolution can also furnish useful information. By observing the reaction products with low resolution, it is frequently possible to investigate nuclear energy-level densities and their dependence upon excitation energy. If interaction cross sections are measured as a function of energy with low energy resolution, it is possible to deduce information about the bulk properties of nuclear matter, such as the depth and the radial dependence of the potential that describes the interaction of a neutron with a nucleus.




**ENERGY DISTRIBUTION** of neutrons from the bombardment of beryllium with deuterons. Proton recoils in a cloud chamber were observed in the early measurement (1936) with 0.9 MeV deuterons. The time of flight of neutrons was measured in a more recent experiment (1967) with 1.8-MeV deuterons. —FIG. 5

### *Polarized neutrons*

A type of experiment that was not even seriously considered when Bethe wrote his review articles involves polarized fast neutrons. It was demonstrated in 1953 that neutrons produced in nuclear reactions are usually partially polarized, that is, different numbers of neutrons have their spins pointing up or down with respect to the reaction plane. This was first shown for the D + D reaction in Switzerland,[13] and shortly thereafter for the p + $Li^7$ reaction by Robert Adair[14] at our laboratory at Wisconsin. Polarized fast neutrons have turned out to be an important tool in the study of nuclear reactions, for they made it possible to investigate directly the spin-orbit interaction that is very strong in nuclei.

Although the advances in fast-neutron physics have been impressive, the accuracy of the measurements does not yet satisfy either nuclear physicists or those involved in reactor development. At least once a year a compilation of requests for cross-section information needed in reaction work is published, and the latest list[15] still contains over 1000 separate requests, about half of which for fast-neutron measurements.

* * *

*This article is based on an invited paper given at the 1968 fall meeting of the New York State Section of the American Physical Society, on the occasion of the dedication of the Joseph Henry Physics Building of the State University of New York at Albany.*

### *References*


1. H. A. Bethe, R. F. Bacher, Rev. Mod. Phys. **8**, 83 (1936); H. A. Bethe, Rev. Mod. Phys. **9**, 71 (1937); M. S. Livingston, H. A. Bethe, Rev. Mod. Phys. **9**, 246 (1937).
2. H. H. Barschall, M. H. Kanner, Phys. Rev. **58**, 590 (1940).
3. J. A. Wheeler, H. H. Barschall, Phys. Rev. **58**, 682 (1940).
4. H. H. Barschall, R. Ladenburg, C. C. Van Voorhis, Phys. Rev. **59**, 917 (1941).
5. H. H. Barschall, R. Ladenburg, Phys. Rev. **61**, 129 (1942).
6. H. I. Zagor, F. A. Valente, Phys. Rev. **69**, 55 (1946).
7. H. H. Barschall, M. E. Battat, Phys. Rev. **70**, 245 (1946).
8. H. H. Goldsmith, H. W. Ibser, B. T. Feld, Rev. Mod. Phys. **19**, 268 (1947).
9. C. K. Bockelman, D. W. Miller, R. K. Adair, H. H. Barschall, Phys. Rev. **84**, 69 (1951).
10. C. H. Johnson, F. X. Haas, J. L. Fowler, Bull. Am. Phys. Soc. **13**, 601 (1968).
11. T. W. Bonner, W. M. Brubaker, Phys. Rev. **50**, 308 (1936).
12. D. W. Glasgow, D. G. Foster, Nucl. Phys. **99**, 170 (1967).
13. P. Huber, E. Baumgartner, Helv. Phys. Acta **26**, 420 (1953).
14. R. K. Adair, S. E. Darden, R. E. Fields, Phys. Rev. **96**, 503 (1954).
15. Compilation of EANDC requests for neutron data measurements, EANDC Report 78 (1968). □