

Cross-Section Measurements Made With Neutrons From a Nuclear Detonation

Time-of-flight experiments, conventionally dependent on neutrons from an accelerator, have long been used in the slow grinding out of cross-section data. Last December, at the AEC's Test Station in Nevada, the vastly larger supply of neutrons from an underground nuclear explosion was employed in a scaled-up time-of-flight experiment. The results of that experiment, which are regarded as preliminary, were reported to the American Physical Society in April, during the 1965 spring meeting in Washington, D.C., and the following article is based on the invited paper presented by Dr. Hemmendinger at that time. More precise results are expected from an experiment carried out on June 11, 1965, data from which are still being processed. The author is a group leader at the Los Alamos Scientific Laboratory in New Mexico.

By A. Hemmendinger

Ever since the first nuclear detonation near Alamogordo, N. M., on July 16, 1945, there has been much speculation, and a few full-scale experiments, on the use of such detonations as a source of neutrons for measurements using time-of-flight definition of neutron energy. Although these time-of-flight experiments are in principle quite simple, they had to await the solution of a myriad of unusual engineering problems. When the United States and other nations agreed in 1963 to discontinue atmospheric testing of nuclear weapons, the Atomic Energy Commission invested considerable effort in the development of techniques for underground testing. In the course of this work, vacuum flight paths hundreds of meters long were used from time to time. They were quite straight, with antiscattering baffles and provision for closure to contain bomb debris and radioactive gases. The dirt fill around the pipe provided excellent shielding for the neutron collimator, and it was natural at this stage of development to consider the possibility of cross-section measurements.

The basic argument in favor of such experiments runs something like this: a laboratory accelerator can produce at most 10^{21} neutrons per year, typically in bursts of $0.1 \mu\text{sec}$ duration and in a broad fissionlike energy spectrum. On the other hand, a modest nuclear detonation, with a yield of one kiloton equivalent of TNT, produces 10^{23} neutrons, in a similar energy distribution and also with a duration not greater than $0.1 \mu\text{sec}$. Thus, for any specified resolution, an experiment requiring the flux of neutrons from a

nuclear explosion would require 100 years of continuous running of an accelerator. In making such a statement we must assume that a scheme for data recording in a time interval of $0.1 \mu\text{sec}$ can be devised, in contrast with the long runs made on accelerators where the low counting rates do not require unusually short time resolution. In practice, we take advantage of this situation: for one percent precision we design an experiment so that there will be 10^4 events in one resolution time, and record current output from a detector as a function of time. Thus we have a continuous record of neutron-induced processes, but in adopting this scheme we sacrifice the possibilities of pulse-height analysis and coincidence counting.

In a quick look at other recent time-of-flight experiments, we find an interesting variation in the neutron wheel used by George Cowan^{1,2} of Los Alamos to separate spatially the resonances of ^{235}U and ^{239}Pu , allowing radiochemical determination of the mass ratios for each resonance. A similar wheel experiment was done by Lindner³ of the Lawrence Radiation Laboratory to show resonances in n, γ activations of gold, hafnium, thorium, and uranium. A collimated neutron experiment can also be done if both source and detector are outside of the earth's atmosphere. Successful measurements of this kind were reported by Sam Bame⁴ of Los Alamos and Richard Albert⁵ of LRL.

The work which I am reporting here in rather brief outline was preceded by several investigations at the Nevada Test Site of the Atomic Energy

Commission, but this experiment on December 16, 1964, was our first opportunity to make measurements that might result in new cross-section data. Many other workers contributed to this experiment. Ben Diven was my partner in the design and direction of this program; on our immediate staff were twelve men,* and we leaned heavily on other supporting groups both at the Nevada Test Site and at Los Alamos.

Experimental Program

The vertical vacuum flight path to the surface of the ground was 187 meters. The 12-in-diameter vacuum chamber contained many antiscattering baffles, and 10 ft below ground surface there was a steel collimator 4 ft long, out of which emerged a 1-cm² beam of neutrons. The space above the collimator was filled, except for a beam pipe, with lead shot and borax to absorb scattered neutrons and gamma radiation due to neutrons stopped in the steel. The resolution time, which was determined mainly by the cables and electronic systems used, was 0.1 μ sec, giving $dt/l \sim 0.5$

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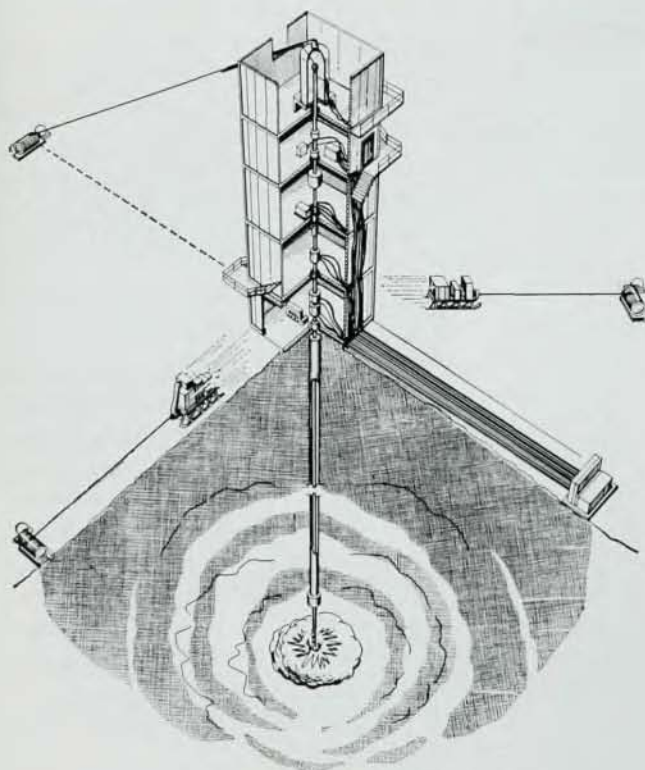


Fig. 1. Schematic drawing showing the instrument tower, sleds leaving the shot location, and the position of the neutron source.



Fig. 2. Photograph of the instrument tower; its dimensions were 17 x 17 x 50 feet.

nsec-m⁻¹, a value not greatly different from the resolution characteristic of modern time-of-flight laboratory experiments.

In Fig. 1 we see a schematic showing the location of the 1.2-kt source, the flight path, and a tower over the hole carrying a number of different experiments. When the bomb explodes there is a ground shock that shakes things up a bit—we find that any damage it does is about equivalent to what happens in shipping by truck from Los Alamos to Nevada. A large bubble of hot gas is formed underground, and when it cools the earth collapses, leaving a large crater. The fall into this crater is quite violent, and we arranged for recovery of some of the experimental hardware. Two sleds are depicted leaving the scene, towed by winches started at shot time.

One instrument sled, mounted directly over the hole, carried a chamber for fission detectors and a set of amplifiers isolated on all sides by inflated inner tubes. The amplifier compartment was air conditioned. Above the sled was a 50-ft-high tower filled with various neutron experiments. Signal cables were placed in a wooden trough to isolate them from other conductors that might introduce multiple grounds. Figure 2 is a photograph of the instrument tower and also shows the cable run to instrument stations.

Fission chambers were constructed much as we learned to build them twenty years ago, with one notable exception: a gaseous ionization chamber using electron collection is not usable in high neutron flux if one seeks resolution as short as 0.1 μ sec; the positive-ion space charge affects the potential distribution in a chamber operating

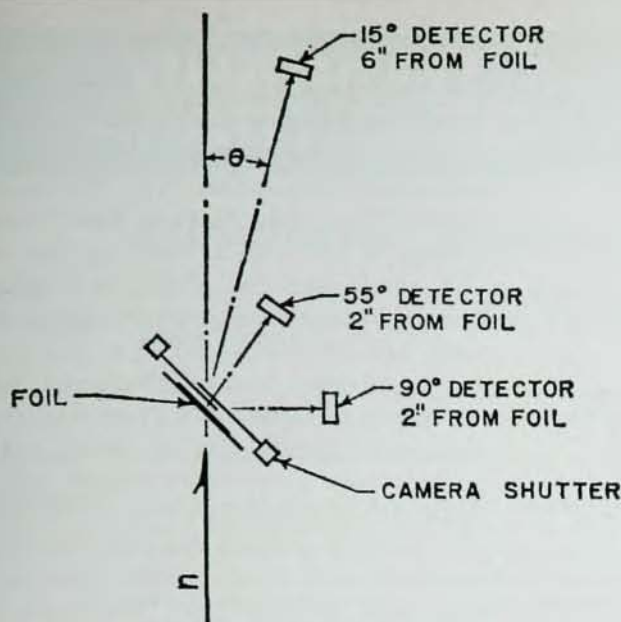


Fig. 3. Fission detector, schematic.

at a few thousand volts so markedly that electrons sit in a potential trough until the positive ions have been swept away, and this takes many microseconds. Another kind of chamber is needed, and one that works fairly well is a solid-state detector. We used diffused junction, totally depleted n-p-n detectors, typically $100\ \mu$ thick, to record the flux of fission fragments. It was necessary to investigate the response of detectors to the intense bursts that were expected, and this was done using a proton beam from an electrostatic accelerator. A proton beam is certainly not the same as a beam of fission fragments, but a proton energy of 830 keV was selected to give at least the same range in the detector as a fission fragment. Other investigations to show the response of gamma-ray detectors were carried out in a flux of $10^7\ \text{R}\cdot\text{sec}^{-1}$, in pulses a few nsec long, obtained from the Los Alamos PHERMEX machine, a high-intensity electron accelerator. The results of these detector investigations, which are already published,⁶ are too involved to describe here, but we did find detectors suitable for this experiment, and many that were unsuitable.

Fission detectors were built as shown schematically in Fig. 3. To allow integration over the angular distribution characteristic of fission fragments, detectors were placed at angles of 15° , 55° , and 90° ; their distances were 6, 2, and 2 in from the foil, and their areas were $1\ \text{cm}^2$. A camera shutter is shown isolating the detectors from the fission foil because some of our targets were so α -active as to damage a detector exposed to them for many hours. This suggests a clear

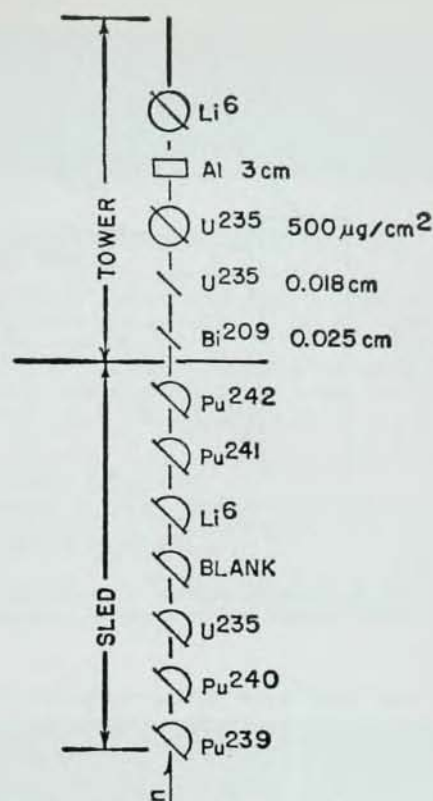


Fig. 4. Experiments on sled and tower, schematic.

advantage of this method of measuring fission cross sections: nuclides can be used that are far too radioactive to use in an experiment lasting days or months in which single counts are recorded. The foil backings were $50\text{-}\mu$ in Ni, which proved to be a poor choice because of $\text{Ni}(n,p)$ reactions at energies above 3 MeV. A ^6Li foil was used as a flux-measuring device; it failed below 500 eV because the signal was too small, and above 2 MeV because its response was not well known; in these regions ^{235}U proved to be a more useful flux indicator.

Another experiment that has interested us is the measurement of the capture-to-fission ratio, a quantity known as α . A relatively thick sample ($250\ \mu$) was needed for this. Since the fission foils were almost completely transmissive, they were placed first in the neutron beam. Our next samples were sufficiently absorbing that they were placed at the top of the tower to allow other experiments below them. To measure α we must record the gamma radiation due to both fission and capture. This was done, and auxiliary laboratory experiments are now in progress to show the fraction of gamma-ray response of the detector due to fissions. Alpha for ^{235}U has already been measured from 3.25 eV to 1.8 keV⁷ and from 30 keV to 1 MeV^{8,9} so we have a set of standards in those energy ranges. In Fig. 4 we see the whole array of experiments on both the sled and the tower. On

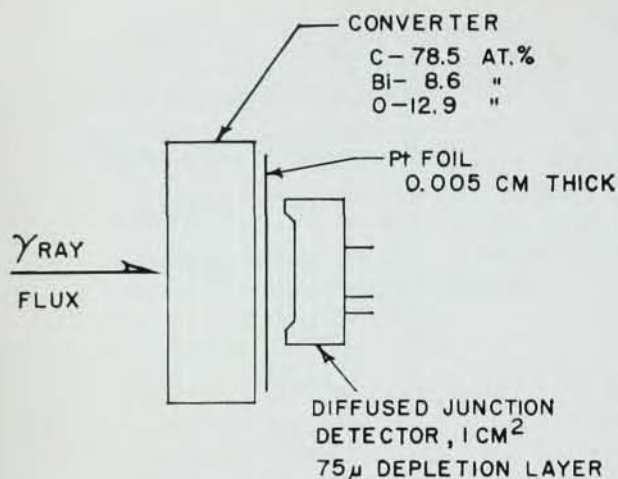


Fig. 5. Schematic drawing of gamma-ray detector, designed for low sensitivity to neutrons.

the sled were fission foils of Pu isotopes 239, 240, 241, 242, the ^6Li and ^{235}U detectors, and a blank foil to show background effects. In the tower, a sample of Bi, which has very little capture, was used in a thickness designed to mock-up the fraction of the signal from ^{235}U due to neutron scattering. At the top of the detector array is an experiment to give the total cross section of Al, mainly because certain Al resonances have been well measured, and this measurement provides a sensitive detection of certain kinds of background and a check on the energy scale.

In Fig. 5 we see the gamma-ray detectors, patterned after those built by Moxon and Rae^{6,10,11} at Harwell, which have particularly low sensitivity to neutrons.

The recording stations were located at a distance from the hole about equal to its depth so that oscilloscopes and other instruments would survive the ground shock. In addition, the electrostatically shielded houses containing these instruments were mounted on a layer of inflated inner tubes for added protection against shock.

To cover the time span from 10 MeV to 10 eV we must record data for about 5 msec, and for the early data we need 0.1 μsec resolution. Oscilloscope sweeps were recorded on plate cameras to give the early data, and for later times a 50- μsec repetitive sweep was used. These scopes were photographed on 35-mm film moving in the Y direction at 100 ft-sec⁻¹. The image reduction ratio was 20:1. The cameras, which were the old General Radio Type 651, were mounted on drill-press stands. To get clean records on moving film, it was necessary to use scopes with P-16 phosphors, which have very fast decay. There were, altogether, 33 oscilloscopes (about half of

these had two beams) and 33 cameras; 13 of the cameras used 35-mm moving film.

To cover the wide-amplitude range of signals, logarithmic preamplifiers were developed by James Lunsford¹² at Los Alamos. These recorded over a range of 10^4 with a resolving time of 0.1 μsec .

A total effort of about two man-years was devoted to optimizing writing speed and resolution, and this included the selection of film, details of film processing, schemes for focusing the scope and cameras, and photometers for setting intensities. Another set of details that required careful study involved time-mark and amplitude calibrations for each film.

A moving picture showing the recovery of sleds was made, as was another showing the tower descending into the crater. Sled recovery was completely successful, but in event of failure we hoped to learn how this job should be done in the future. The movie showed the tower hitting bottom with a severe jolt. The tower was thoroughly ruined, but it was possible to recover much of the experimental equipment from it. The tower after ground subsidence is shown in Fig. 6.



Fig. 6. Photograph of the instrument tower after the shot.

CHARGED PARTICLES

Extending the capabilities of research equipment

Results from Tandem Research Program

The Tandem Research Group has made notable progress in the past year. Significant experimental results from the program are:

1. 250 mA high-brightness positive ion beam from an expanded-plasma source operating at 38 kv.

2. 270 μ A analyzed beam of H_1^+ ions out of the Research Tandem with 320 μ A H^- injection and water-vapor stripping.

3. 2.0 μ A analyzed dc beam of He^- ions. The previous maximum current routinely available has been 0.1 μ A with the EN source.

Doubly Charged Helium Ions

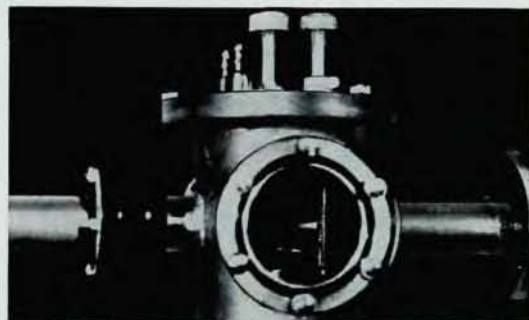
Components are now available for converting 3, 4 and 5 MeV machines to produce He^{++} ions at higher energies. Specifications: 30 μ A at 5.0 MeV; 10 μ A at 7.0 MeV; 5 μ A at 10.3 MeV. More than double this current performance has been demonstrated but with some loss in stability and reliability. Multiple-charge states (2, 3 and 4) of neon, oxygen

and nitrogen have also been produced with the new kit installed in a 3 MeV Van de Graaff. Beam energies from 5.04 MeV to 9.8 MeV and beam currents from 0.1 to 10 μ A were observed. For details on the new He^{++} kit and experimental results, write for Technical Note #13.

Optical Spectroscopy of Excited Atomic States

When an energetic beam of ions is passed through a thin foil, the charge state of the ion may change, either up or down. The emitted particles may be left in states of electronic excitation from which visible light is subsequently emitted during de-excitation. The emitted light spectrum is characteristic of the excited ion. When particle beams of approximately 0.4 μ A or more are used, the light is sufficiently intense for spectroscopic analysis.

The refinement and application of this technique promises to be of major importance in the theory of atomic structure, in measuring hot plasma temperatures, and in acting for the means of energy loss in fast fission fragments in an absorber. Perhaps most importantly, it will help determine the relative abundance of the elements in the sun and other stars, which is the basis for theory of stellar evolution, the origin of the chemical elements, the age

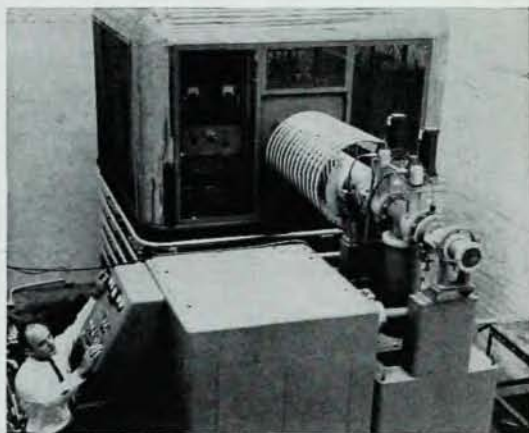


A nitrogen beam, 0.8 μ A at 2 MeV, passes from right to left through a carbon foil approximately $9 \mu\text{g}/\text{cm}^2$ thick, of astronomical objects and the nature of the stellar energy. For further details, ask for Technical Note #10.

Intense Ion Beams at 500 kv

The ICT-500 keV positive ion accelerator now being built by High Voltage Engineering operates at energies from 100 to 500 keV dc and pulsed. In performance tests, the machine has produced analyzed ion beam currents from 4 mA at 100 keV to 10 mA from 300 to 500 keV. 10 mA dc positive ion beam currents of H^+ , H_2^+ and D^+ have been produced at a target located 6 feet from the end of the acceleration tube. Beam diameter is 15 millimeters maximum for all particles over the entire energy range. Previous experience with a similar machine of 300 keV maximum energy showed 15 mA of d_2^+ and a 3 centimeter beam diameter. The ICT-500 positive ion accelerator is designed for dc and pulsed operation in the nanosecond and microsecond range with a minimum pulse length of 2 nsec. at a repetition rate of 2.5 Mc/s. Pulse content is 1 mA protons and 0.7 mA deuterons.

The particle source utilized with the ICT-500 positive ion accelerator is an expanded plasma type which has produced 70 mA total beam at 500 kv.



The high-brightness, intense ion beam produced by the ICT-500 accelerator is eminently suited for laboratory production of 14 MeV neutrons for cross-section measurements, dosimetry studies, weapons-effect simulation and special low-density target experiments.

For detailed information, write to Technical Sales, High Voltage Engineering Corp., Burlington, Mass. or HVE (Europa) N. V. Amersfoort, The Netherlands. Subsidiaries: Electronized Chemicals Corporation, Ion Physics Corporation. ARCO Division, Walnut Creek, California.



HIGH VOLTAGE ENGINEERING

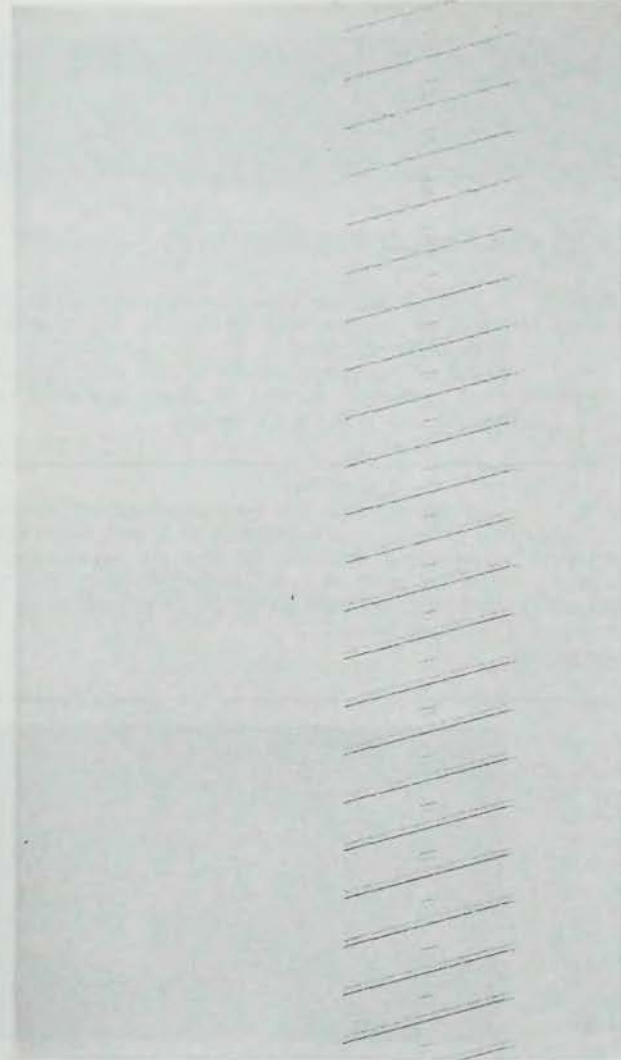


Fig. 7. Oscillogram recorded on 35-mm moving film. The repetitive sweep was 50 microseconds long; image reduction ratio was 20:1; film speed was 100 ft-sec⁻¹.

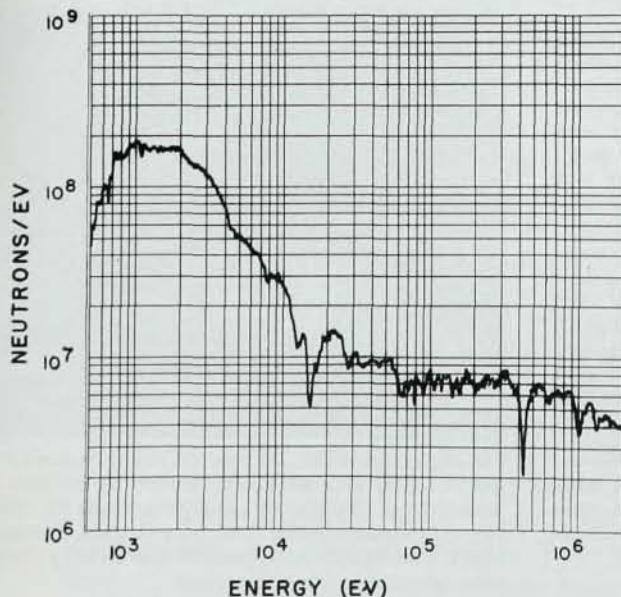


Fig. 8. Neutron flux at the fission detectors, measured in neutrons-eV⁻¹ through the 1-cm² collimator aperture.

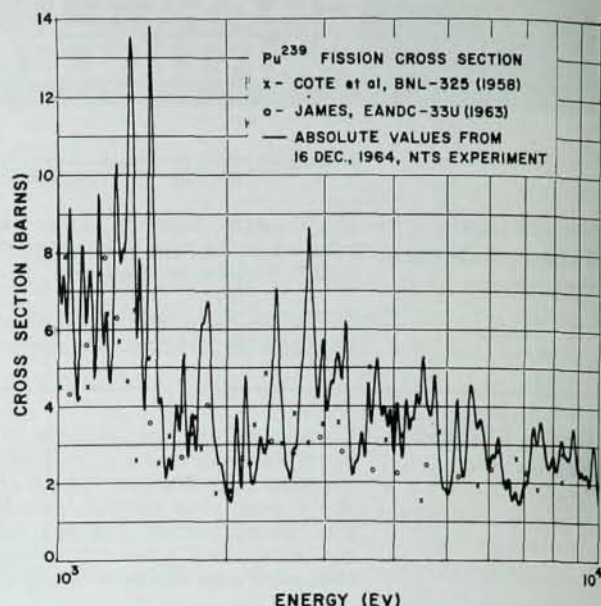


Fig. 9. Fission cross section for ²³⁹Pu. For comparison, independent data of Côté (crosses) and James (circles) are shown.

Results

A typical record on moving film is shown in Fig. 7. After these traces were read and digitized on a projection comparator provided with an IBM card punch (a process which took about 2 months), the production of cross-section data became a matter of machine computation. Data processing from the December experiment is still in progress, but some preliminary results are available. All corrections known to us have been made, but not all of the data have been used, in the sense that integrations over the angular distributions¹³ in fission have not been completed.

In Fig. 8 we see the neutron flux as recorded by the ⁶Li detector. Figure 9 shows the fission cross section for ²³⁹Pu from 1 to 10 keV. The circles are data reported by the electron linac group at Harwell.¹⁴ In Fig. 10 we see the fission cross section for ²⁴¹Pu starting at 1 keV; so far, no data for this isotope have been reported between 100 eV¹⁵ and 0.25 MeV.¹⁶ Figure 11 shows the ²³⁵U cross section from 10-25 eV. The peaks shown here, which were determined by counting single fissions from our film record, correspond to well-known resonances, but their heights are in error because of poor statistics. Also "ghosts" appear on the low-energy side of most peaks, and these are evidently caused by reflection from the

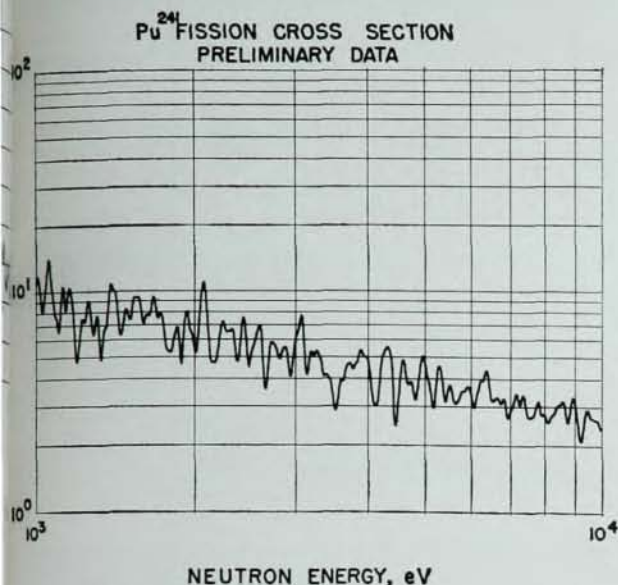


Fig. 10. Fission cross section for ^{241}Pu .

bottom of the hole. In future work, steps will be taken to eliminate these ghosts.

In our first attempt at measuring cross sections from an intense single burst, we acquired some new high-resolution cross-section data, and we feel that we have demonstrated the value of this technique. We made a number of mistakes, and we anticipate further sophistication of these experiments. Plans for the future include more detailed study of backgrounds and refinements in recording

References

1. G. A. Cowan, A. Turkevich, C. I. Browne, and Los Alamos Radiochemistry Group, *Phys. Rev.* **122**, 1286 (1961).
2. G. A. Cowan, B. P. Bayhurst, and R. J. Prestwood, *Phys. Rev.* **130**, 2380 (1963).
3. M. Lindner, Lawrence Radiation Laboratory, University of California, Livermore, Calif., Report No. PNE-113P, 1962 (unpublished).
4. S. J. Bame, *Bull. Am. Phys. Soc.* **9**, 76 (1964); see also: Los Alamos Scientific Laboratory, Los Alamos, N.M., Report No. LADC-6170, 1963 (unpublished).
5. R. D. Albert, *Bull. Am. Phys. Soc.* **9**, 76 (1964).
6. A. Hemmendinger, M. G. Silbert, A. Moat, *IEEE Trans. Nucl. Sci.* **NS-12**, 304 (1965).
7. G. deSaussure, L. W. Weston, R. Gwin, J. E. Russell, R. W. Hockenbury, Oak Ridge National Laboratory, Oak Ridge, Tenn., Report No. ORNL-3738, 1965 (unpublished).

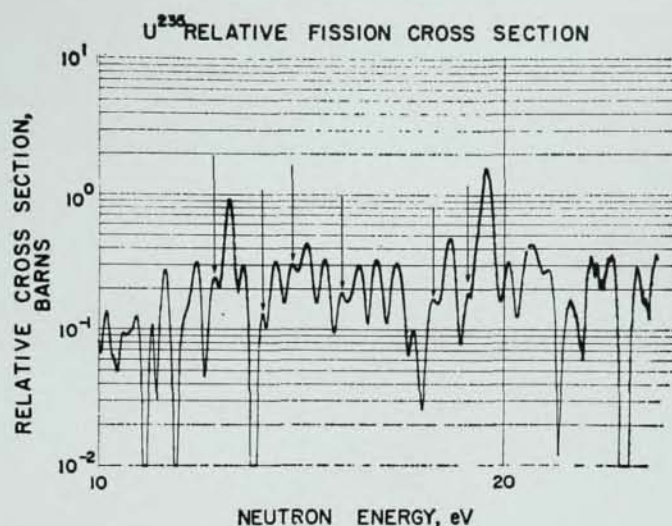


Fig. 11. Fission cross section for ^{235}U , relative value only. Comparison with other measurements reveals the presence of ghosts, indicated by arrows, which were probably caused by reflections from the bottom of the shot hole.

techniques, and we see how to increase detector outputs by a factor of fifty, which will materially decrease statistical fluctuations. In an experiment scheduled for June we propose to measure fission cross sections for ^{233}U , ^{239}Pu , ^{240}Pu , ^{241}Pu , ^{241}Am , ^{242}Am , capture-to-fission ratios for ^{240}Pu and ^{233}U , and, using a ^3He liquid scintillator developed by Lee Aamodt of Los Alamos to count scattered neutrons, the scattering, capture, and total cross sections of Th.

8. J. C. Hopkins and B. C. Diven, *Nucl. Sci. Engrg.* **12**, 169 (1962).
9. B. C. Diven, J. Terrell, and A. Hemmendinger, *Phys. Rev.* **109**, 144 (1958).
10. M. C. Moxon and E. R. Rae, *Nucl. Instr. Methods* **24**, 445 (1963).
11. R. L. Macklin, J. H. Gibbons, T. Inada, *Nucl. Phys.* **43**, 353 (1963).
12. J. S. Lunsford, *Rev. Sci. Instr.* **36**, 461 (1965).
13. J. E. Simmons and R. L. Henkel, *Phys. Rev.* **120**, 198 (1960).
14. G. D. James, European-American Nuclear Data Commission, Report No. EANDC-33U, 1963 (unpublished) p. 14.
15. T. Watanabe, M. S. Moore, O. D. Simpson, National Reactor Testing Station, Idaho Falls, Ida., Report No. IDO-16976, 1964 (unpublished).
16. H. L. Smith, R. K. Smith, and R. L. Henkel, *Phys. Rev.* **125**, 1329 (1965).