

TWO NEUTRON SCIENCES

Improvements in sources, detectors, models and data analysis have produced a flood of neutron-cross-section information. Drifting farther and farther apart in the flood are measurers of cross sections and designers of neutron devices. The result has been two sciences instead of one.



by Herbert Goldstein and David T. Goldman

NEEDS FOR MICROSCOPIC neutron data in nuclear-energy applications have continued to expand over the years. The last two decades have seen steady and at times dramatic progress in the detail and extent to which neutron cross sections can be measured or calculated. Pulsed neutron sources, with associated time-of-flight techniques, now dominate almost all energy ranges from fractions of an electron volt to many millions of electron volts. Concurrently, improved detectors such as large liquid scintillator tanks have been developed, and on-line computers have been designed to manage and analyze experiments involving many parameters.

In consequence, cross-section data have been pouring from the laboratories, threatening to drown the would-be user in a cascade of numbers, even while he protests that his needs are still not adequately satisfied. Theoretical models and tools have also appeared, most notably a phenomenological optical model for the average

properties of fast-neutron cross sections and multi-level formalisms describing resonance behavior with interfering levels.

The very growth of the neutron-cross-section field has brought its own problems. During wartime efforts, designers of neutron devices and cross-section measurers worked in close contact, indeed were often united in the same person. But as the fields of microscopic and macroscopic neutron physics have grown in complexity and sophistication, designers and measurers have inevitably tended to drift apart and go their separate ways. Paradoxically, the lifting of security restrictions has emphasized this division. When the work was classified, the only way they could publish their investigations was to tell each other about it, usually at special information meetings attended by both sides. Now there are separate professional societies and meetings for those, say, who do research in reactor physics and those who study neutron interactions with nuclei. The cross-fertilization and mutual involvement have correspondingly diminished.

Therefore, two advisory committees of the US Atomic Energy Commission, the Nuclear Cross Sections Advisory Group and the Advisory Committee on Reactor Physics, have for some time urged a series of meetings on interactions between neutron technology and nuclear physics of neu-

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tron cross sections. What may be the first of such a series was held at the Shoreham Hotel in Washington last March as a conference on neutron-cross-section technology.

Deltas in data

The role that cross sections play in neutron technology, chiefly in the workings of self-multiplying systems, was described in some 15 papers. Most of them might be called "sensitivity studies," examining the effect of changes in the input microscopic data on the calculated or measured performance parameters of some bulk system. The parameter most often studied was the multiplication constant k , roughly the ratio of neutrons born in one generation to those lost by absorption or leakage in the previous generation. For systems that are just critical, k is exactly unity. Other parameters were also used at times to measure sensitivity to cross-section data; these include effective lifetimes of reactor cores, safety factors such as effect of voids in coolants or temperature coefficient of reactivity $k - 1$ (arising from Doppler broadening of resonance shapes), and even the shape of the neutron spectrum itself.

Studies of thermal-reactor systems, made by Robert L. Hellens (Brookhaven) and others, indicate that variations Δk in reactivity due to uncertainties in available cross sections are of the order of 1%, about the same as uncertainties in composition or dimensions. Most of the effects were as much the result of uncertainties of cross sections in the resonance region (to 10 or 100 keV) as in the nominally thermal region of the neutron spectrum. These same areas of ignorance on the cross sections weighed even more heavily in fast reactor systems discussed by Paul Greebler (General Electric Co.) and David Okrent, Harry Hummel and E. R. Specht (all from Argonne). A series of test comparison calculations of clean fast reactors shows critical mass uncertainties of 20% or more, mostly traceable to variations in cross-section data. Although critical mass is a much more sensitive parameter than k , the variation is still significantly greater than for thermal reactors.

Other important parameters such as breeding ratio, Doppler temperature coefficient or void effects in sodium coolant, are also largely uncertain for lack of accurate cross sections. As might be expected the Washington meeting found that the most influential cross sections are those of fissionable nuclei. Fission and absorption cross sections are particularly influential, but inelastic scattering and radiative capture in structural materials are also important.

These papers did not exhaust the discussions on applications of cross sections, which ranged from questions of accidental criticality in space power applications that use radioactive isotopes such as ^{238}Pu (E. H. Oltewitte and Vahé Keshishian, Atomics International) to needs for capture cross sections in study of nucleosynthesis of elements (George Bell, Los Alamos Scientific Laboratory). Thoma Snyder (General Electric, San José), in a far ranging paper, pointed out some of the problems that will arise in the 1980's when nuclear power production will about equal the total electric-power production rate by all energy sources today. As by-products, rare isotopes such as the heavy plutonium and americium isotopes will be produced annually in ton quantities and the properties of infrequent but annoying contaminants such as ^{228}Th will be of considerable economic importance.

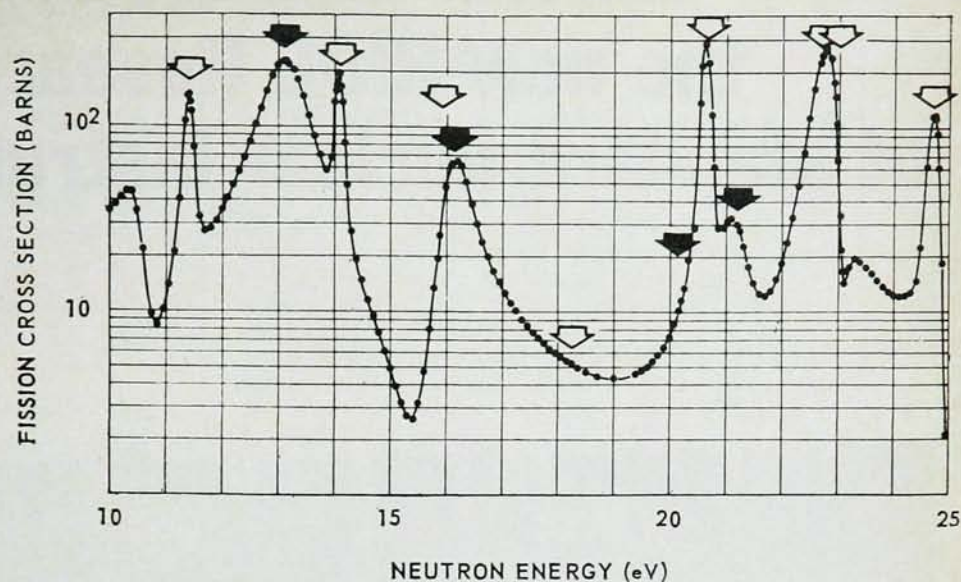
Physics of reactors

Speakers delivering reactor papers tended to talk primarily to other reactor people. But for the most part the cross-section measurers fought their way in dogged fascination through the occasionally heavy thicket of jargon. One pearl produced during a discussion of some integral experiments was that "the universe is worth about seven cents." (Rough translation: in this experiment neutrons scattered back by objects outside the test assembly contribute to the reactivity about as much as 7% of the delayed neutrons arising in fission.) Another Washington paper described measurements on Dirty Jezebel (a critical assembly consisting of a bare sphere of ^{239}Pu with various added materials). The cross-section theorists gave back as good as they received and some (but by no means all) of the reactor people had their difficulties with strength functions, doorway states, distorted-wave Born approximation and Ericson fluctuations.

Invited speakers presented a number of tutorial papers on cross-section-measurement problems. John Harvey (Oak Ridge) spoke on interpretation of measurements in the resonance region (1 - 100eV) in terms of resonance parameters. His survey was complemented by a contributed paper of F. H. Frobner (General Atomic) and others on the use of self-indication techniques, particularly in radiative capture, to give resonance parameters. Both papers indicated that in exceptional cases neutron widths could be measured to 2% (when data for several types of cross sections were available) but that 5-10% accuracy for radiative width was about the best one can do.

Moving up in energy, J. H. Gibbons (Oak

MOCK CROSS SECTIONS simulating fission of ^{241}Pu for neutrons from 10 to 25 eV. The resonance energies, chosen randomly from experimental distribution functions, are shown by arrows; solid arrows are used for $2+$ resonances and open arrows for $3+$ resonances. From a talk by M. S. Moore and O. D. Simpson, of MTR. —FIG. 1



Ridge) described measurement capabilities in the 0.1–100-keV range, emphasizing techniques for radiative-capture cross sections employing large scintillator tanks. He stressed that such measurements, unlike transmission experiments, require knowledge of both detector efficiency and incident flux. The results consequently are of inherently lower accuracy than those for total cross section.

Among other review papers was that of Alan B. Smith (Argonne) who spread before his audience a profusion of wares—particularly elastic angular distributions and inelastic-scattering excitation functions—many taken with his highly automated fast time-of-flight system going up to 2.0 MeV in neutron energy.

Cross sections from bombs

Most striking among the cross-section measurements presented at the conference was a series of papers on experiments conducted with underground nuclear explosions as sources.¹ Although the exotic nature of the source is enough to give the experiments a special cachet, even more impressive is the abundance of precise data obtained and the speed with which the complicated analyses have been performed (most of the results shown came from the Petrel shot in June 1965). Neel Glass and his colleagues (Los Alamos) described measurements of the radiative-capture cross section of ^{238}U that are roughly comparable in resolution to previous total-cross-section data from Columbia,² but the new results have such excellent statistics that the group could see 20 weak resonances below 2 keV that were missed by the Columbia experimenters.

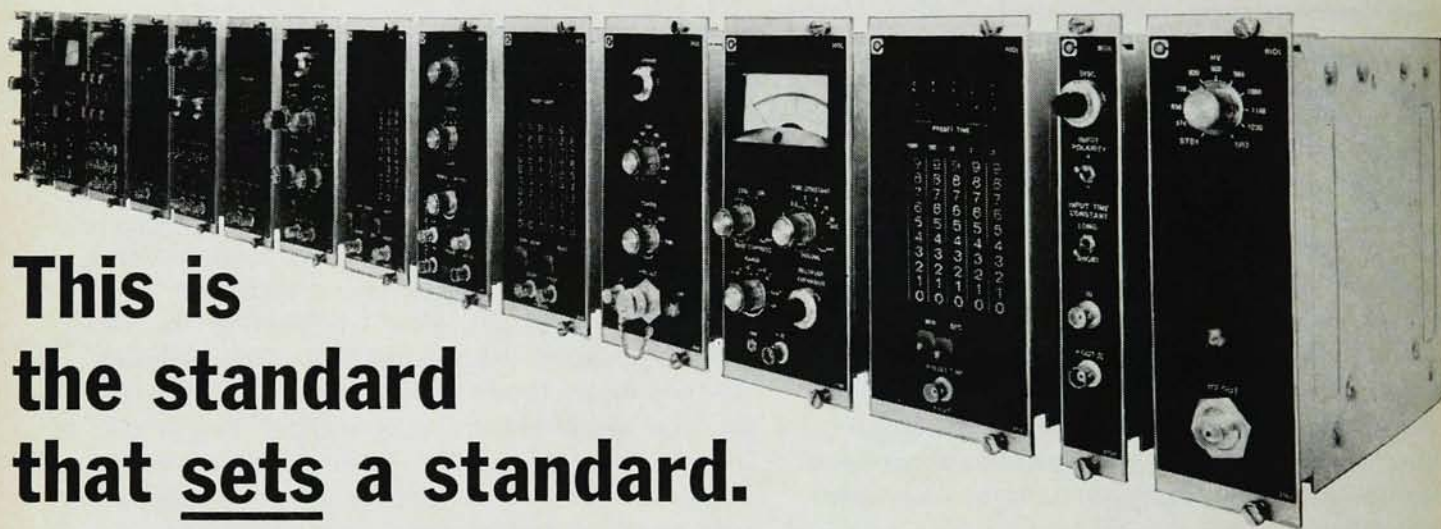
Fission-cross-section data on ^{241}Pu with resolved resonances up to 200 eV were presented in a joint paper from the Materials Testing Reactor and Los Alamos. Again, although the resolution was not much better than had been obtained in previous measurements at Rensselaer Polytechnic Institute,³ the tremendous intensity of the source improved statistics so that many previously unseen small resonances were clearly indicated. To those still accustomed only to the Breit-Wigner single-level formalism the sophisticated multilevel analysis of the ^{241}Pu results proved something of an eye-opener. Other Petrel experiments were on fission cross sections of ^{233}U and ^{240}Pu and on absorption cross sections of superheavy actinides and transuranics.

Benjamin Diven (Los Alamos) described some of the projected measurements with bomb sources. He emphasized that data so far obtained, useful and interesting as they are, constitute only trial runs. They could have been equally well obtained with existing accelerator sources, given enough running time. But where the bomb source would really come into its own would be in the measurement of radioactive samples. Backgrounds from such radioactivity make measurements of radiative capture impossible with conventional sources, where counting must be stretched over hours and days. With the bomb source all measurements are completed in 3 millisec. Plans are therefore to include ^{233}Pa and some hot fission-product samples in future shots.

Multilevel analysis

Mention has been made of multilevel analyses of resonance data. A number of papers stressed that

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for fissile nuclei such as ^{233}U and ^{241}Pu (and to some extent ^{235}U) multilevel description of interfering resonances was both necessary and practicable. This was true not only for analysis of experimental data but also for applications in the calculation of reactor parameters. Interference effects can produce apparent resonant structure that grossly distorts the underlying level scheme, as has been pointed out by T. Lynn,⁴ but analysis techniques are usually able at least to indicate the correct number of levels involved.

M. S. Moore (MTR) demonstrated how the multilevel description could be used, for applications to integral systems, to extend the resonance structure of these nuclei to energies above those at which they had been measured. Using probability distributions of level parameters derived from analysis of ^{241}Pu data from the Petrel shot, Moore created by Monte Carlo methods some "cross-section curves" for this nucleus. Though they of course differ in detail from actual measurements, both the qualitative features and the rederived distribution of level parameters agree with experimental data. (See figure 1.) One could therefore calculate mock cross sections in this way to energies of about 1 keV (10 times higher than the experimental data) and use them with some confidence in reactor calculations.

Analysis of ^{241}Pu data, along with some unreported radiochemical measurements of ^{239}Pu fission by George Cowan (Los Alamos) (also at the Petrel shot), gave strong evidence that average fission width has a spin dependence. The lower spin states have more channels through which fission can occur. Levels with lower spin tend therefore to have high fission width (a phenomenon suspected by Eugene Wigner about 15 years ago) but because of small neutron width the resonances are so low that they appear mainly as a kind of background effect.

A number of integral experiments described at the conference also appear to require these broad fission levels. A good example was reported by a group from Atomic Weapons Research Establishment, Aldermaston; they found little temperature variation (through Doppler broadening) of the net fission rates in a sphere of ^{239}Pu irradiated by neutrons from an antimony-beryllium source.

In the fast region—100 keV to many MeV—reported applications of the optical model were legion, and proponents of various versions and differing systems of parametrolgy argued their cases strongly. Francis Perey (Oak Ridge) pleaded in vain that extrapolations of existing cross sec-

A Fermion Oracle

The story is often told of the early days of the Manhattan Project that when reactor designers were stumped for lack of a neutron-cross-section value they would put their problem before Fermi. Inevitably he would protest he could not help them; the cross section had not been measured and could not be predicted. Ignoring his refusals, the questioners would then begin to recite slowly a string of numbers, all the while watching Fermi closely. When his eyes lit up—that was the number to use!

Even during the Manhattan Project this Fermion oracle was not quite an adequate source of neutron-cross-section data and so a considerable program to obtain the needed measurements was begun.

tions by way of the optical model should be left to the "factory-trained expert"; it was clear that the do-it-your-selves were not at all moved. Truth to tell, some strikingly successful applications of the model were shown, even for such an unlikely candidate as ^7Li .

Something of a running discussion developed over whether the effect of fluctuations in level parameters should be included in statistical calculations of reactor cross sections based on the optical model. Peter Moldauer (Argonne) had the last word when he pointed out that fluctuation phenomena could not be left out of calculations averaged over many levels without doing violence to the model. Including the effects of parameter variations among uncorrelated levels in calculations of average fission or radiative-capture cross sections had been standard for almost a decade. There is no reason to ignore such effects in inelastic scattering wherever a paucity of available channels makes them significant.

Compile and evaluate

It is clear from what has already been described of the conference that the division of those attending into cross-section measurers and users is too simple. One must obviously add the theoretical nuclear physicist. But two relatively new classes also made their appearance—the compilers and the evaluators. In view of the flood of data now coming from experiments the job of the compiler grows daily more complicated. The quantity of numbers is so great that they cannot be published in the usual form in scientific journals; yet the measurements are in effect useless unless the numbers are available not only for visual perusal but also for quantitative manipulation in digital computers.

Murray Goldberg, head of the Sigma Center

at Brookhaven, described the tape library storage and retrieval system developed there, containing then about 250 000 n-tuples of data points. Though at least as sophisticated as similar systems in other fields, it is barely keeping abreast of experimental output, and new systems are under discussion. He also posed to his audience the question of the future of BNL-325, the famous "barn book." The task of producing a supplement to the last edition has grown to almost unmanageable proportions. It is not clear what form future editions should take.

The evaluator is a sort of a middle man between the experimental data and the input to reactor or similar integral calculations. Cecil Lubitz (Knolls Atomic Power Laboratory) and Donald Harris (Bettis, Westinghouse), in invited papers, described some of the functions and problems of evaluators. Inadequately analyzed data have to be interpreted (for example, Doppler and resolution broadening must be removed). Where no data exist, available theoretical models must be drafted into service. And where several sets of data are available, judgment must be rendered as to which is the "best" set, or more truthfully what limits are likely to contain within them the true behavior. K. Parker (AWRE Aldermaston) discussed some computer techniques for evaluation of experimental data, capable of reducing the amount of subjective hand manipulation that is now usually performed. In particular he presented some curve-fitting techniques based on the notion of a mathematical "spline" (for example, a function of overall minimized curvature) that carries out in a rational manner much of the smoothing now left to the eye. He has incorporated a number of these techniques in a curve-fitting code called BARDOT (Best Approximation of Raw Data off Tape).

Among a number of fine examples of the evaluation process presented to the conference, let us mention one: W. C. Davey (Argonne), discussing fast fission cross sections, revealed clearly the difficulties in deciding among a dozen sets of measurements. He marshaled the reasons for his final choice of a curve for ^{235}U that is weighted heavily in favor of some recent data by White,⁵ even though they were 6-7% lower than many of the other sets. Davey noted that White's points were rather sparsely spread in energy and expressed the wish that more points had been measured. A graphic reminder of the extreme difficulty of these accurate measurements was then provided when J. F. Barry, a colleague of White, pointed out from the floor that the published points

had taken six years to measure. The ensuing discussion also illustrated the feedback that can sometimes be obtained from integral measurements. It was remarked that a number of experiments with critical assemblies could be better fitted to calculated predictions if White's smaller cross sections were used.

The final session was devoted primarily to an examination of future developments in our capabilities in cross-section measurements. A number of reasonable extrapolations from present pulsed neutron sources were presented, along with some completely different approaches. One was left with the impression that none of these new ideas represented great steps beyond existing techniques. On the contrary, there was the feeling that the potential of machines now available or under construction had not yet been fully exploited. With sufficient interest, people and financial support, the facilities presently in existence could go far toward both meeting applied needs and providing new insights into nuclear processes.

As banquet speaker, Alvin M. Weinberg, director of Oak Ridge, put the neutron-cross-section field into perspective in relation to the overall problem of governmental attitude toward scientific research. Weinberg has been a strong proponent of the thesis that the best claim science has for public support is its eventual practical usefulness to society, looking on "basic science as overhead on applied science." Conceding that in nuclear physics the basic and applied threads of the science have shown the inevitable tendency to fragment and diverge, he argued rather for a strengthening of lines of communications between these two threads. In the past they have served to "fertilize and fructify each other." If meetings such as this can help intertwine the two threads, "the resulting stouter rope will not only sustain a heavier burden of application, but also a deeper probing into the puzzle of nuclear structure." □

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AEC Report CONF 660303, to be issued shortly, will contain the conference proceedings.

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