BOOK REVIEWS

Selection of books for review is based on the editors' opinions regarding possible reader interest and on the availability of the book to the editors. Occasional selections may include books on topics somewhat peripheral to the subject matter ordinarily considered acceptable.

WORTH THE EFFORT

Title Reactor Physics in the Resonance and Thermal Regions

Editors Albert J. Goodjohn and Gerald C. Pomraning

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Reviewer Bal Raj Sehgal

These books are the proceedings of a national topical meeting of the American Nuclear Society held at San Diego in February, 1966. Volume I brings together the papers presented on neutron thermalization; Volume II, those on neutron resonance absorption. Most of the papers are review papers presented by invitation and come from both American and European workers in the fields. Fortunately, the organizers of the meeting knew their business well and the invited authors are recognized leaders in their particular specialties.

That these books are useful to reactor physicists and core designers can be stated without reservation. They bring together an up-to-date (1966) single source of information on the latest experimental techniques, analytical methods, theory, and data in the fields of neutron thermalization and resonance absorption. As is true for proceedings of any meeting, not all reactor physicists and designers in the readership of *Nuclear Applications* will be interested in all of the papers. However, there is enough material here for everybody to derive some benefit. These books are not text books, but a thesis research student in these fields will find the papers very useful.

Volume I

Volume I contains 18 papers, and the subject matter can be divided into three broad areas concerning (a) atomic motions in moderators and the scattering law, (b) integral thermalization experiments and theory, and (c) the calculational methods for neutron spectra in heterogeneous reactor cells.

There are five papers in area (a). The papers by J. A. Young and by J. U. Koppel review the theoretical work done at General Atomic on scattering law for crystalline and hydrogenous moderators, respectively. Their new codes GASKET and FLANGE calculate the neutron scattering cross section $\sigma_s(E' \rightarrow E)$ from atomic dynamical models in which some parameters are fixed from experimental data on elastic constants, infrared or neutron double differential scattering. It is found for crystalline moderators that, although in some cases the phonon frequency spectrum may be quite different from the measurements, the reactor spectra are reproduced quite well. For water, the model is refined enough to give excellent agreement with the measured $\sigma_s(E)$ and the spectra in homogeneous media. Koppel also discusses the interesting differences between neutron scattering with ortho and para liquid hydrogen.

The papers by Adrente et al. (Italy) and Rahman (ANL) are concerned with the difficult problem of atomic motions in liquids. Adrente et al. present a hindered translational model in which atoms carry out harmonic oscillations at energies below a potential barrier and free translation above that. The potential barrier energy is assumed to be the activation energy for self diffusion. The calculations of mean square displacement of proton in water agree fairly well with the measurements. The paper by Rahman describes an exact computer calculation for motion of 864 particles of liquid argon. A beautiful picture of the process of self diffusion is presented. The paper by Brugger (Phillips Petroleum) considers the problem of trying to extract information about the scattering sample (gases, liquids, solids) from the measured neutron double differential scattering data. These three papers can be used for future work in constructing models for moderators.

There are three papers in the area of integral thermalization by Corngold (BNL), J. R. Beyster et al. (GA), and P. B. Daitch (RPI), respectively. Corngold discusses the pulsed experiments in detail and the physics information obtained from them. That the pulsed experiments haven't fulfilled the early high hopes is pointed out. The eigenvalue problem and the presence of discrete and continuous regions is succinctly presented. The comparison of theory and experiment is reported for light and heavy water and for graphite and Be. The paper is rich in both physics and mathematics—a special trademark of Corngold. Beyster et al. present an excellent and complete review of General Atomic work on integral thermalization. The paper discusses the development and applications of new kernels for moderators and compares the measure-

ments and the calculations of neutron spectra in homogeneous moderators. The measurements of single differential scattering $\sigma_s(E' \rightarrow E, \theta)$ and the total cross section $\sigma_s(E)$ for the common moderators are also reported and compared with calculations. It is the feeling that measured spectra in pure water and D_2O can be satisfactorily predicted ($< 10\%$). Further work in very heterogeneous H_2O systems and crystalline moderators is still needed. Daitch reports the work done in RPI, where the effort is specialized to the areas where a large pulsed accelerator can yield understanding or useful data. Work has been done mostly on cross sections and time-dependent spectra. Some spectra have also been measured in multiplying heterogeneous media. An interesting idea is presented for measuring resonance integrals by using pulsed-neutron techniques.

The last ten papers in Volume I are on various methods of calculating spectra in heterogeneous reactor cells. One immediately notices two different approaches, i.e., the American and the European. The American method is that of completely numerical calculation, fully utilizing the modern high-speed computers. The Europeans (except the English and the Swedes), on the other hand, place more reliance on analytical development and try to cut down the computer time and space requirements. The four European papers use the secondary model of Cadilhac et al., with the combination of collision probability theory (for spatial heterogeneity) to predict spectra and reaction rates which are in quite close agreement with the results of the completely numerical US code, THERMOS. One US paper by Robinson and Ferziger also employs the mathematical approach (Case's method) to calculate disadvantage factor for a two-region slab lattice cell. The spatial distribution is calculated exactly in this method; however, it is not easy to get much detail in the energy variable. The results check pretty well with THERMOS as long as the cell is not very thick optically. It is my opinion that as the scattering kernels become more sophisticated and more stringent demands are made on accuracy, the analytical approach will be replaced by the purely numerical methods.

Perhaps the most rewarding US paper is by Pomraning (GA), who reviews the generally used transport methods in calculating spatially dependent spectra. These are the P_N (or B_N), the *DSN*, and collision probability (THERMOS) methods. Ancillary problems like preparation of group cross sections, leakage effects, and anisotropic scattering are also discussed. A brief comparison of calculations and experiments is included. The paper is so complete and well written that one wishes the various codes using these methods were listed.

A brief but clear exposition of the Monte Carlo methods used in the Naval reactor program for calculation of thermal spectra is presented by Gelbard (BAPL). The problem of calculating foil activations in a reactor cell serves as a basis for illustrating some of the techniques used in calculation, e.g., the adjoint method. A related paper is by Nakache and Kellman (UNC), who present details of the code THERMOPILE and present results of some initial calculations. It is shown that the cell reaction rates can be obtained rather accurately in a short computer time. Monte Carlo methods are exact and can handle complex cell geometries and, therefore, will be used more and more as bigger and faster computing machines are available. A Swedish paper by Jonsson and Pekarek describes their code CLEF, which uses collision probability methods and Egelstaff kernel to calculate thermal spectra. The added advantage of the CLEF code is that it calculates the collision probabilities for a cluster cell exactly. A thorough comparison of the calculated and measured thermal foil activation ratios in the Marviken power reactor is presented and found to be satisfactory.

A paper by N. Francis (KAPL) presents the theory on the still largely unexplored area of calculating spectra with variational methods. Only a few codes use these methods and it is not clear whether these methods will supplant the transport or the Monte Carlo methods.

Volume II

There are 17 papers in this volume, out of which 7 are concerned with the measurements and the rest with the calculations.

J. A. Harvey (ORNL) discusses the measurement of total cross section in the resonance energy range and the evaluation of resonance parameters. The presentation is very clear and almost unique in its ability to make the experimental considerations evident to the theoreticians. The shape and area methods of analysis and the errors associated with the resonance parameters due to the uncertainties in the resolution function and Doppler broadening are explained. The advisability of complementary capture measurement for resonances whose $\Gamma_n \cong \Gamma$ is pointed out. A related paper by Haddad et al. (GA) describes the techniques used in the measurement of capture cross section and the analysis used in deriving resonance parameters. Above $\cong 10$ eV, the capture measurements compete with the transmission measurements, since they provide a much better estimate of Γ_γ. A combination of various types of measurements, i.e., transmission area, capture area, and the self-indication ratio provides the best handle on an accurate determination of resonance parameters. Haddad et al. discuss this aspect and recommend the "best" combinations for various types of resonances.

Papers presented by Hellstrand, by LeSage and Sher, by Brooks, by Feiner and Esch, and by Amyot et al. describe integral experiments on resonance absorption. Such measurements are necessary to provide a check on the microscopic resolved and unresolved resonance parameters. A reactor designer is more concerned with this type of measurement, since it tells him how much capture and fission he should expect for his system.

Hellstrand (Sweden) reviews the effective resonance integral and the Doppler coefficient measurements made on fertile materials. Various types of the experiments and the attendant uncertainties are discussed. A set of "best" correlations of the form: $I = A + B\sqrt{S/M}$ are presented for U metal, UO_2, Th metal, and ThO_2 rods. Measurements of effective resonance integral of uranium carbide rods are reported by Amyot et al. (Italy) and compared by equivalence to Hellstrand's U metal and UO_2 measurements. Also presented are calculations for the resonance integral of ^{240}Pu and comparisons with experiments. Difficulties in the calculation of reso-

nance capture for cluster lattices with organic moderator are described. A similar paper by Feiner and Esch (KAPL) reviews the measured capture and fission integrals (and thus $\bar{\alpha}$) for fissionable isotopes. A section dealing with the usual corrections necessary to the integral data is very useful. All the recent measurements of the integrals are listed and recommendations are made for the values of capture and fission integrals for ^{235}U, ^{233}U, and ^{239}Pu.

The paper by Brooks (South Africa) deals with another type of integral measurement in the resonance energy range, i.e., α and η. This measurement is simple in principle, but hard in practice. The η measurement requires some fancy analysis of the scattering corrections (due to thick sample size). The α experiment puts stringent requirements on detection techniques in order to discriminate between fission and capture gamma rays. Results of α presented for ^{235}U seem to check with the capture and fission integral measurements. The paper by LeSage and Sher (Stanford University) describes the method of measuring infinite dilution capture integrals with the Moxon-Rae detector. For certain materials this method offers many advantages over the reactivity and activation methods of measurement. Comparison of the measurements is done with the cadmium ratio method. Results are reported for some ten clad and control-rod materials, e.g., niobium and hafnium.

J. J. Schmidt (Germany) is in a class by himself. He is the evaluator par excellence. He takes data from various experimental sources, compares them, and recommends the "best" according to his judgement. In this paper he does this for the resonance parameters of ^{235}U, ^{238}U, and ^{239}Pu. In addition, the recommended parameters for unresolved range are also tabulated. These recommendations have been used in preparing the ENDF/B set of cross sections. Recommendations about the kind of measurements still needed are also made.

Three papers in Volume II are concerned with cross sections and resonance integrals for fissionable isotopes. Garrison (GA) deals with the effect of interference between two neighboring levels on the cross section and the cross-section area. The approach is mainly through the two-level Kapur-Peierls formalism, and calculations are reported for light elements (scattering resonances) and fissionable elements. For fissile elements it is found that a weak level can have an important distorting effect on a neighboring strong level. Calculations for change of cross-section area are reported for some illustrative cases. The paper is quite detailed and more pertinent to nuclear physicists working in the reactor field. The Adlers (Illinois University) present results of calculations for resonance integrals for ^{235}U in some uranium/graphite systems. The set of multilevel parameters generated by them is used and the effect of overlap has been taken into account. Some comparisons have been made with the single-level Breit-Wigner parameters. However, no conclusions about cross sections are drawn because of the preliminary nature of the multilevel parameters. Besides this, there are instructive sections on exact Doppler broadening, slowing down flux calculations, and background cross sections. It is our hope that the work continues to fruition, since it will bring fissile-element cross sections on the same level of reliability as those for fertile elements. Moore and Simpson (Phillips Petroleum) explore the idea of using fission theory and the measured resolved resonance parameters to generate mock resonances for fissile elements in the unresolved range. Plutonium-241 is taken as an illustrative example and the generated mock resonances are compared with the recent data obtained from the Petrel bomb test. The agreement is reasonably good in this case and it is possible that this approach will yield dividends in the near future as more and better resolved data is obtained and spin assignments are made.

Two papers from Brookhaven National Laboratory by Goldstein and by Levine, respectively, describe the intermediate resonance (IR) and the Monte Carlo methods of calculation of resonance integrals. The former method has now been extended to include IR treatment for moderator scattering in two-region heterogeneous cells. The reliance placed on analytical development in this approach is quite similar to those of Europeans in the thermalization theory. The IR method has the advantage of simplicity and ease of calculation and has been incorporated in some English codes. However, in complex geometries the accuracy of this method is reduced because of the assumptions of flat flux and the representation of collision probabilities in a Wigner-type rational approximation. The Monte Carlo codes described by Levine, on the other hand, are big machine codes and do an exact calculation for resonance capture in complex geometries. Main features of the available codes are reported and some discussion of sampling for distributions is presented. Results of calculations with the code REPETITIOUS for ^{238}U rods are compared with the deterministic numerical calculations. Calculation of Doppler coefficient with the Monte Carlo codes is clarified.

There are two English papers contributed by Tyror et al. and by Askew which describe the codes ARGOSY and WIMS, respectively, for calculation of lattice reactivities and foil activation rates. Calculations are presented for a whole series of uranium-graphite and uranium-water lattices, and detailed comparisons are made with the measurements. The conclusion drawn from these analyses is that the resonance capture of ^{238}U in thermal systems should be reduced by 10%. This assertion has been investigated recently by the Brookhaven analysis group in a paper at the 1967 London meeting of the British Nuclear Energy Society on thermal reactors, and such a discrepancy was not observed. It may be that the English codes are over-calculating the ^{238}U resonance capture integral.

Finally, there are two papers on fast-reactor systems, where the energy region of interest goes over to the unresolved range and the cross sections of all elements are most uncertain. Besides that, the methods of calculation are not as well developed as for thermal systems. There is a great concern over the safety of fast systems, since the calculation of temperature (or void) coefficients is not so certain and from all evidence the magnitudes of the coefficients are small and the sign could be positive.

In the paper by Hwang (ANL) the effect of the overlap of resonances of

both fertile and fissile elements on the Doppler coefficient of reactivity is investigated. The treatment is quite sophisticated, but is based on single-level Breit-Wigner representation. The task of analyzing for this effect in the unresolved region where only statistical parameters are available is not easy and there are many uncertainties in the parameter data. It is found that overlap effect slightly increases the negative Doppler coefficient for the large fast reactors. Secondly, it is shown that the narrow resonance approximation for moderation holds reasonably well for fast reactors. A very solid review of the state-of-the-art in the calculations, measurements, and their comparisons of the Doppler and sodium void coefficients in fast reactors is presented by Greebler and Pflasterer (GE). The evidence presented suggests that the sodium void coefficient may be harder to predict than the Doppler coefficient and the comparisons of theory and experiment have been unsatisfactory. The measured Doppler effect for fertile materials has been calculated to within 20%. However, for ^{239}Pu the calculations and measurements disagree violently. Besides the uncertainties in unresolved resonance data, the uncertainties in cross sections of the other elements present affect the predicted direct and adjoint fluxes. It is found that generally the calculations predict a slightly harder spectrum. Much more work on cross sections and calculational methods is needed in this area of prime future importance.

In conclusion, I have enjoyed reading these papers and have learned a lot from them. It was a big job and had me snowed under for quite some time. It was worth the effort, however.

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