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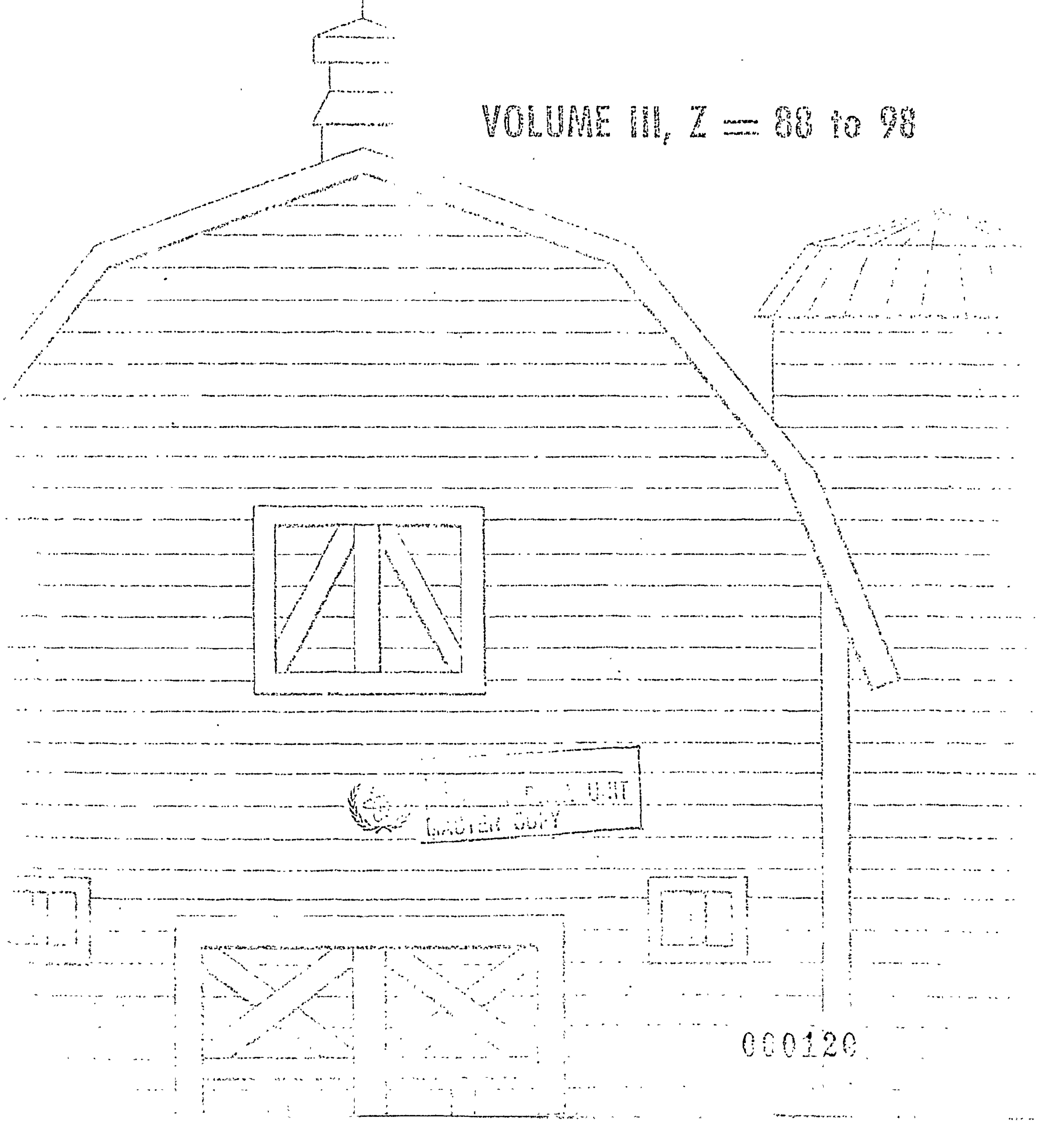
Second Edition

SUPPLEMENT NO. 2

NEUTRON CROSS SECTIONS

VOLUME III, Z = 88 to 98



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NEUTRON CROSS SECTIONS

VOLUME III, Z = 88 to 98

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INTRODUCTION

It is more than five years since the issuance of Supplement No. 1 to the Second Edition of BNL-325. A great number of new measurements of neutron cross sections have been made and must be included in any attempt to up-date the information contained in the Second Edition (1958) and in Supplement No. 1 (1960). The magnitude of the task is indicated by the fact that it is necessary to issue this Supplement in several volumes.

The present Supplement supersedes the previous issues only when there is new information or new interpretations of old information. A goodly amount of the previous issues is not superseded; and the user will be well advised to keep the two previous issues near at hand.

In recognition of the needs of a wide variety of users of this compilation, the present Supplement includes and explicitly refers to all experimental data which can influence the choice of values to be recommended. Thus the sophisticated user, whose opinions may not necessarily coincide with our own, has at hand whatever information is available and can make his own judgment.

The coverage of information is complete but not exhaustive; older work is not included when there is a convincing amount of newer work done with distinctly better techniques. We take care to refer to private communications and to unpublished work by the name of at least one person associated with the work, together with the institution and the year the work was finished. The reader thus can, by some effort, find out more about the work if he desires to. We hope that as a result future publications will include more frequent references to the persons who made the measurements, and fewer references to BNL-325! The only credit we can take is for the "Recommended" values and for the curves we have drawn through the experimental points on the graphs.

The format differs from preceding versions in ways that are intended to be better for the user. The more normal size should ease the storage of this volume along with other reference books. The volume is arranged strictly by chemical elements and by their isotopes. THERMAL CROSS SECTIONS, RESONANCE PARAMETERS, and CROSS SECTION CURVES for one element or isotope are together on successive pages, separate from the next element or isotope. The format is fluid, varying from one page to the next to suit the information to be presented. The reference sources are listed as close to the data as is feasible. Comments associated with the references are only informative and should not serve as a substitute for the reader's consulting the reference himself.

THERMAL CROSS SECTIONS

Although "thermal" cross sections are not in principle different from cross sections at any other neutron energy, we treat them separately here because of their usefulness in many applications, and because many of them are measured by unique specialized techniques applicable only to thermal neutrons. (Nevertheless, the energy dependence of cross sections in the thermal energy range is treated in the section on CROSS SECTION CURVES.)

For each element or isotope, we take up the different types of thermal cross sections in the following order:

Total (σ_T) Absorption (σ_A) (n,γ) ($\sigma_{n\gamma}$) Fission (σ_F)	Reaction Cross Sections
α ($\sigma_{n\gamma}/\sigma_F$) η ($\bar{\nu} \times \sigma_F/\sigma_A$) $\bar{\nu}_p$ (prompt neutrons per fission)	Ratios
Total Scattering (σ_S) Coherent Scattering (σ_{Coh})	Scattering Cross Sections

The present Supplement differs slightly from previous issues of BNL-325 in the way the types of Reaction Cross Sections are interpreted. In this Supplement we emphasize the nuclear process involved, rather than the method of observation.

"Absorption" appears here as a type heading only when two or more types of nuclear processes may be contributing to the absorption. Whenever possible, we use the specific nuclear process as a heading. For example, when no process other than neutron capture (n,γ) is energetically possible, we list absorption measurements together with those by activation, gamma emission, etc., — all under the heading (n,γ). For fissile isotopes, (n,γ) and Fission are the major reaction included in Absorption.

The quantity $\bar{\nu}_p$, the average number of prompt neutrons emitted per fission, appears as a type heading and is to be distinguished from $\bar{\nu}_d$ (the average number of delayed neutrons per fission), and from $\bar{\nu}$ (the sum of the two). For the experiments wherein $\bar{\nu}$ was measured, we deduce $\bar{\nu}_p$ by subtracting the values of $\bar{\nu}_d$ that were measured by G.R. Keepin, T.F. Wimett and R.K. Zeigler, *Phys. Rev.* 107, 1044 (1957). The typical measurement of $\bar{\nu}_p$ has been a comparison with $\bar{\nu}_p$ for another isotope taken as a standard. When the standard was Cf^{252} (undergoing spontaneous fission), we renormalize the author's reported value when necessary to make it consistent with Cf^{252} $\bar{\nu}_p = 3.78 \pm 0.02$, a value that we choose as best fitting the known independent measurements on Cf^{252}. When the standard was U^{235}, U^{233}, or Pu^{239}, we renormalize to be consistent with the Least Squares Value of $\bar{\nu}_p$ for that standard in the present volume, but with the error increased to reflect a greater uncertainty in $\bar{\nu}_p$ values when considered by themselves.

A "thermal" cross section may correspond to any of a variety of neutron energy distributions, from a pure monoenergetic 2200-meter/second beam to the full spectrum of reactor neutrons (indicated in previous issues of this compilation by *, for "Pile neutrons") as the other extreme. We attach one of the following indications of energy distribution to each measurement listed:

$E_n = 0.0253$ eV
Monoenergetic 2200 m/s neutrons

Thermal spectrum
Presumably Maxwellian, but not necessarily at room temperature

Sub-cadmium spectrum
Obtained by cadmium difference measurement

Thermalized spectrum
Neutrons predominantly thermal, as in a reactor shield or thermal column

Reactor spectrum
Pile neutrons, fraction of thermal neutrons dependent on position in reactor.

"Resonance Integrals" appear in the tabulations of thermal cross sections here whenever they have been determined by cadmium ratio measurements or other experimental methods. These are "infinite dilution" Resonance Integrals, and they are defined to include the so-called 1/v contribution. We do *not* list, however, Resonance Integral values that have been obtained by computation from resonance parameters.

Bold-face type is used to indicate a "Recommended" or "Best" value for each type of thermal cross section covered. As a rule, the Recommended value is the weighted mean of those individual experimental values listed below it for comparable energy distributions. Recommended cross-section values are usually (but not invariably) for $E_n = 0.0253$ eV monoenergetic neutrons; this is invariably the case if no energy distribution is stated. For the three principal fissile isotopes, U^{233}, U^{235}, and Pu^{239}, however, we list "Least Squares Values" that form a consistent fit to the ensemble of experimental information available on these isotopes. These least squares values were computed by R. Sher and J. Felberbaum in BNL-918, using the method described in BNL-722. They took into account most of the experimental values listed in this Volume for σ_A, σ_F, α, η, and $\bar{\nu}$; but their normalizations and error assignments frequently differed slightly from ours. They also took into account experimental values for inter-isotopic ratios of these quantities, and many of those ratios we do not list. It should therefore not astonish the user to find that the Least Squares Value for any given type of cross section does not appear to be a best fit to the data displayed before him. Nevertheless, we recommend these Least Squares Values as the best ones to use, and we put them in bold-face type to indicate this.

RESONANCE PARAMETERS

Resonance parameters are important for succinct description of the energy dependence of cross sections; they are subject to striking change with each new experimental measurement; and they are intensively examined by users and measurers of cross sections. Therefore we list the values reported by the various experimenters below a "Recommended" value in bold-face type for each of the parameters which are known well.

The rationale of our use of bold-face type, and of setting down "Recommended" values in general, needs some explanation. In general, the values in bold-face type are a self-consistent set of values that in our judgment best describe the resonances of the entire element. As a rule (but not always) they are simply weighted means of the various experimenters' values. An apparent exception to this rule frequently occurs with the neutron widths, Γ_n and Γ_n^0; a Recommended value may appear unrelated to the experimental values appearing below it in the table. In this case the exception is only superficial; for we consider all the Γ_n and the Γ_n^0 values together in determining Recommended values. A real exception to the rule occurs occasionally with the values of the resonance energy, E_0. If Experimenter A and Experimenter B agree in observing several resonances but disagree as to the energy scale, the Recommended values strike some kind of mean between them (below A, say, and above B). If, however, through instrumental limitations A was unable to observe some of the resonances which clearly appeared in B's data, the Recommended energy values for these resonances are likely still to be above B's values. The spacings between levels are thus more fairly deducible from the Recommended values, since the entire set of parameters is self-consistent.

It is more difficult to explain why no Recommended value is given for some parameters; — in particular why, when a single experimenter has performed the only measurement, his value is not invariably "Recommended." The criterion is basically the confidence that can be attached to the reported result. If the experimenter indicates doubt or suggests that a resonance may be due to a possible contamination of the sample, we make no recommendation, and his value appears in light type. When it is evident, from the graph of the data given by the experimenter or otherwise, that the resonance he reports is a very small one and thus is less certain than some of the others, again we may not recommend this value. In the case of negative energy (bound level) resonances, we seldom make recommendations; for generally the assignment of a bound level is not unique. In the case of the highest energy resonances, where a single experimenter has ventured to report dozens of resonances, we may put all his values in light type. This means, not that they are all in doubt, but rather that the existence and absolute energies of these resonances are not so well confirmed as are those at lower energies.

In the case of the odd-mass nuclides, for which there can be two values of the spin J of the compound state and of the statistical weight factor g of the compound state and for which most of the information on neutron widths has been reported as $2g\Gamma_n$, the column in the table is labelled $2g\Gamma_n$. For a few of the resonances, however, the value of J may have separately been determined; and in those few cases the quantity Γ_n itself can be deduced. The symbols $\Gamma_n =$ precede the Recommended numerical value of Γ_n in such a case, but the individual experimental values of $2g\Gamma_n$ are tabulated in the same column, in accordance with the column headings. Thus, to take an actual instance, $\Gamma_n = 0.88 \pm 0.03$ was tabulated as a recommended value above a group of values (of $2g\Gamma_n$) ranging from 1.16 to 2.2.

For fissile isotopes, we follow the authors in listing in the "Miscellaneous" column the quantity η/ν, which is an abbreviation for $\Gamma_F/(\Gamma_F+\Gamma_\gamma)$.

We record multilevel fitting parameters in the same manner as the customary single-level parameters, but we do not record the interference terms. The text indicates which of the references used multilevel fitting.

Values enclosed in parentheses (frequently found in the Γ_γ column) are values which the experimenter assumed in order to compute one or more other resonance parameters. They have no direct experimental basis.

All known resonance parameter data for the elements Z = 88-100 are included in this volume. In contrast to the remainder of this Supplement, the user need not consult any earlier issues to find older information which has not changed since 1960.

CROSS SECTION CURVES

For each isotope, this section includes all the information not otherwise covered; which is information generally about the energy dependence of neutron cross sections. (For the angular dependence of differential cross sections, the reader should consult BNL-400, "Angular Distributions in Neutron-Induced Reactions.")

The material is ordered in the following way. Low-energy cross sections come first, in the progression:

$$\begin{array}{lrcl} \text{Slow} & (0 & \leq E_n \leq & 1 \text{ eV}) \\ \text{EV} & (1 & \leq E_n \leq & 10{,}000 \text{ eV}) \\ \text{MeV} & (0.01 & \leq E_n \leq & 200 \text{ MeV}) \end{array}$$

Occasionally these categories overlap, and a curve is labelled "Slow and EV," etc.

Within each energy category, the material is arranged according to type of cross section, in this order:

Total (σ_T)	Gamma Emission
Fission (σ_F)	(n,2n)
α (σ_F/σ_T)	(n,3n)
(n,γ) (Capture, $\sigma_{n\gamma}$)	(n,4n)
Capture + Fission ($\sigma_{n\gamma} + \sigma_F$)	(n,p)
$\bar{\nu}_p$ (prompt neutrons per fission)	(n,pn)
Total Scattering	(n,d)
Elastic Scattering	(n,dn)
Nonelastic	(n,t)
η (neutrons/nonelastic collision)	(n,He^3)
Inelastic Scattering	(n,α)

The refinement of experimental techniques in neutron physics, leading to more numerous and more precise measurements of cross sections over wider ranges of energies, forces us to abandon the standard plots of (log σ) vs (log E_n) that have been the predominant feature of previous issues of BNL-325. We endeavor in this Supplement to choose flexibly whatever presentation is best suited to the data at hand, including nongraphical presentations.

As in the past, every experimental measurement is included that contributes significantly to one's knowledge of the value of a cross section at each energy. This does not mean that we include every data point ever measured. On the graphs, particularly in energy regions where a cross section varies smoothly with energy, individual data points may be omitted or replaced by averaged values; when this is done, a note is usually added to the text. In the vicinity of resonance peaks, low-resolution data are generally not plotted when adequate high-resolution data are available. Experimenters' error bars are attached to the points where they do not interfere with clarity.

Whenever it is possible to do so, we indicate a reasonable interpretation of the data by a smoothed curve running generally through the points on each graph. This curve is drawn intuitively, by eye; no attempt is made to perform a least squares fit to any predetermined shape of curve. The user who has no strong opinions of his own may find the curve a convenient one to use as a generally recognizable guide, and he may even treat it as an "evaluated" or "recommended" curve representing the physical situation in question. We hesitate to put the stamp of high authority on these curves, for they have intangible uncertainties. When the choice of a curve is particularly open to doubt, we draw it in as a dashed curve.

On some of the Fission cross section plots in the lower resonance energy region, smoothed Total cross section curves are drawn in lightly above the data and above the heavier Fission curve that is drawn smoothly among the points. This is done as a convenience to the user who may wish to compare Fission and Total cross section data. Where necessary, the energy scale of the lighter Total curves have been adjusted to keep the resonance peaks and valleys in registration with those of the Fission curve.

The data on the $\bar{\nu}_p$ plots are normalized in keeping with the remarks made about $\bar{\nu}_p$ under THERMAL CROSS SECTIONS, above.

A table of numerical values sometimes appears in the text following a graph in order to cover energy regions not included in the graph. When measurements are few, a tabular or textual presentation is used entirely.

After each graph or table is a bibliographic listing of the sources of the data, together with pertinent comments on such matters as experimental method, normalization, and corrections. Whenever we plot or list an experimental value that is different from the originally published value, we explain the change. Other comments about the graph in general, or about data in previous issues of BNL-325, appear after the bibliography.

ACKNOWLEDGMENTS

We are deeply indebted to many persons for their skilled assistance in preparing this Supplement.

J.A. Harvey of Oak Ridge National Laboratory gave invaluable advice and assistance with the resonance parameters; and he chose the Recommended value of the parameters in this volume. J.H. Gibbons of Oak Ridge gave valuable advice and direct help in preparing curves in the kilovolt energy region, particularly the (n,γ) curves. D.T. Goldman of the Knolls Atomic Power Laboratory lent us help with the thermal cross sections.

P.A. Michael, G.S. Lellouche and S. Pearlstein gave most effective help in programming and arranging the plotting of the multitudinous data for the fissile isotopes.

We appreciate greatly the help given us by S.O. Moore of the Brookhaven Reactor Cross Section Evaluation Group who organized the information on η, $\bar{\nu}$, nonelastic and inelastic cross sections; A.M. Daly and S. Ogden of the Brookhaven Neutron Cross Section Compilation Group who prepared many of the original graphs; G.R. Cox of the Graphic Arts Department who ably supervised the preparation of the final graphs; and J. Wasson who prepared the manuscript.

We are grateful to the experimentalists, too numerous to name here, who made special efforts to provide us their data in a useful form and answered our questions regarding their techniques. We hope for the continued cooperation of these people and other users of this book. Since supplementing this compilation is a continuing task, we trust that newly acquired data will be sent to the Sigma Center, here at Brookhaven, as soon as it becomes available. We shall appreciate criticisms, suggestions, and notes of any errors in graphs or text.

$_{88}Ra^{226}$
1620 y

RESONANCE PARAMETERS

$I^{\pi} = 0^{+}$

E_0(eV)	Γ(mV)	Γ_n(mV)	Γ_n^0(mV)	Reference
0.537±0.006	29±1	0.021±0.001	0.029±0.001	Pevzner 56

M.I. Pevzner, L.S. Danelyan, and Yu. V. Adamchuk, *Atomnaya Energiya* **1**, 67 (1956). [Transl. in *J. Nuclear Energy* 4, 366 (1957). [USSR]. Transmission measurement. Mechanical velocity selector. Shape analysis.

CROSS SECTION CURVES

MeV—(n, 2n)

E_n = 14.5 MeV, σ = 1.6±0.2 b.
L.P. O'Conner and J.L. Perkin, *J. Inorg. Nucl. Chem.* **13**, 5 (1960). [Aldermaston]. Following chemical separation sequence, counted 3.3-h Pb^{209} betas in Ra^{225} decay chain.

MeV—(n, 3n)

E_n = 14.5 MeV, σ = 0.63±0.07 b.
L.P. O'Connor and J.L. Perkin, *J. Inorg. Nucl. Chem.* **13**, 5 (1960). [Aldermaston]. Following chemical separation sequence, counted Bi^{212} and Po^{212} alphas in Ra^{224} decay chain.